

# Maori Population Growth in Pre- Zealand: regional population dynamics inferred from summed probability distributions of radiocarbon dates

Journal:	<i>Journal of Island &amp; Coastal Archaeology</i>
Manuscript ID	UICA-2018-0020
Manuscript Type:	Article
Date Submitted by the Author:	15-May-2018
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Keywords:	Demography, Polynesia, New Zealand Archaeology, Summed Probability Distribution of Radiocarbon Dates

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Maori Population Growth in Pre-contact New Zealand: regional population dynamics inferred from summed probability distributions of radiocarbon dates

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**Abstract**

Past population dynamics play a key role in integrated models of cultural change in Polynesia. A key aspect of these models is the interplay between food-production and population growth. Located on the margins of Polynesia, New Zealand presented considerable challenges to traditional Polynesian food-production: many crops were not successfully established and those that were produced greatly reduced yields. Despite these differences, little empirical analysis of Maori population has been carried out in New Zealand. Here, we reconstruct past population dynamics using summed probability distributions of radiocarbon dates (SPDRD). Utilizing advanced quantitative methods we statistically compare observed SPDRD with known models of population growth and carry out a comparative analysis of growth between three economic regions. Finally, we investigate local-scale population deviations across these regions. Our results confirm established ideas regarding the shape of population growth and regional variation in population trajectories, particularly between horticultural and non-horticultural zones. Within the horticultural zone we our results also reveal regional and local-scale variation in population growth. Crucially, our results have an empirical basis and are placed within an absolute chronological context allowing further investigations of key trends.

**Key Words**

Demography - Polynesia - New Zealand Archaeology - Summed Probability Distributions of Radiocarbon Dates

## Introduction

Population size, density, and dynamics have long occupied a central stage in the anthropological and archaeological debates, from early conflicts between Malthusian and Boserupian views on carrying capacities (Lee 1986) to the more recent dispute on their role in explaining cumulative cultural evolution (see Vaesen et al 2016 and Henrich et al. 2016). Demography has also been identified as a catalysts for a wide range of social behaviours, including group fission/fusion dynamics, changes in land tenure systems, and inter-group conflict (Turchin 2005, Kelly 2013, Crema 2014). Reconstructing past demographic patterns thus plays an important component of integrated explanations of long-term change in the archaeological record (Shennan 2000).

Polynesia is a region in which the importance of population dynamics in socio-cultural change is well recognised (e.g. Kirch 1984, Kirch and Rallu 2007 [and references therein], Puleston and Tuljapurkar 2008). Here, a logistic pattern of population growth forms a key component of generalised cultural sequences in the region (Kirch 1984). This sequence suggests small founding populations underwent rapid demographic expansion, fuelled by the exploitation of pristine environments containing rich wild resources such as marine mammals, turtles, and ground-nesting seabirds (Anderson 2002, Walter *et al.* 2006). These resources supplemented limited returns during the establishment and transition to food-producing economies (Kennett *et al.* 2006). Agricultural expansion and intensification led to further population growth, investment in landesque capital (Ladefoged and Graves 2007), and expansion production into marginal zones, such as the leeward regions of some Hawaiian islands (Kirch 1984, 2007). Ultimately, when productive and spatial expansion was exhausted, environmental constraints and/or social processes imposed by emerging socio-political hierarchies led to a reduction in growth and levelling-off of populations (Kirch 1984).

Despite the applicability of this model at a broad scale, it is widely recognized that feedback loops between ecological, demographic, and cultural factors led to unique regional scale variation in population growth and related cultural patterns (Kirch 2007). Key contributors to this variation were the suitability of regional environments for Polynesian food-production and the level of friction associated with establishing these systems (Anderson 2001, Kirch et al. 2004, Kirch 2007a, Lee and Tuljapurkar 2008, Thomas 2008).

Few places in Polynesia presented greater friction than New Zealand, an isolated landmass lying across the sub-Tropical to sub-Antarctic zones, well outside the tropical climes familiar to its first colonists. New Zealand's relatively cool climate was generally hostile to tropically adapted

Polynesian domesticates, many crops species were not successfully established and those that were produced greatly reduced yields (Leach 1984, Walter *et al.* 2006). The large latitudinal range and varied topography also created differential conditions for crops. This variation can be summarized using three informal regions (Figure 1). The northern North Island of New Zealand is warmer, less susceptible to frosts and is generally regarded as the optimal horticulture zone in the country (Walter *et al.* 2006). Central New Zealand presented cooler, harsher conditions for tropically adapted cultigens, which necessitated greater focus on supplementary foraging activities throughout the pre-contact sequence (Walter *et al.* 2006). Finally, southern New Zealand has limited or no evidence for horticultural activity (Leach 1984, Basset *et al.* 2004, Walter *et al.* 2006).

These regional variations, particularly the horticultural/non-horticultural divide, are hugely influential in the development of models of Māori population growth. Despite the variation in conditions, the horticultural zone is typically treated as homogeneous in terms of population dynamics, with a logistic pattern of growth favored (McGlone *et al.* 1994). This assumption is traditionally based on two strands of evidence. The first is an analysis of osteological material by Brewis *et al.* (1990), which is highly problematic due to its use of variables (e.g. starting population size, length of prehistoric sequence) and methods (e.g. counting bone pitting associated with pregnancy) that, since publication, have been revised or overturned (Anderson 1991, Ubelaker and De La Paz 2012). The second is indirect evidence, such as the development of *pa*. *Pa* are fortified sites connected with defense, group identity and status signaling (Barber 1996, Walton 2001). Their emergence is regarded as a marker of increased resource competition bought on by a population at carrying capacity (Groube 1970, Davidson 1984, Anderson 2016). Thus, the appearance of *pa* around AD 1500 (Schmidt 1996) is used as a temporal marker for the onset of the 'leveling-off' period of logistic population growth.

Similar indirect evidence is also used to infer patterns of population in the non-horticultural zone. Here, archaeological evidence suggests early sites in were located in rich wild resource patches where high-ranking resources (e.g. seals [*Arctocephalus forsteri*] and moa [Aves: Dinornithiformes]) formed the basis of the local economy and fueled early growth (Anderson and Smith 1996, Smith 2011). Early settlements followed the patterns predicted by the ideal free distribution, whereby on-going hunting led to decreasing foraging efficiency and eventual abandonment of one patch for another until resources were exhausted within the region (Anderson and Smith 1996, Nagaoka 2002, Kennett *et al.* 2006). The inability to grow tropical Polynesian crops in the southern region (Basset *et al.* 2004) meant that this faunal collapse was

potentially catastrophic for local populations (Anderson and Smith 1996, Jacomb *et al.* 2010). Thus, archaeologists argue that the pattern of population change may follow a 'boom and bust' scenario (Jacomb *et al.* 2010).

The current understanding of Māori population growth in New Zealand is heavily influenced by ideas from Polynesia, which place regional economies at the core of growth models. In particular, the division between horticultural and non-horticultural forms the basis of favored regional growth scenarios. However, while the development of models using indirect evidence allows the inference of a generic pattern of growth anchored to key events in the sequence, its weakness is the inability to identify specific spatio-temporal variations. Such variation is not only possible but likely given evidence from historical sources and recent modeling of large-scale disparity in the spatial density of populations (Davidson 1984; McCoy 2017).

The importance of demographic processes in understanding cultural change over the long term necessitates a renewed focus on this area of pre-contact archaeology in New Zealand. This paper uses summed probability distributions of radiocarbon dates (SPDRD) to develop empirical models of Māori population growth in New Zealand. Using recently developed quantitative methods (Shennan *et al.* 2013, Timpson *et al.* 2014, Crema *et al.* 2016, Crema *et al.* 2017) we assess the veracity of the logistic growth model at a national and regional scale. We then investigate spatial variation in population growth both with and without the imposition of *a priori* regional divisions to develop a multi-scalar understanding of population growth over time in New Zealand.

### ***Summed Probability Distributions of Radiocarbon Dates in New Zealand***

This research uses SPDRD to develop proxies for Maori population. The difficulties associated with other proxy measures in New Zealand (e.g. the absence of foundations from which to base house counts) mean the SPDRD approach provides one of the few avenues in which to investigate past population. The basis of this method is the assumption that a relationship exists between the number of dates and population size (Rick 1987, Shennan *et al.* 2013). While their reliability as a proxy of population changes has been questioned (e.g. Torfing 2015, but see Timpson *et al.* 2015), and ideally they should be part of a suite of independent proxies (cf. Downey *et al.* 2014, Palmisano *et al.* 2017), their construction within an absolute chronological framework make them exceptionally well suited for cross-regional studies (see Crema *et al.* 2017 for review). The idiosyncrasies of the calibration process and the spurious patterns derived by

sampling error make the visual interpretation of these curves highly problematic and potentially misleading. To overcome this issue a number of quantitative approaches have been recently developed (e.g. Shennan *et al.* 2013, Timpson *et al.* 2014, Crema *et al.* 2016), providing a statistical framework for comparing observed SPDRD against a variety of null models fit for different research questions.

*Data*

To produce SPDRD a large body of radiocarbon dates were collected from the online New Zealand Radiocarbon database (<http://www.waikato.ac.nz/nzcd/>) and from published and grey literature. We have taken a conservative approach to date selection, focusing only on charcoal or wood dates. These materials represent the remains of activities (e.g. cooking) that occurred consistently throughout the sequence thus avoiding bias caused by changing cultural behavior (e.g. changing economic focus). Available wood and charcoal dates were screened for reliability prior to analysis. The 315 dates included in this analysis (Table 1) were derived from species considered reliable for dating based on a small to medium in-built age (McFadgen *et al.* 1994) and were due to their secure archaeological context, single dates from sites were retained for the purposes of this research. Rejected dates included those derived from species with high in-built age (McFadgen *et al.* 1994) and/or dubious context (see supplementary material for more information).

While a minimum sample size of 500 dates has been proposed in the past (Williams 2012), the estimate does not take into account spatial and temporal scale (the estimate was based on the assessment of a c. 40,000 year sequence in Australia), nor it is based on formal power analysis associated to specific statistical tests. While we are not able to estimate the precise power of our analysis (and hence cannot estimate the probability of committing a type-II error), we regard the reduction of type-I error as more closely aligned with our objectives and hence consider a sample of 315 radiocarbon across the c. 500 year pre-contact sequence as sufficient.

*Regions*

Recent considerations of Maori population have been formulated within a broad three-region framework associated with optimal, sub-optimal and non-horticultural regions (e.g. Walter *et al.* 2006). To investigate if population dynamics vary across these economic regions we formalized these regions based on the occurrence and density of horticultural features (e.g. food storage pits), which provide a reasonable – if coarse – proxy for levels of horticultural food-production. The northern region is defined here as the area containing approximately 80 *per cent* of recorded

pit sites in New Zealand. The central region is defined as the remaining areas where evidence of horticulture is present while the Southern region is defined by the absence of horticultural features (Basset *et al.* 2004). Any bias introduced by the regional classification is offset by the use of the spatial permutation test (outlined below), which does not use *a priori* regional divisions.

### Methods

This paper draws on a range previously published methods developed to quantitatively assess SPDRDs (Shennan *et al.* 2013, Timpson *et al.* 2014, Crema *et al.* 2016, Crema *et al.* 2017). These methods are outlined in detail in these publications and in the supplementary material; here we provide a basic description of the techniques we employed and their relationship to the goals of this research.

The creation of SPDRD and subsequent analyses were carried out in the R Statistical environment (R Core Team 2017) using the *rcarbon* package (Bevan and Crema 2017). Multiple dates from a single context were 'binned' to reduce "wealth bias" (i.e. significant inter-site and inter-context differences in sampling intensity); samples from the same site separated by more than 100 radiocarbon years were grouped into separate bins. Dates were then calibrated and pooled within the bins to ensure archaeological context contributed only a single date distribution to the overall SPDRD (see Timpson *et al.* 2014). Calibration was carried out using the southern hemisphere 13 calibration curve (Hogg *et al.* 2013); dates were not normalized in order to avoid artificial peaks in the SPRD (cf. Weninger *et al.* 2015). Finally, the pooled mean probabilities from the bins were summed to produce an empirically based SPDRD, which was smoothed using a 50-year rolling mean.

Our first analysis tests the hypothesis that Maori population growth at both a national and regional scale conforms to a logistic pattern. Following the procedures outlined in S1 we statistically compare the observed SPDRD to the simulation envelopes generated from fitted logistic models (the null models). Instances where the observed SPDRD falls outside the envelope (red and blue areas in Figure 2) are regarded as significant local departures, while the extent to which the observed SPDRD differ from the null is assessed using a global p-value.

The second analysis focuses on understanding regional variation in population dynamics. To do this we compare each region's SPDRD to a null model representing a proxy of New Zealand wide Maori population dynamics. Here, the null hypothesis is that all regional SPDRD will have the same shape, indicating they are derived from the same underlying pattern of population growth. Thus, any deviation from the null model (red or blue areas in Figure 3) can be



interpreted as regional variation in population dynamics. Null model envelopes for the first two analyses were based on 5000 random permutations.

Finally, in recognition of the potential impact of applying *a priori* regional divisions in our analysis we apply the spatial extension of SPDRD analysis proposed by Crema *et al.* (2017). The spatial permutation test develops local growth models using a spatial bandwidth of 100 km and compares this to a null model representing the growth rate across New Zealand. As in the previous analysis, the null model is that growth is spatially homogeneous and therefore significant deviations from the trend are represented by either hot spots (greater than expected growth) or cold spots (lower than expected growth). Hot and Cold spots are derived using p-values; however, due to potential inflation of type I error derived by multiple testing we also provide q-values (false discovery rates; see Crema *et al.* 2017 for details). Script and data used in all analyses are available from [https://github.com/andybrown81/NZ\\_Population](https://github.com/andybrown81/NZ_Population).

**Results**

Before discussing the specific results we wish to highlight a key trend that aids in the interpretation of the Figures 2 and 3. Using the observed New Zealand SPDRD (Figure 2, top left) as an example, we can see a pattern of growth until c. AD 1500-1550 at which point growth ‘levels-off’ before appearing to decline later in the sequence. We regard this pattern as spurious based on evidence from the null models, where the underlying date distribution (dashed red line Figure 2) is known to be stable between AD1500 and 1900, yet the calibrated date distribution (grey envelope Figure 2) displays peaks and a decline matching the observed SPDRD. Thus, we argue this pattern is the outcome of the calibration process (c.f. McFadgen *et al.* 1994) and not as a sign of a weakening Maori population at the end of the sequence (but see the discussion of the southern region below).

*Model testing*

The model testing approach was employed to test if regional population trends were consistent with the null model of logistic growth. The New Zealand wide SPDRD conforms to the confidence envelope developed from the fitted logistic model (*global*  $p=0.4445$ ), which is characterized by rapid growth until growth levels off around AD 1500. Thus, at the national scale, we cannot reject the hypothesis that Maori population growth did follow such a logistic trend.



The northern SPDRD closely follows the envelope derived from the fitted logistic model; however, the global deviation between the observed and null models is regarded as significant by the test (*global*  $p=0.0002$ ). This is caused primarily by the higher than expected probability density of the observed curve before AD 1400, although it is worth noting that the remaining portions of the SPDRD fit comfortably within the simulation envelope predicted by the logistic growth model.

No significant variation between the observed data and the null logistic model is present in the central region (*global*  $p=0.4513$ ). However, in this region the fitted logistic model has a slower growth pattern with 'levelling off' occurring around AD 1650-1700. Therefore, while we cannot reject the logistic model, it is important to understand that the shape of logistic growth is very different between the northern and central regions. Inspecting the central SPDRD, it also appears to form a 'stepped' pattern where population grows to a point, levels-off and then grows again (Kirch 1984). However, because these fluctuations are contained within the confidence envelope, we cannot regard them as significant in this instance. It is worth noting that this region has the smallest number of bins, and hence we cannot exclude the possibility that the lack of a significant deviation from the null is the result of low power.

The southern region shows significant (*global*  $p=0.0012$ ) deviation from the null, initially overshooting and then substantially undershooting the expectations of the model toward the end of the sequence where population appears to level off at a much lower density than the other regions. In order to be an optimal fit of the data, the null model does not level off at the peak of the SPDRD (c. AD 1350), were it to do so it seems likely that the significance of the population decline would be much larger in this region. In any event, the results provide clear evidence that logistic growth does not occur in this region. Qualitatively, the boom and bust scenario proposed for the southern region (Hamel 1982, Jacomb *et al.* 2010) appears to be a better model.

### *Permutation Tests*

The permutation testing approach compares regional population growth with a model representing general growth trends in New Zealand. Figure 3 shows that all regions substantially deviate from the null model (*global*  $p = 0.0002$  in all cases). This confirms that, despite support for the logistic model at the national scale, there are significant regional differences in the timing and nature of population change.

The northern region exhibits a significantly lower density of dates in the early phase until approximately AD 1450-1500 at which point it either exceeds or is on trend with the pattern New Zealand wide. This suggests that population density was relatively low in the early period and was instead concentrated in the period after AD 1450 where it was much denser than elsewhere in New Zealand.

The central SPD has a lower than expected density of dates early, although it is closer to the null model than the northern region. The initial growth peaks and levels-off at AD 1450 until c. AD 1650 where it rapidly grows and levels-off at a greater than predicted density. The model testing using a smoothed logistic curve found this pattern could be explained as logistic growth; however, drawing on observed data, the permutation test shows the mid-sequence ‘flattening’ of growth is significant. This suggests a stepped growth pattern may be regarded as a reasonable model of growth for central New Zealand.

Finally, the southern region shows a higher density of dates in the early period of the sequence with a sharp decline after approximately AD 1450 followed by a leveling-off of population at a greatly reduced density than that predicted by the null. Like the model testing, this result is consistent with a boom and bust scenario, albeit one where small populations remain in the region (Hamel 1982).

*Spatial Permutation Test*

Our final analysis assesses spatial variation in population growth without the use of *a priori* regional classifications, which we note are coarse and may obscure finer-grained patterns. Figure 4a shows the pattern of geometric population growth in New Zealand and the five transitions at which we measure growth (I: AD 1200-1300 to 1300-1400; II: AD 1300-1400 to 1400-1500; III: AD 1400-1500 to 1500-1600; IV: AD 1500-1600 to 1600-1700; and V: AD 1600-1700 to 1700-1800). Figure 4b highlights the general growth rate at each of these transitions. The results are consistent with the expected patterns of logistic growth - initial rapid growth followed by a reduction of growth towards zero once carrying capacity is reached.

Local-scale SPDRD were produced by using a distance decay bandwidth of 100 kilometres from each observed sites. Assessment of the raw local growth rates across the five time slices (Figure 5) shows a clear variation, although, at this point the results may be influenced by the calibration phenomena discussed above. To overcome this we compare the local growth patterns to a null

model based on national growth trends (Figure 6). The purpose of this analysis is to identify significant positive or negative deviations (hot and cold spots) from this trend.

Our results (Figure 6) suggest there is significant spatial heterogeneity in the growth rates within and between the three areas defined in previous analyses (although there is no evidence of spatial heterogeneity within the southern region). This may suggest that population growth in the non-horticultural zone generally followed the same trend, but population growth varied significantly in the horticultural zone, such that a basic optimal/sub-optimal division does not sufficiently capture the variation, particularly during early transitions.

Over the first three transitions population growth is strongest in the northern half of the North Island, with hot spots consistently present in the Western Bay of Plenty, Waikato and Auckland areas. Interestingly, while displaying growth (Figure 5), the Far North shows up as a cold spot (i.e. an area of lower than expected growth) in transition I (AD 1200-1300 to 1300-1400; Figure 6) despite presenting optimal climatic conditions for crops. This result may also explain the pattern of growth in the northern regional SPDRD; hot spots and on trend growth areas may have been significantly tempered by the Far North cold spot producing a slower growth pattern than expected. In the final two transitions (IV: AD 1500-1600 to 1600-1700; and V: AD 1600-1700 to 1700-1800) North Island population appears to have stabilized, there are two areas of divergence. The first is a potential cold spot (with p-values 0.05 but q-value > 0.05) located around modern day Auckland. The second is a hot spot in Taranaki (both q and p-value < 0.05), which may account for the later growth of population in the central region SPDRD.

As already mentioned, the non-horticultural zone (southern region) exhibits relatively homogeneous population dynamics, with on-trend growth in transition I (AD 1200-1300 to 1300-1400) followed by significant declines in the remaining transitions. This homogeneity may relate to the low sample size in the region, but it is also generally consistent with growth followed by collapse, but these results suggest an absence of a 'boom', or hot spot in the southern New Zealand during transition I or transition II (AD 1300-1400 to 1400-1500) as observed in our regional models. Interrogating this result further we find that, on average, the southern region does exhibit higher geometric growth in transition I (e.g, northern = 0.012 v. southern = 0.018). However, the lower density of sites in this region creates a wider significance band that incorporates the individual local SPDRD leading the model to regard it as insignificant. Figure 7 illustrates this point. Here we see that growth in the first transition is higher than the theoretical expectations (dashed red line) in the three sites but the simulation envelopes are substantially wider for sites B and C because of the smaller sample size (i.e. smaller number of sites in the

local bandwidth). This can be overcome by increasing the spatial bandwidth; however, this effectively returns us to large-scale regional analysis.

*Discussion*

This research has developed the first empirical models of pre-contact Māori population dynamics in New Zealand. Using advanced quantitative methods we have tested established ideas about the shape of population growth and their variation across different economic regions. The development of local SPDRD has revealed a diversity of population trajectories within the horticultural zone that contributes to a fine-grained picture of spatio-temporal variation in population dynamics. This can contribute directly to integrated models of cultural change in New Zealand.

As outlined earlier, while the logistic model of population growth is widely applicable to Polynesian societies, it requires testing due to context specific feedback between people, culture and environment (Kirch 2007). The established population models in New Zealand have undergone no such scrutiny, therefore our first analysis sought to test if logistic growth was a reasonable model of growth at a national and regional scale. Our results largely confirmed established ideas of Māori population growth. Specifically that logistic growth was a reasonable model nationally and in the northern and central regions, both within the horticultural zone. Despite a smaller sample size, logistic growth can be statistically rejected in the southern region where the SPDRD shows a ‘boom and bust’ pattern consistent with what is suggested by the archaeological literature (Jacomb *et al.* 2010).

The non-rejection of logistic growth in the central region provides an interesting case study of one of the limitations of our approach. Specifically, we find that a modified logistic curve with relatively gradual growth and population peak around AD 1650 cannot be rejected. However, we note that the smooth growth of the null model is not replicated in the SPDRD where a ‘stepped’ pattern is observed (a pattern that is supported by the permutation test). The reason for the non-rejection of the null lies in the wide simulation envelope produced as a result of fewer data points in this region. Thus, while our analyses allow the rejection of specific null models, it does not provide a means to select the ‘best’ model from a range of options as offered by other quantitative approaches (e.g. model selection methods).

While the above results are a useful contribution to New Zealand archaeology, the greater value in our results is the ability to provide fine-grained understanding of spatio-temporal variations in Maori population growth. Focusing first on the southern region, a clear contrast with the other zones can be seen. While qualitatively based, our results appear consistent with the established 'boom and bust' model (Hamel 1982, Anderson and Smith 1996; Jacomb et al. 2010). The rapid 'boom' was probably fuelled by access to big game species. During this period serial over-exploitation led to resource pressure. Decreasing foraging efficiency at sites was mitigated by movement to new patches, so the length of the boom likely reflects the time it took to 'hunt out' patches within the region. The 'bust' around AD 1400 is broadly consistent with the timing of faunal collapse in the region. Smith (2005) suggests seals were extirpated in southern New Zealand within 200 years of settlements while detailed analysis of moa extinction suggests lowland species, which were more easily exploited, were hunted out within decades and that the total extinction of all moa in the South Island occurred by AD 1450 at the latest (Holdaway *et al.* 2014). This supports the idea that resource depression drove population collapse or widespread abandonment of the southern region with some low-level occupation maintained (Anderson and Smith 1996, Jacomb et al. 2010).

Cross-referencing the growth curves it is apparent that the northern region exhibits growth during the period of decline in the south, which could be the result of migration from the southern region. The arrival of even a few thousand immigrants (cf. Holdaway et al. 2014) could have had a significant impact on the competition for resources in the north, and may have had been a contributed to the appearance of *pa*. However, our data cannot differentiate endogenous growth from that which arises as a result of immigration and more evidence is required before firm inferences can be made about the nature of population decline in the south and its impact elsewhere in New Zealand.

In the horticultural zone the northern and central regions present two distinct patterns of growth. The northern region exhibits a pattern consistent with the generic logistic model outlined earlier in this paper. Unpacking this further, the regional model suggests exponential population growth until c. AD 1500 after which growth levels off. The growth is relatively slow compared to the southern region where peak density is reached c. AD 1350. This pattern is consistent with established scenarios of population growth (Davidson 1984, McGlone *et al.* 1994) and the expected economic model of the north. It is argued that northern populations were less reliant or had a lower degree of access to high-ranking wild resources, such as New Zealand fur seal and moa (Walter et al. 2006, Allen 2012), which fuelled population growth in the other

regions. Instead, higher temperatures, good rainfall and fewer frost days per annum - the optimal environment for horticulture in New Zealand - likely led to an early focus on establishing crops (Walter et al. 2006). While optimal in New Zealand, conditions in the north were still relatively harsh compared to Polynesia and it is likely that there was a significant period of experimentation (Barber 2010) and an associated lag in returns during the early period. Moreover, more optimal returns from food production are likely to be achieved through positive economies of scale (i.e. with increasing workforce) and with production investment (Kennett et al. 2006), both of which may lead to a slower growth but ultimately denser populations.

The second part of the logistic model involves a decrease in growth rate as population reaches carrying capacity. Established models of population growth in New Zealand infer this levelling off from around AD 1500 based on the emergence of *pa* and state that the carrying capacity, and therefore population density, was much greater in northern New Zealand (Davidson 1984, McGlone et al. 1994, McCoy 2017). Our model confirms the established models in terms of timing and spatial variation (i.e. higher population density in the north). Furthermore, taking into account calibration effects, the results show the AD 1500 level of population was maintained until European contact. Understanding exactly what this density was for analytical purposes (e.g. as a check of productive capacity estimates) is complicated by uncertainty around projections of Maori population size, which, as Chapple (2017) points out, are currently based on estimates or methods with little empirical basis.

The central region provides the greatest deviation from established population models in New Zealand. While we cannot reject the logistic model in this region, the shape of the data suggests a 'stepped' pattern of growth is a more reasonable model to apply. The initial growth period in the central region follows a similar pattern to the north, but levels off earlier and at a much lower density. Walter et al. (2006) suggest the horticultural economy in this zone was marginal and was supplemented with wild resources. It is possible that, like the southern region, the loss of game resources by around AD 1450 (Holdaway et al. 2014) may have caused growth to stall, though the presence of horticulture in this region sustained population, albeit at a reduced density to optimal zones, after the loss of big game species. Another possibility is that climatic deterioration during the middle period of the New Zealand sequence led to the large-scale abandonment of gardens in central New Zealand as the southern extent of the horticultural zone retreated north (Anderson 2014). While some populations were lost, those in the northern central region continued, with the combined pattern leading to the observed mid-sequence leveling-off of



growth. It is worth noting that these scenarios are not mutually exclusive and could have occurred in tandem.

A particularly interesting aspect of the central model is the secondary growth phase, which occurs around AD 1650. This growth may reflect the resurgence of populations in the north of the central region after successfully adjusting their horticultural practices to the sub-optimal conditions. Alternatively, and perhaps more convincingly given the rapid nature of the change, the population growth could be the result of an influx of people from within the densely populated and contested northern region. This later interpretation matches oral traditions of population movements to the South Island and lower North Island during the latter part of the sequence (Anderson 2016). It is also consistent with emerging narratives about the complexity (e.g. multiple occupation and abandonment events) of Māori settlement history (Maxwell et al. 2018) and patterns of population expansion from optimal to marginal environments in Polynesia (Kirch 2007a).

Finally, another aspect of the central population model demonstrates the possible implications of greater demographic understanding in New Zealand. It is generally accepted that *pa* emerge as a behavioral outcome of population density reaching carrying capacity, which leads to resource competition and greater inter-group conflict (Anderson 2014). Our northern results support this idea, showing maximum population density was reached around the same time as the commencement of *pa* construction in AD 1500 (Schmidt 1996). Yet, in the central region, peak population density occurs c. AD 1650 around 150 years after the peak in the northern region. If we do connect *pa* with populations at carrying capacity, this result raises the possibility that *pa* were a later phenomenon in the central region. One clear hurdle to this interpretation is the AD 1500 date advanced by Schmidt (1996). However, while Schmidt collected radiocarbon dates from *pa* across New Zealand, his reliability criteria reduced the number of dates down to sixty, all of which were from *pa* within the northern region. Some support for this idea can be found in McCoy's (2017) spatial analysis of *pa* dates, which hints at some degree of southern progression of *pa*. However, in his model *pa* appear concurrently across the North Island, although this may be due to the use of unfiltered dates in the analysis. On this basis, it is possible that variation in the timing of *pa* construction did occur. Alternatively, the 'flat' period of growth in the central region between AD 1450 and AD 1650 indicates some form of carrying capacity was met. This may have elicited a similarly competitive social arena and the development of *pa* around the same time as in the northern region. Was this the case, it leads back to the previous question: by what mechanism did carrying capacity increase in the central region?



To this point we have discussed population dynamics according to economic regions; however, given the diversity of environments within some of these regions and the relatively coarse means by which the regions are defined, it was useful to investigate growth at a local-scale. The application of the spatial permutation test (Crema et al. 2017) allows a greater understanding of intra-regional growth and the assessment of the regions as analytical units. With respect to intra-regional growth, the southern regions does not seem to exhibit spatial heterogeneity in growth. While we cannot dismiss the fact that this is due to smaller sample sizes it is worth noting that such pattern would be consistent with the economically driven model of population growth discussed above, whereby food gathering and faunal collapse presented similar conditions throughout the region. For the horticultural zone, our results suggest the broad optimal/sub-optimal divisions of the northern and central regions obscures variation in population dynamics, particularly during the early centuries and within select areas, such as Auckland and Taranaki, which exhibit a population cold spot and hot spot respectively, during the later phase. The exact causes of these variations are beyond the scope of this paper; however, there is a clear need for greater understanding of the local-scale patterns and their underlying processes, particularly in terms of the establishment of horticulture and subsequent human/landscape interactions.

**Conclusion**

Population is widely recognized as a key component of socio-cultural change in the past. While widely researched elsewhere in Polynesia, the ephemeral nature of New Zealand’s archaeological record has made it difficult to achieve anything beyond generalized demographic reconstructions using traditional methods. Therefore, while the validity of summed probability distributions as a proxy for population has been questioned (e.g. Contreras and Meadows 2014), the method provides the only realistic way of developing population models in New Zealand. Our results reveal broad agreement with established population models: optimal horticultural areas display logistic growth with denser population and probably more complex socio-political organization, while the non-horticultural southern region underwent relatively rapid growth before faunal collapse led to population collapse or large-scale abandonment of the region. While the horticultural central region is often conceived in the same terms as the northern region, our results showed clear divergence, which we argue is the result of the suitability of the regional for Polynesian production systems. Finally, our spatial permutation tests revealed local-scale variation both between and within regions. This suggests that, despite their explanatory utility, large-scale regional divisions obscure varied regional trajectories of growth that have the

potential to elucidate more fully Māori cultural change in New Zealand. The investigation of these variations within the context of broader studies of human-landscape interaction during the settlement phase should be a key goal of New Zealand archaeology.

### ***Acknowledgements***

The authors wish to thank Andrew Bevan, Stephen Shennan, Aimee Foster and Tim Thomas for providing valuable feedback on this research and early drafts of this paper. AB was funded by the Leverhulme Trust project grant (ECF2016-355).

### ***References***

- Anderson, A. 1991. The chronology of colonisation in New Zealand. *Antiquity* 65: 767-95.
- Anderson, A. 2001. No meat of the beautiful shore: the prehistoric abandonment of subtropical Polynesian Islands. *International Journal of Osteoarchaeology* 11 (1): 14-23.
- Anderson, A. 2002. Faunal collapse, landscape change and settlement history in Remote Oceania. *World Archaeology* 33 (3): 375-90.
- Anderson, A. 2014. Emerging Societies, AD 1500-1800, in A. Anderson, J. Binney & A. Harris (eds), *Tangata Whenua: an illustrated history*. Wellington: Bridget Williams Books.
- Anderson, A. 2016. The Making of the Maori middle ages. *Journal of New Zealand Studies* 23: 2-18.
- Anderson, A. & I.W.G. Smith. 1996. The Transient Village in Southern New Zealand. *World Archaeology* 27 (3): 359-71.
- Allen, M. 2012. Molluscan foraging efficiency and patterns of mobility amongst foraging agriculturalists: a case study from northern New Zealand. *Journal of Archaeological Science*, 39(2): 295-307.
- Barber, I. 1996. Loss, change, and monumental landscaping: towards a new interpretation of the 'Classic' Maori emergence. *Current Anthropology*, 37: 868-80.
- Barber, I. 2010. Diffusion or innovation? Explaining lithic agronomy on the southern Polynesian margins. *World Archaeology*, 42 (1): 74 – 89.

- 1  
2  
3 Bassett, K., H. Gordon, D. Nobes, & C. Jacomb. 2004. Gardening at the edge: documenting the  
4 limits of tropical Polynesian kumara horticulture in southern New Zealand. *Geoarchaeology* 19:  
5 185-218.  
6  
7  
8 Brewis, A., M. Molloy & D. Sutton. 1990. Modelling the prehistoric Maori population. *American*  
9 *Journal of Physical Anthropology* 81: 343-56.  
10  
11  
12 Chapple, S. 2017. New Zealand numbers from nearly nowhere: 80,000 to 100,000 Maori circa  
13 1769. *New Zealand Journal of History*, 51(2): 104-121.  
14  
15  
16 Crema, E. 2014. A simulation model of fission-fusion dynamics and long-term settlement  
17 change. *Journal of Archaeological Method and Theory* 21: 385-404  
18  
19  
20 Crema, E., J. Habu, K. Kobayashi and M. Madella. 2016. Summed Probability Distribution of  $^{14}\text{C}$   
21 Dates Suggests Regional Divergences in the Population Dynamics of the Jomon Period in  
22 Eastern Japan. *PLoS One* 11(4): e0154809.  
23  
24  
25 Crema, E.R., Bevan, A., Shennan, S., 2017. Spatio-temporal approaches to archaeological  
26 radiocarbon dates. *Journal of Archaeological Science* 87: 1–9.  
27  
28  
29 Contreras, D. & J. Meadows. 2014. Summed radiocarbon calibrations as a population proxy: a  
30 critical evaluation using a realistic simulation approach. *Journal of Archaeological Science*, 52:  
31 591–608.  
32  
33  
34 Davidson, J. 1984. *The Prehistory of New Zealand*. Auckland: Longman Paul.  
35  
36  
37 Downey, S.S., Bocaage, E., Kerig, T., Edinborough, K., Shennan, S., 2014. The Neolithic  
38 Demographic Transition in Europe: Correlation with Juvenility Index Supports Interpretation of  
39 the Summed Calibrated Radiocarbon Date Probability Distribution (SCDPD) as a Valid  
40 Demographic Proxy. *PLoS ONE* 9, e105730.  
41  
42  
43 Groube, L. 1970. The origin and development of earthwork fortifications in the Pacific, in: R.  
44 Green and M. Kelly (eds), *Studies in Oceanic Culture History Vol 1*. 133-64. Honolulu: Bishop  
45 Museum Press.  
46  
47  
48 Hamel, J. 1982. South Otago, in: N. Prickett (ed.), *The First Thousand Years* 129-150. New  
49 Zealand Archaeological Association Monograph 13. Palmerston North: Dunmore Press.  
50  
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60

- Henrich, J., R. Boyd, M. Derex, M.A. Kline, A. Mesoudi, M. Muthukrishna, A. Powell, S. Shennan and M. Thomas. 2016. Understanding cumulative cultural evolution. *Proceedings of the National Academy of Sciences*, 113(44): 6724-6725.
- Hogg, A., Q. Hua, P. Blackwell, M. Niu, C. Buck, T. Guilderson, T. Heaton, J. Palmer, P. Reimer, R. Reimer, C. Turney & S. Zimmerman. 2013. SHCal13 Southern Hemisphere Calibration, 0–50,000 Years cal BP. *Radiocarbon*, 55(4): 1889-1903.
- Holdaway, R., M. Allentoft, C. Jacomb, C. Oskam, N. Beavan & M. Bunce. 2014. An extremely low-density human population exterminated New Zealand moa. *Nature Communications* 5: 5436 doi: 10.1038/ncomms6436
- Jacomb, C., R. Walter & C. Jennings. 2010. Review of the Archaeology of Foveaux Strait, New Zealand. *Journal of the Polynesian Society* 110 (1): 25-59.
- Kelly, R. 2013. *The Lifeways of Hunter-Gatherers: The Foraging Spectrum* (2<sup>nd</sup> Edition). Cambridge: Cambridge University Press.
- Kennett, D., A. Anderson & B. Winterhalder. 2006. The Ideal Free Distribution, Food Production, and the colonization of Oceania, in D. Kennett and B. Winterhalder (eds), *Behavioural Ecology and the Transition to Agriculture*. 265-88. Berkley: University of California Press.
- Kirch, P. 1984. *The Evolution of the Polynesian Chiefdom*. Cambridge: Cambridge University Press.
- Kirch, P. 2007a. Paleodemography in Kahikinui, Maui, in P. Kirch & J. Rallu (eds), *The Growth and Collapse of Pacific Island Societies: Archaeological and Demographic Perspectives*. 90-107. Honolulu: University of Hawai'i Press.
- Kirch, P. 2007. "Like Shoals of Fish": archaeology and population in pre-contact Hawaii, in P. Kirch & J. Rallu (eds), *The Growth and Collapse of Pacific Island Societies: Archaeological and Demographic Perspectives*. 52-69. Honolulu: University of Hawai'i Press.
- Kirch, P. & J. Rallu. 2007. *The Growth and Collapse of Pacific Island Societies: Archaeological and Demographic Perspectives*. Honolulu: University of Hawaii Press.
- Kirch, P., A. Hartshorn, O. Chadwick, P. Viousek, D. Sherrod, J. Coil, L. Holm and W. Sharp. 2004. Environment, Agriculture, and Settlement Patterns in a Marginal Polynesian Landscape. *Proceedings of the National Academy of Sciences*, 101(26): 9936 – 41.

- Ladefoged, T. & M. Graves. 2007. Modelling agricultural development and demography in Kohala, Hawai'i, in P. Kirch and J. Rallu (eds), *The Growth and Collapse of Pacific Island Societies: Archaeological and Demographic Perspectives*. 70-89. Honolulu: University of Hawai'i Press.
- Leach, H. 1984. *1,000 Years of Gardening in New Zealand*. Wellington: Reed.
- Lee, R. 1986. Malthus and Boserup: a dynamic synthesis, in: D. Coleman & R. Schofield (eds), *The State of Population Theory*. 96-130. Oxford: Blackwell.
- Lee, C. and S. Tuljapurkar. 2008. Population and prehistory I: Food-dependent population growth in constant environments. *Theoretical Population Biology*, 73(4): 473-482.
- Maxwell, J., McCoy, M., Tromp, M., Hoffman, A. and I. Barber. 2018. The Difficult Place of Deserted Coasts in Archaeology: New archaeological research at Cooks Beach (Pukaki), Coromandel, New Zealand. *Journal of Island and Coastal Archaeology*, 13 (1): 1-20.
- McCoy, M. 2017. Geospatial Big Data and Archaeology: prospects and problems too great to ignore. *Journal of Archaeological Science*, 84: 74-94.
- McFadgen, B., F. Knox & T. Cole. 1994. Radiocarbon curve variations and their implications for the interpretation of New Zealand prehistory. *Radiocarbon* 36: 221-36.
- McGlone, M., A. Anderson & R. Holdaway. 1994. An ecological approach to the Polynesian settlement of New Zealand, in D. Sutton (ed.), *The Origin of the First New Zealanders*. 136-163. Auckland: Auckland University Press.
- Nagaoka, L. 2002. Explaining subsistence change in southern New Zealand foraging theory models. *World Archaeology*, 34: 84-102.
- Palmisano, A., Bevan, A. and S. Shennan. 2017. Comparing archaeological proxies for long-term population patterns: An example from central Italy. *Journal of Archaeological Science* 87: 59-72.
- Puleston, C. & S. Tuljapurkar. 2008. Population and prehistory II: Space-limited human populations in constant environments. *Theoretical Population Biology* 74(2):147-60.
- R Core Team. 2017. R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing.
- Rick, J. 1987. Dates as data: an examination of the Peruvian preceramic radiocarbon record. *American Antiquity* 52: 55-73.

Schmidt, M. 1996. The commencement of pa construction in New Zealand prehistory. *Journal of the Polynesian Society* 105: 441 – 60.

Shennan, S. 2000. Population, Culture History, and the Dynamics of Culture Change. *Current Anthropology*, 41(5): 811-35

Shennan, S., S. Downey, A. Timpson, K. Edinborough, S. Colledge, T. Kerig, K. Manning & M. Thomas. 2013. Regional population collapse followed initial agriculture booms in mid-Holocene Europe. *Nature Communications* 4: 2486 doi: 10.1038/ncomms3486.

Smith, I.W.G. 2005. Retreat and resilience: fur seals and human settlement in New Zealand, in G. Monks (ed.), *The Exploitation and Cultural Importance of Sea Mammals*. 6-18. Oxford, Oxbow Books.

Smith, I.W.G. 2011. Pre-European Maori exploitation of marine resource in two New Zealand case study areas: species range and temporal change. *Journal of the Royal Society of New Zealand*. doi: 10.1080/03036758.2011.574709

Thomas, T. 2008. The long pause and the last pulse: Mapping East Polynesian colonisation, in S. O'Connor, G. Clark & F. Leach (eds), *Islands of inquiry: Colonisation, seafaring and the archaeology of maritime landscapes*. 97-112. Canberra: ANU E Press.

Timpson, A., S. Colledge, E. Crema, K. Edinborough, T. Kerig, K. Manning, M. Thomas & S. Shennan. 2014. Reconstructing regional population fluctuations in the European Neolithic using radiocarbon dates: a new case-study using an improved method. *Journal of Archaeological Science* 52: 549-557.

Timpson, A., Manning, K., Shennan, S., 2015. Inferential mistakes in population proxies: A response to Torfing's "Neolithic population and summed probability distribution of 14C-dates." *Journal of Archaeological Science* 63: 199–202.

Torfing, T. 2015. Neolithic population and summed probability distribution of 14C dates. *Journal of Archaeological Science* 63: 193-98.

Turchin, P. 2005. Dynamical feedbacks between population growth and sociopolitical instability in agrarian states. *Structure and Dynamics*, 1(1). Retrieved from <http://escholarship.org/uc/item/0d17g8g9>

Ubelaker, D. & J. De La Paz. 2012. Skeletal indicators of pregnancy and parturition: a historical review. *Journal of Forensic Sciences* 57(4): 866-72.

Vaesen, K., M. Collard, R. Cosgrove and W. Roebroeks. 2016. Population size does not explain past changes in cultural complexity. *Proceedings of the National Academy of Sciences*, 113(16): 2241-2247.

Walter, R., I.W.G. Smith & C. Jacomb. 2006. Sedentism, subsistence and socio-political organisation in prehistoric New Zealand. *World Archaeology* 38(2): 274-90.

Walter, R. & M. Weisler. 2017. East Polynesian connectivity, in T. Hodos (ed.), *The Routledge Handbook of Archaeology and Globalization*. 369-86. New York: Routledge.

Walton, A. 2001. The Burden of Defence in Prehistoric New Zealand. *Archaeology in New Zealand*, 44(1): 47-57.

Weninger, B., L. Clare, O. Joris, R. Jung and K. Edinborough. 2015. Quantum Theory of Radiocarbon Calibration. *World Archaeology*, 47: 543-566.

Williams, A. 2012. The use of summed radiocarbon probability distributions in archaeology: a review of methods. *Journal of Archaeological Science*, 39: 578–589.



## Tables

**Table 1. Breakdown of class 1 radiocarbon dates used in this analysis.**

Region	Dates	Bins
Northern	153	112
Central	73	47
Southern	89	55

For Peer Review Only

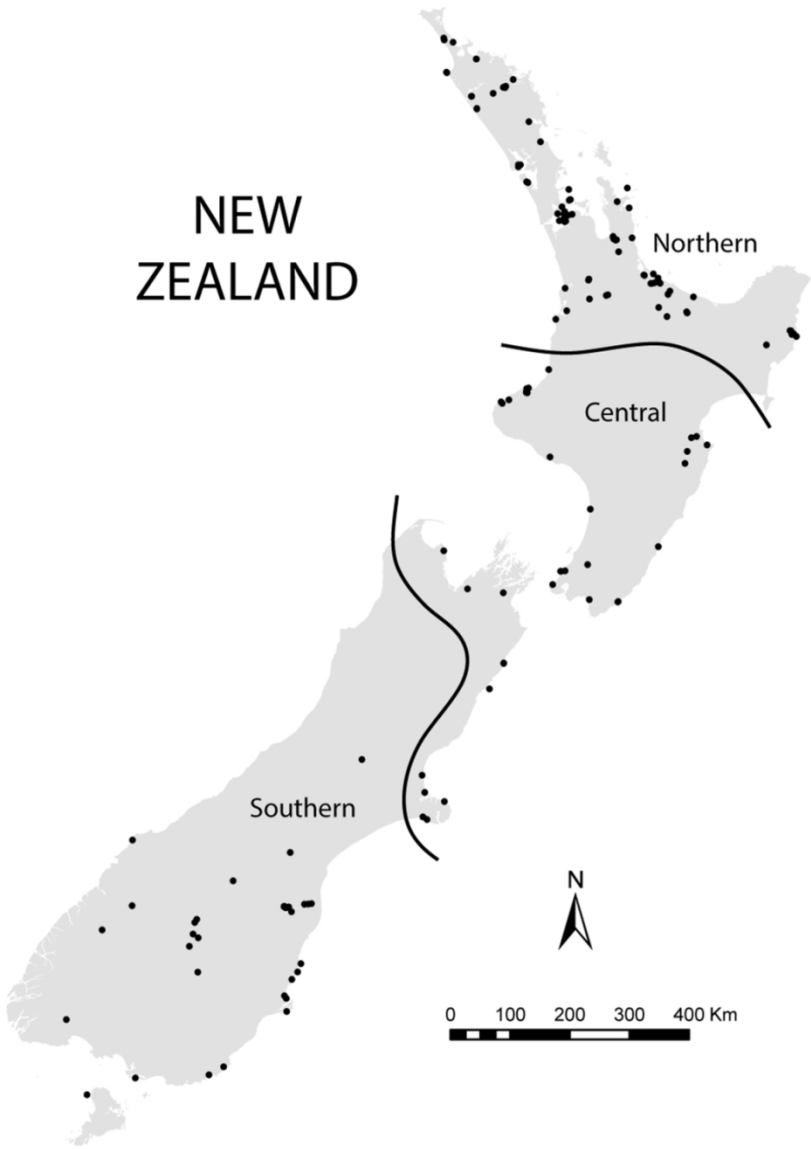


Figure 1 – Distribution of sites yielding radiocarbon dates for this analysis and the three economic sub-regions of New Zealand used in this analysis.

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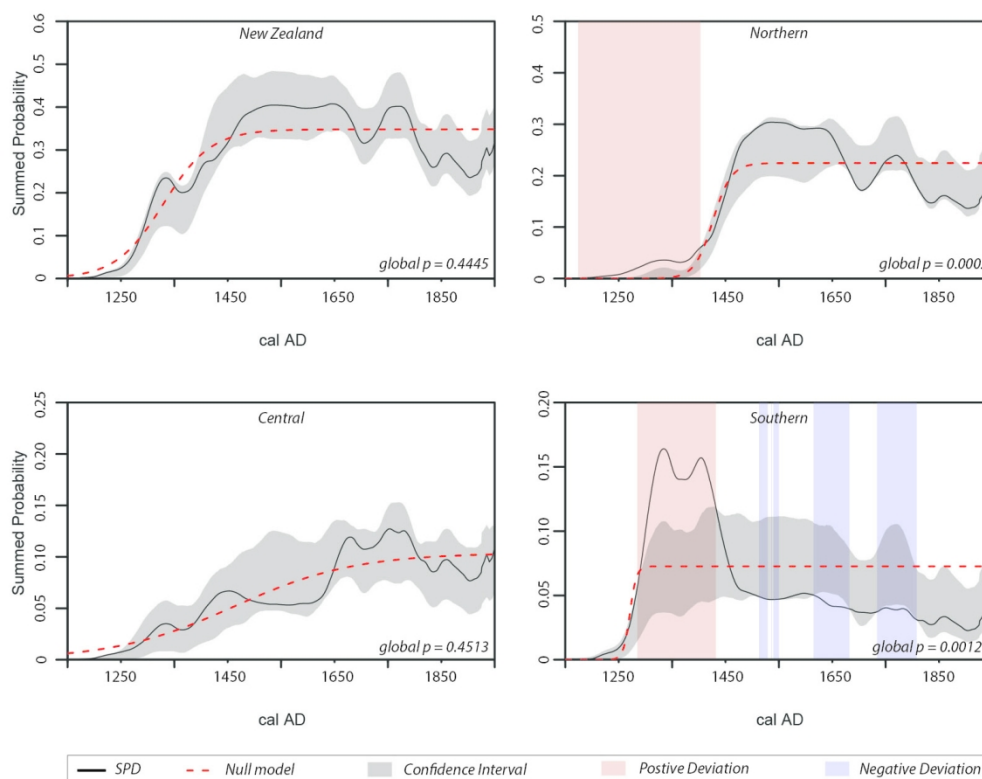


Figure 2 – Model tests showing the similarity between observed data and fitted logistic models of growth. Observed SPD for each region shown with a solid black line, fitted null model (logistic growth) shown with the red dashed line, grey areas represent the confidence envelope derived from the null model. Red and blue bands represent areas where the observed SPD significantly deviates from the null model (e.g. red areas are those where regional population exceeds the expectations of the null, blue areas are those where population is beneath expectations).

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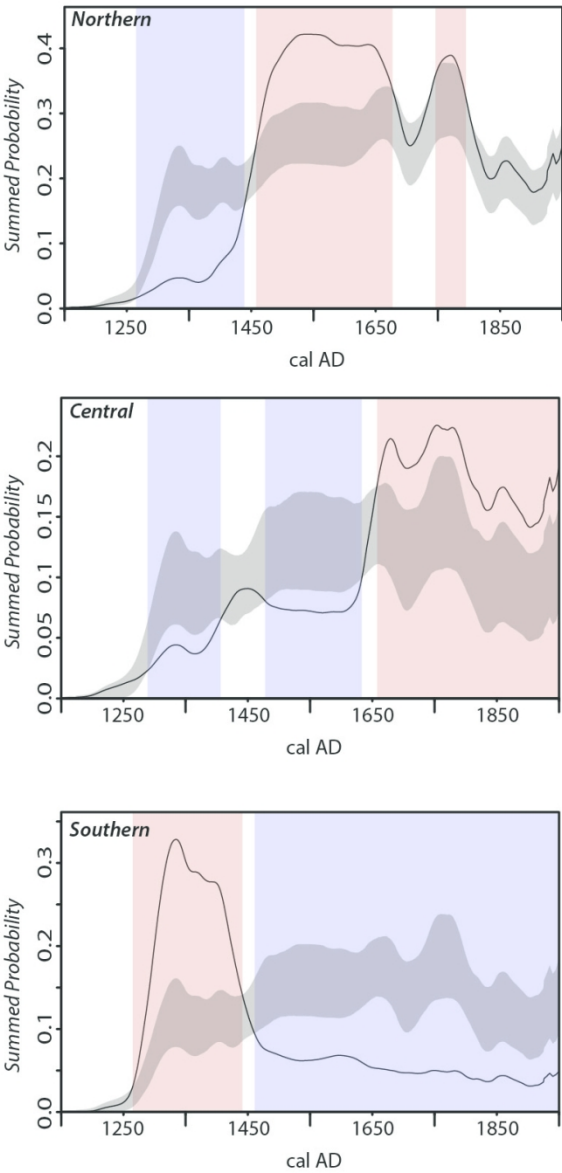


Figure 3 – Permutation tests showing variation between regional population growth. Observed SPDRD for each region shown with a solid black line. Grey areas represent the confidence envelope for the null model, red and blue bands represent areas where the observed SPD significantly deviates from the null model (e.g. red areas are those where regional population exceeds the expectations of the null, blue areas are those where population is beneath expectations).

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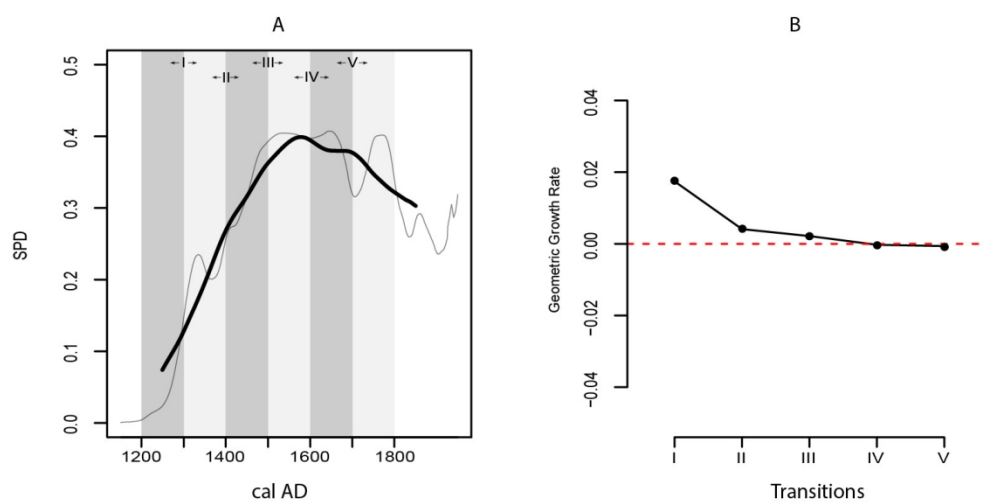


Figure 4 – A, the observed SPDRD for New Zealand (thin black line) with a 50-year rolling mean (thick black line) showing the growth trajectory across each of the transitions (I-V). B, observed rate of growth at each transition computed from the SPDRD in A.

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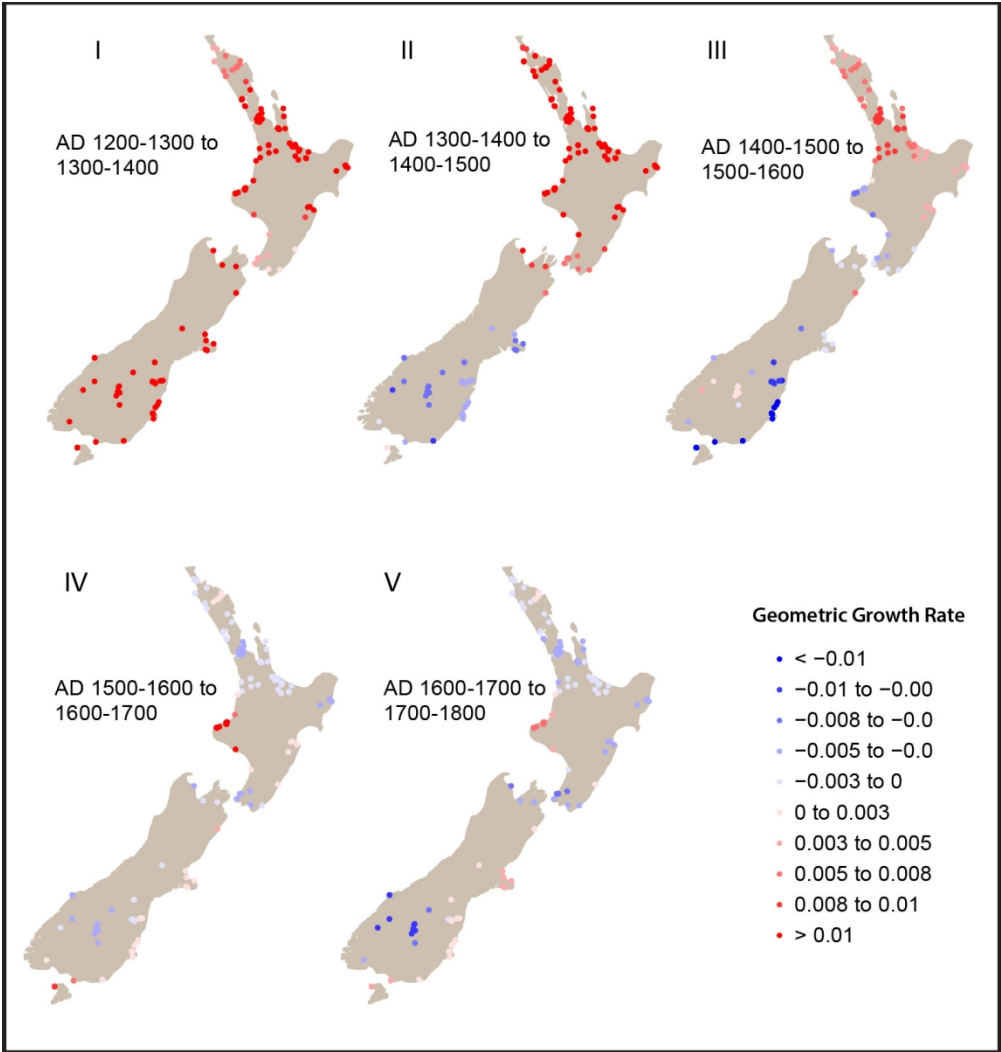


Figure 5 – Local geometric growth rate for each transition.

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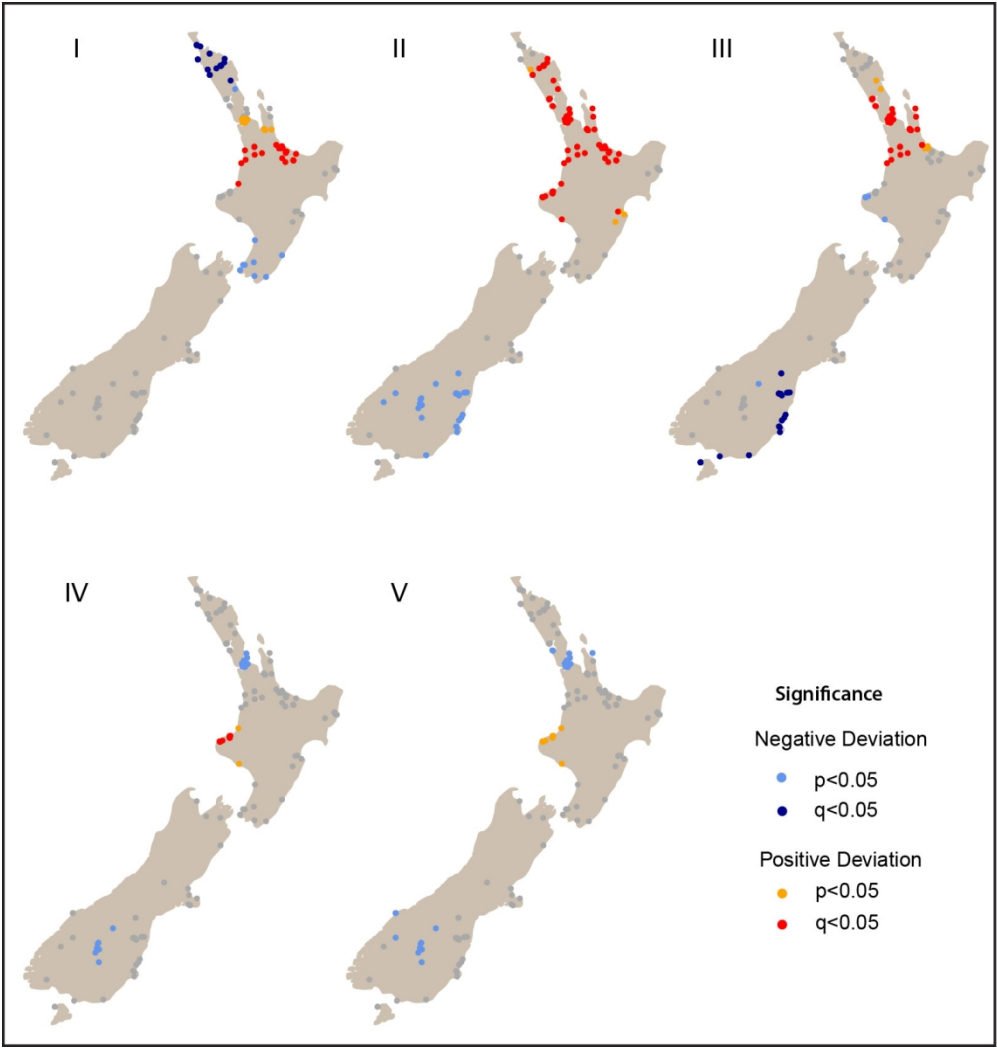


Figure 6 – Spatial permutation test showing areas where growth is significantly higher or lower than the null. Significance is shown in terms of q-values (more robust against false positives) and p-values (see S1).

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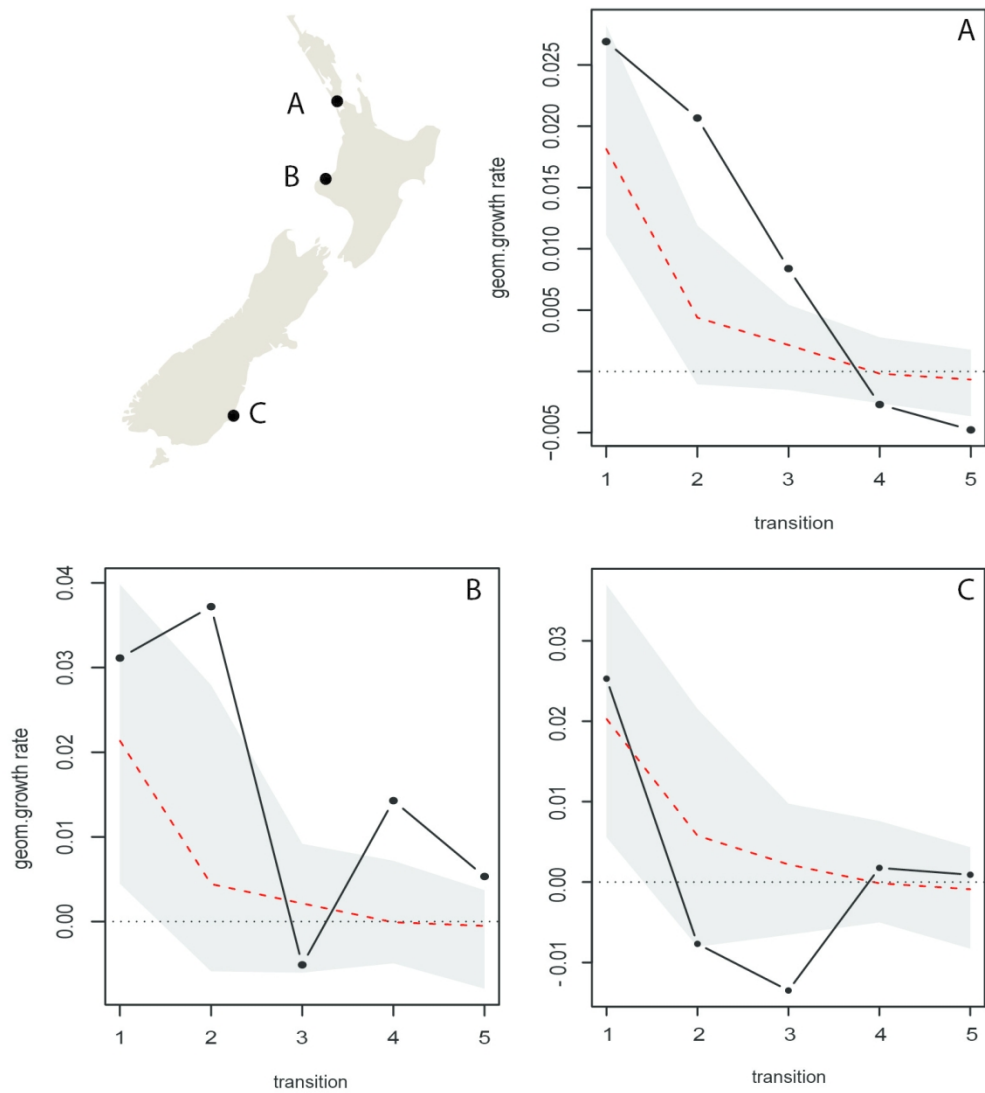


Figure 7 – Observed geometric growth rates at three locations in New Zealand. Where growth at a transition falls outside the grey confidence envelope is its regarded as a significant local deviation from the null.

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## Introduction

This supplementary information provides further information about data selection and analytical steps taken in the analysis of SPDs. All scripts and data are available online via [https://github.com/andybrown81/NZ\\_Population](https://github.com/andybrown81/NZ_Population).

## Data

Analyses were carried out using a collection of radiocarbon dates sourced from the following locations:

- New Zealand Radiocarbon database ([www.waikato.ac.nz/nzcd/](http://www.waikato.ac.nz/nzcd/))
- Published literature
- Grey literature, particularly unpublished cultural resource management reports provided by Heritage New Zealand Pouhere Taonga

All available archaeological dates (geological dates were omitted) were compiled in a database.

We then applied a conservative selection criterion to the corpus of dates to counteract potential biases in the dataset. First, we selected only wood and charcoal dates. These materials arise from

activities that were performed consistently (e.g. cooking) and therefore our results should not be influenced by large changes in cultural behaviour, particularly changing economic activities, which may mimic demographic shifts by inflating the site-to-population ratio.

Secondly, charcoal and wood dates were then subjected to a simplified chronometric hygiene (e.g. Anderson 1991) in order to remove any potentially spurious dates. Thus, we required dates to:

- Have secure archaeological context; however, unlike Anderson (1991) single dates from sites were retained for the purposes of this research.
- Derive from species considered reliable for dating and deemed to have minimal in-built age (McFadgen *et al.* 1994: Table S1)

Table S 1. The life expectancy of plant species commonly used for dating in New Zealand (from McFadgen *et al.* 1994)

Short (<100 years)	Medium (100-300 years)	Long (>300 years)
<i>Aristotelia serrata</i>	<i>Ackama rosifolia</i>	<i>Agathis australis</i>
<i>Brachyglottis</i> sp.	<i>Alectryon excelsus</i>	<i>Dacrydium cupressinum</i>
<i>Carmichaelia</i> sp.	<i>Beilschmiedia</i> sp.	<i>Halocarpus kirkii</i>
<i>Carpodetus serratus</i>	<i>Cordalinea australis</i>	<i>Lagarostrobos colensoi</i>
<i>Cassini</i> asp.	<i>Corynocarpus laevigatus</i>	<i>Laurelia novaezealandia</i>
<i>Coprosma</i> sp.	<i>Discaria toumatou</i>	<i>Libocedrus bidwillii</i>
<i>Coriaria</i> sp.	<i>Dysoxylum spectabile</i>	<i>Metrosideros</i> sp.
<i>Corokia macrocarpa</i>	<i>Hoheria</i> sp.	<i>Nothofagus</i> sp.
<i>Geniostoma rupestre</i>	<i>Knightia excelsa</i>	<i>Phyllocladus</i> sp.
<i>Hebe</i> sp.	<i>Kunzea ericoides</i>	<i>Podocarpus totara</i>
<i>Hedycarya arborea</i>	<i>Myrsine divaricata</i>	<i>Prumnopitys spicatus</i>
<i>Leptospermum scoparium</i>	<i>Myoporum laetum</i>	<i>Vitex lucens</i>
<i>Leucopogon fusciculatus</i>	<i>Nestegis</i> sp.	
<i>Lophomyrtus obcordata</i>	<i>Olearia</i> sp.	
<i>Macropiper excelsus</i>	<i>Pseudopanax</i> sp.	
<i>Melicytus ramiflorus</i>	<i>Paratropus microphylla</i>	
<i>Melicytus</i> sp.	<i>Pittosporum eugenoides</i>	
<i>Myrsine australis</i>	<i>Pittisoprum tenuifolium</i>	
<i>Myrsine</i> sp.	<i>Plagianthus</i> sp.	
<i>Olearia rani</i>	<i>Sophora microphylla</i>	
<i>Psuedopanax arboreus</i>	<i>Sophora</i> sp.	
<i>Psuedopanax crassifolius</i>	<i>Weinmannia</i> sp.	
<i>Psuedowintera</i> sp.		
<i>Pteridium esculentum</i>		
<i>Schefflera digitata</i>		
<i>Tree fern</i>		

## Method

The methods used in this paper were based on quantitative analysis of summed probability distributions (SPDs) developed by Shennan *et al.* (2013), the non-parametric extension devised by Crema *et al.* (2016) and the spatial permutation test developed by Crema *et al.* (2017). These sources can be consulted for further information on the method; the basic workflow for each method is outlined below.

### 1. Developing SPDs

The first step in all analyses is the creation of SPDs. This process follows the following steps.

- Radiocarbon dates are 'binned' according to their archaeological context (*e.g.* site or site phase; Step A - Figure S2). Dates retrieved from the same site are aggregated into a specific bin when their distance in  $^{14}\text{C}$  age time was less than 100 years (the exact procedure consist of carrying out a hierarchical cluster analysis using the complete linkage method and then using a cut-off value of 100 years to separate the observations). Bin sensitivity analysis (Figure S1) shows that the arbitrary choice of 100 years has no impact on the accuracy of results.
- Dates are calibrated using the southern hemisphere 13 calibration curve (Hogg *et al.* 2013) using the *rcarbon* package (Bevan and Crema 2017), part of the R statistical environment (R Core Team 2014). Multiple dates within a bin are calibrated and summed 'inside' the bin and subsequently divided by the number of dates so that each archaeological context contributes a single date distribution to the overall SPD (Step B - Figure S2).
- The pooled mean probabilities from the bins are summed to produce an empirically based SPD for each region (Step C - Figure S2).

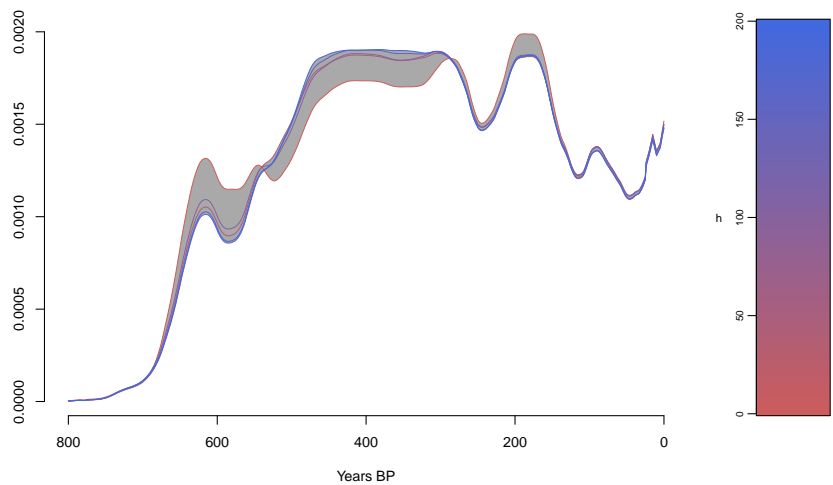


Figure S 1 – Bin sensitivity analysis showing the arbitrary choice of a 100 year cut-off has no impact on results (i.e. all bin sizes fit within the simulated envelope).

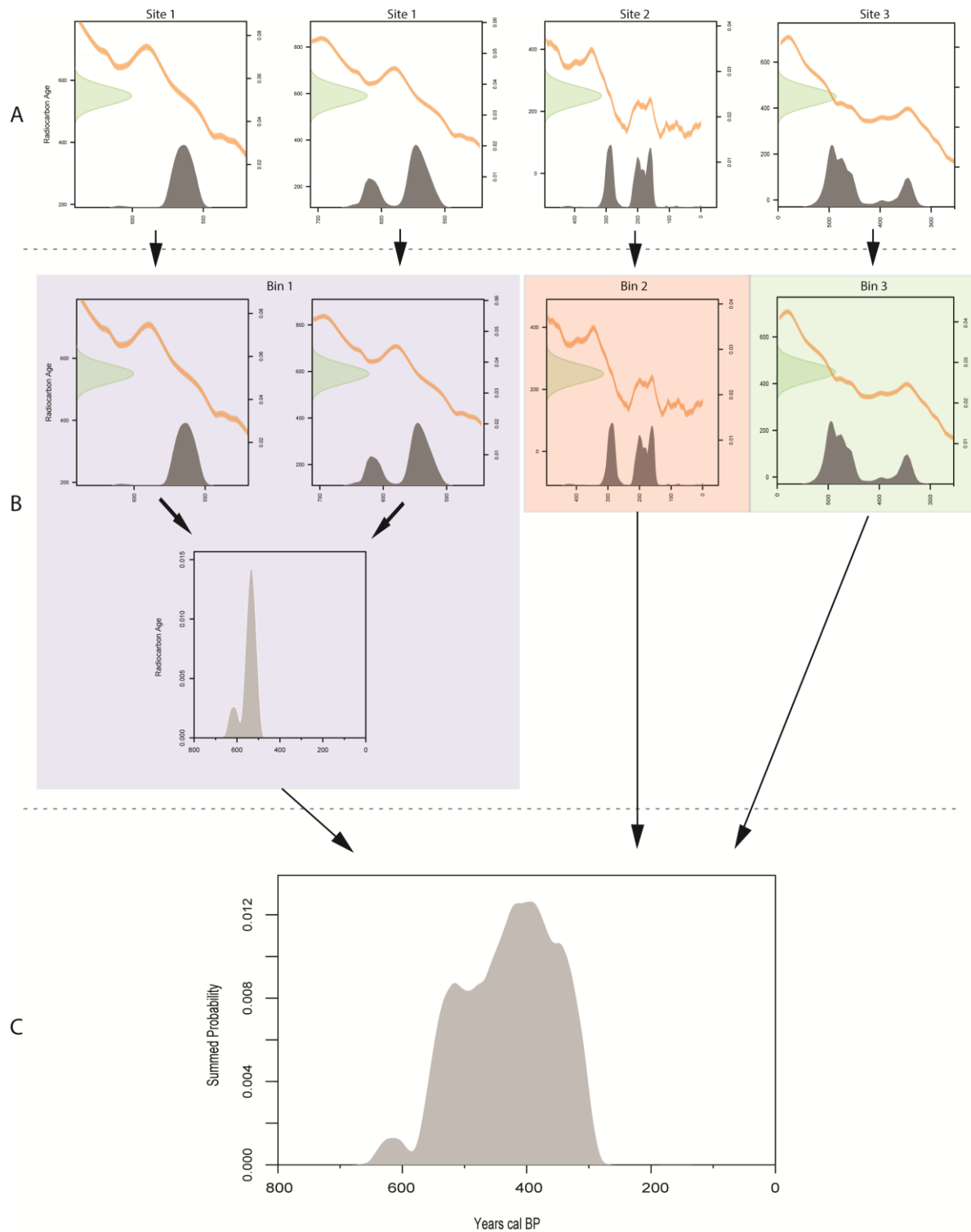


Figure S 2 – Basic workflow involved in creating summed probability distributions (SPDs)

2. Model Testing

The model testing procedure compares the observed SPDs with null models derived from known distributions of dates. The purpose is to test specific hypotheses about the pattern of population growth, in this paper we use a fitted logistic model of growth. The steps are as follows:

- Following the steps outlined above we created SPDs for New Zealand and three sub-regions – northern, central and southern (Step A - Figure S3).
- Each observed SPD has a logistic model fitted (Step B - Figure S3).
- A radiocarbon model is then simulated; the probability of each date being sampled is based on an adjusted fitted null model that takes into account the non-linearity of the calibration curve. Error ranges associated with each date are produced by randomly sampling with replacement from the pool of errors present in the observed data. The dataset is made up of the same number of bins that contribute to each regional SPD.
- The simulated uncalibrated dates are then calibrated and theoretical SPD RD are generated.
- This approach was repeated 5,000 times and a local Z-score produced to remove the effects of short term wiggles and other trends in the data. Using the simulated data, a 95% upper and lower envelope is computed (Step C - Figure S3).
- Observed SPDs are then compared to the simulation envelopes. Portions of the observed regional SPD that fall outside the envelope are said to be statistically significant local deviations from the null model (red and blue areas in Step D - Figure S3). Based on the methods outlined by Timpson *et al.* (2014) a significance value is then calculated by calculating the area outside the 95% confidence range for both the observed data and each simulated SPD. The proportion of simulations which have a summary statistic as or more extreme than the observed data provides the global *p*-value for each region.
- In the example below (Figure S3 – Step D) the plot of the left exhibits significant positive deviations (red area) and negative deviations (blue areas) from the logistic model. The plot on the right has no significant deviations from the model suggesting the fitted model is a reasonable approximation of the population curve in that example.



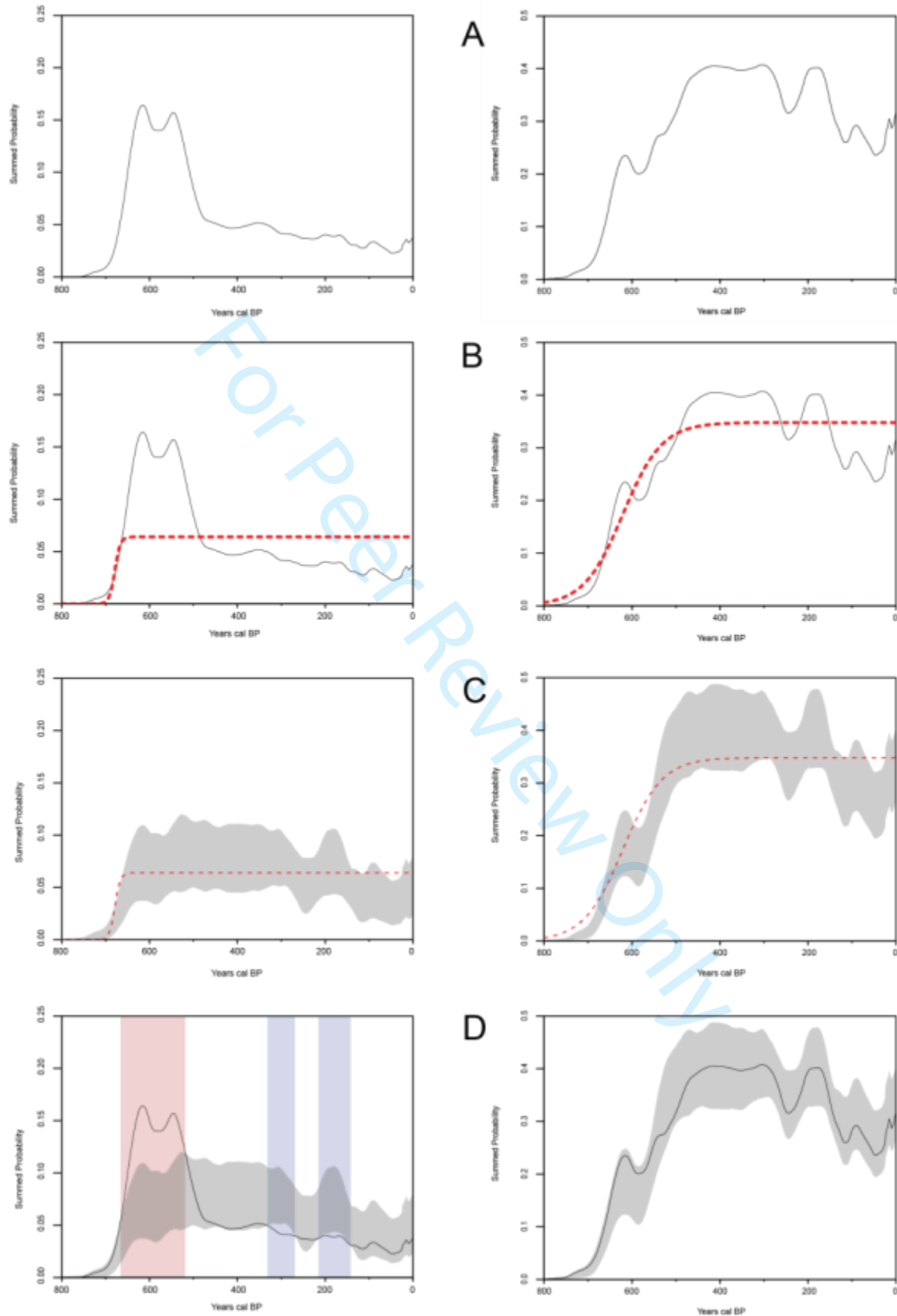


Figure S 3 – The basic steps involved in the model testing procedure outlined above.

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**3. Regional Comparison (Permutation testing)**

This research is also concerned with empirically testing the variation between regions in New Zealand. To achieve this each region is compared to a null model based on the SPD of radiocarbon dates from across New Zealand.

- Regional SPDs are produced following the methods outlined above (Figure S4).
- To develop the null model the regional assignment of each bin is dropped to create a nationwide dataset. Uncalibrated dates are then randomly sampled from this dataset; the number of dates drawn is the same as the number of bins which contribute to each regional SPD. An SPD is generated from the randomly sampled dates (Step A - Figure S4).
- The previous step is repeated 5,000 times for each region and a local Z-score produced to remove the effects of short term wiggles and other trends in the data.
- Using the simulated data, a 95% upper and lower confidence envelope is computed (Step B - Figure S4). Observed SPDs from each region are then overlaid onto the confidence interval envelopes. Portions of the observed regional SPD that fall outside the confidence envelope are said to be statistically significant local deviations from the null model. Based on the methods outlined by Timpson *et al.* (2014) a significance value is then calculated by calculating the area outside the 95% confidence range for both the observed data and each simulated SPD. The proportion of simulations which have a summary statistic as or more extreme than the observed data provides the global *p*-value for each region.
- In the below example the observed southern SPD significantly exceeds the null model representing the general growth trends across New Zealand (red area, Step C – Figure S4) before declining below the null model (blue area, Step C – Figure S4).

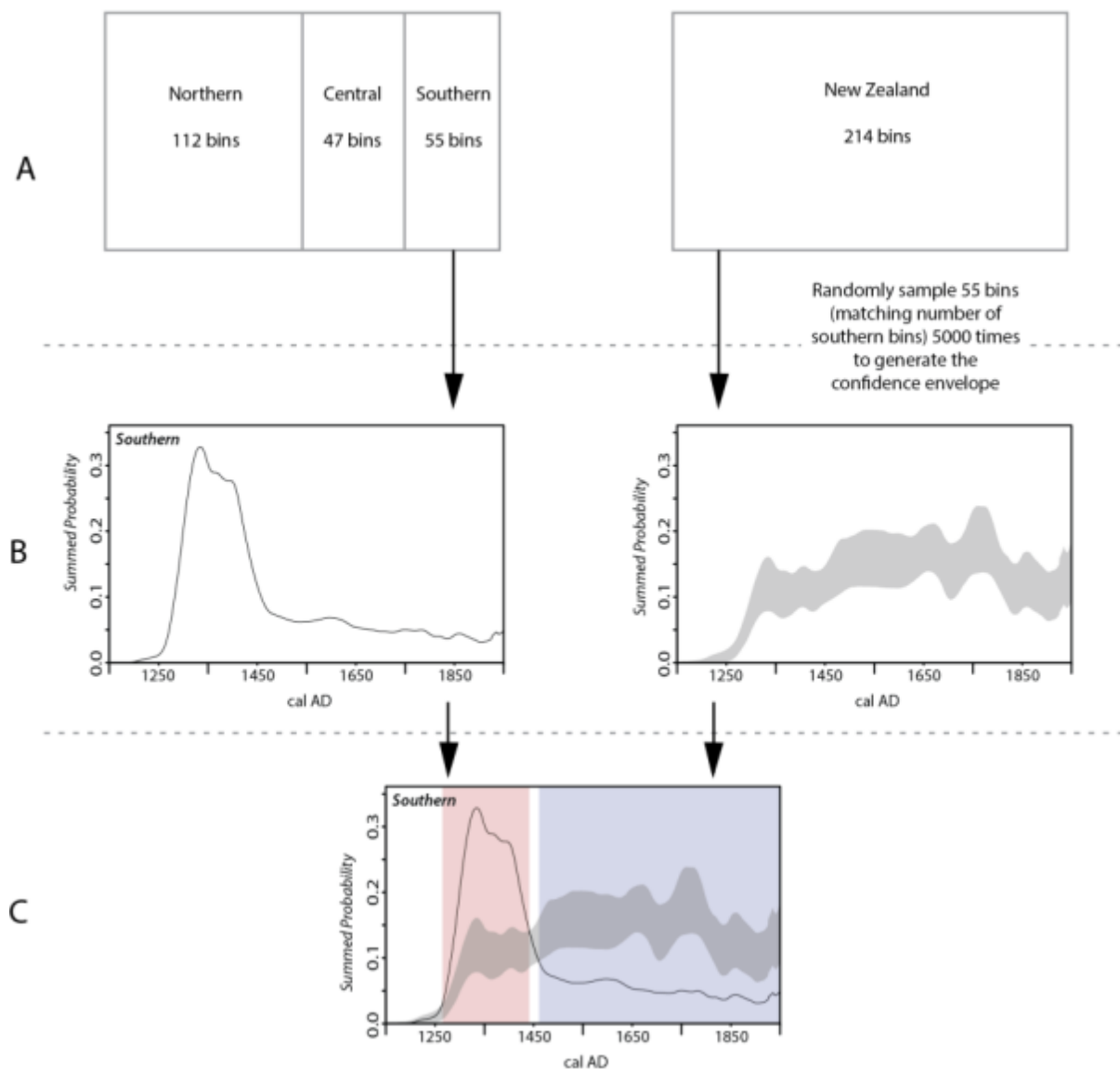


Figure S 4 – The steps involved in the permutation test procedure outlined above.

4. Spatial Permutation Test

The spatial permutation is an extension on the permutation test outlined above, with the crucial difference being that the spatial permutation tests allows for the assessment of variation without the imposition of *a priori* regions of analysis. The steps involved in the spatial permutation test are outlined in details by Crema *et al.* (2017) and can be summarised as follows:

- Site SPDs are created following the first three steps outlined in the ‘developing SPDs section’ above. The fourth step, combining local SPDs based on regions is not carried out.
- Local SPDs are created by weighting the contribution of sites based on their distance to focal site using a Gaussian distance decay function with a bandwidth of 100km.
- with sites nearer to the focal contributing more to the local SPD.
- Define the time slices to be analysed, the current research uses one-hundred year slices between AD 1200 and 1800.
- Weighted SPDs for each location and temporal slices are calculated using the methods outlined above.
- Calculate the geometric growth rate at the transitions between time slices. This provides the observed pattern of growth across New Zealand.
- The permutation test is carried out to test the significance of growth. This is done by randomly shuffling the bins from each site to new locations and calculating the weighted SPDs within each time slice. This is simulation process is carried out 5000 times.
- Hot and cold spots (areas of significance) are defined as areas where the local growth exceeds the growth observed in the simulations.
- Following the methods discussed in Crema *et al.* (2017), two measures of significance are produced in the course of the spatial permutation test. *P*-values are measures of significance between observed local growth and simulated growth rates. However, because of our use of a multiple testing approach, there is a potential for compounding false positive results (i.e. some local SPDs will be higher or lower than the theoretical expectation by chance alone). We therefore compute the more robust *q*-value by adjusting *p*-values to account for false discovery rate. Thus, in our results, a *p*-value of 0.05 suggests that 5 *per cent* of all tests will result in false positives, a *q*-value means that only 5 *per cent* of results with a value of 0.05 or below are false positives.

## Discussion of Method

The methods used are robust to many potential biases in the New Zealand data. The potential of sites with extensive dating programs to be over-represented is overcome through aggregation of dates based on archaeological context (i.e. the binning routine described above). Comparisons of SPDRD based on relative shape, and not date density, accounts for bias introduced by regional differences in sampling intensity (e.g. northern region having nearly double the bins of the other regions). Finally, difficulties imposed by ‘wiggles’ in the calibration curve (McFadgen *et al.* 1994) are overcome through the comparison of observed data with theoretic models that have passed through the same calibration process. This process includes the effects of calibration in the model simulation envelopes, allowing us to determine if SPDRD fluctuations are likely to be genuine (i.e. are outside the envelope) or simply a result of idiosyncrasies in the calibration curve and/or sampling error (i.e. inside the envelope). Despite these efforts, it remains possible that our results are influenced by other factors, such as temporal variation in site-to-population ratio. For example, a change in settlement size from large villages to smaller dispersed camps increases the number of residential features that may be dated. This may in turn inflate the SPDRD giving the appearance of higher population density although in fact it remains unchanged. In New Zealand the nature and abundance of resources had an impact on the aggregation and dispersal of Maori population (Allen 2012); however, the underlying pattern of settlement shows remarkable spatio-temporal consistency (Walter *et al.* 2006), reducing the likelihood of systematic bias in our results. Nevertheless, the identification of potential biases, together with the integration of other dating materials (e.g. marine shell), are key directions for the development of SPDRD analysis in New Zealand.

## References

- Bevan, A. & E. Crema. 2017. Rcarbon: methods for calibrating radiocarbon dates.
- Crema, E., J. Habu, K. Kobayashi and M. Madella. 2016. Summed Probability Distribution of  $^{14}\text{C}$  Dates Suggests Regional Divergences in the Population Dynamics of the Jomon Period in Eastern Japan. *PLoS One* 11(4): e0154809.
- Crema, E., Bevan, A. and S. Shennan. 2017. Spatio-temporal approaches to archaeological radiocarbon dates. *Journal of Archaeological Science* 87: 1-9.

- Hogg, A., Q. Hua, P. Blackwell, M. Niu, C. Buck, T. Guilderson, T. Heaton, J. Palmer, P. Reimer, R. Reimer, C. Turney & S. Zimmerman. 2013. SHCal13 Southern Hemisphere Calibration, 0–50,000 Years cal BP. *Radiocarbon*, 55(4): 1889-1903.
- McFadgen, B., F. Knox & T. Cole. 1994. Radiocarbon curve variations and their implications for the interpretation of New Zealand prehistory. *Radiocarbon* 36: 221-36.
- R Core Team. 2017. R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing.
- Shennan, S., S. Downey, A. Timpson, K. Edinborough, S. Colledge, T. Kerig, K. Manning & M. Thomas. 2013. Regional population collapse followed initial agriculture booms in mid-Holocene Europe. *Nature Communications* 4: 2486 doi: 10.1038/ncomms3486.
- Timpson, A., S. Colledge, E. Crema, K. Edinborough, T. Kerig, K. Manning, M. Thomas & S. Shennan. 2014. Reconstructing regional population fluctuations in the European Neolithic using radiocarbon dates: a new case-study using an improved method. *Journal of Archaeological Science* 52: 549-557.
- Williams, A. 2012. The use of summed radiocarbon probability distributions in archaeology: a review of methods. *Journal of Archaeological Science*, 39: 578–589.