A High-Resolution Chronology of Human Arrival and Environmental Impact in Northland, New Zealand

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Abstract

Our understanding of when Polynesian colonists first arrived in New Zealand, how the landscape was altered, and the pace of anthropogenic modification has been primarily sourced from archaeological evidence and environmental histories collected from the South Island. Research from the South Island suggests that once humans arrived in New Zealand around 1300 AD they quickly and dramatically impacted the environment. Though more research has been undertaken on the North Island recently, the north remains under-researched compared to the south regarding these issues. The variety of subsistence practices available in this sub-tropical microclimate and the wetter, less combustible forests may have led to different land use practices and pace of landscape alteration compared to the drier, cooler climate of the South Island.

For this project two lacustrine systems proximal to archaeological sites in Northland, New Zealand were cored, and a multi-proxy approach was undertaken to create a high-resolution chronology of anthropogenic environmental change. The age-model was used to identify the timing of human arrival and develop a catchment specific environmental history to determine the speed and duration of land use in this area to compare to records from the south. Thorough testing was performed to identify reliable radiocarbon targets to provide confidence in the precision for the chronology. Elemental and isotopic carbon and nitrogen measurement, C:N ratios and X-ray fluorescence (XRF) measurements were performed on the lake sediments to create catchment specific proxy data. These data, supported by the age-depth model and pollen and charcoal records, were used to determine the pace and intensity of local land use through time.

The results of the research indicate that pollen concentrated from post-human impact sediment produced unreliably old ^{14}C ages and could not be used to develop the lake chronologies through those time-depths. However, terrestrial macrofossils appear to have returned accurate ages for deposition and can be used in cultural landscapes to build chronologies. The age-depth model projects human arrival for the Far North District between 1164-1277cal AD, suggesting that this area was colonized early in New Zealand's settlement history. The isotopic and elemental data for both lakes show evidence of human modification of the environment but raise the possibility that different processes were occurring in each lake. The pace of human modification of the landscape appears to be longer in duration compared to environmental records from the south but indicate that shortly after Polynesian arrival the study area was completely altered by anthropogenic modification.

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1. A Multi-Proxy Approach

1.1 Introduction

One of the longest-running debates in New Zealand archaeology has been when Polynesian settlement of New Zealand occurred. Though a consensus age of approximately 1300 AD is now generally agreed upon for human arrival (Anderson, 2002; Higham and Jones, 2004; Jacomb et al., 2014; Wilmshurst et al., 2008; Wilmshurst et al., 2011), the timing of regional settlement within New Zealand is less certain. Much of the archaeological evidence of early settlement has been found on the South Island (Anderson et al., 1996; Jacomb et al., 2014; McWethy et al., 2010). Environmental reconstructions from the south support early arrival to the region and immediate and intense environmental impact occurring directly after arrival (McWethy et al., 2010; McWethy et al., 2009). Less research has been published from the North Island, though several important and early sites have been identified there. In Northland, one such site, Houhora, has provided archaeological and some radiocarbon evidence suggesting this region was colonized early in New Zealand's settlement history (Anderson and Wallace, 1993; Furey, 2002; Petchey, 2000; Shawcross and Roe, 1966). Northland may have been selected specifically for its subtropical climate favouring all six of the Polynesian cultigens that the first settlers established successfully in New Zealand (Barber, 2004; Chappel, 2013). The quickness and severity of landscape change after arrival, as identified from the South Island, has also been observed in some of the environmental histories on the North Island (Elliot et al., 1997; Striewski et al., 2009). However, some researchers have suggested that the forests of the wetter northern regions may have been less combustible than the drier south (McGlone, 1983; McWethy et al., 2010; Perry et al., 2014). Recent research on lake sediments near Auckland suggests that the pace of initial anthropogenic landscape change in that region may have been less acute upon initial human occupation than recorded on the South Island (Newnham et al., 2018) which could in part be caused by reduced combustibility of the forests.

While the archaeological history of Northland indicates that this region may have been colonized early, the pace, intensity and initial timing of anthropogenic landscape alteration in this warm, wet climate remain poorly understood. Environmental reconstructions from this area could provide valuable information about the scope and chronology of human impact in a region that has not yet been thoroughly studied. However, modern pastoralism has affected many of the archaeological sites in northern New Zealand (Barber, 2001), which can make the sites difficult to accurately date and assess. Nevertheless, direct research on archaeological features is not the only way to learn about human settlement and land use. Human environmental modification can also be distinguished in sediment records by fluctuations in the abundance of charcoal and alterations to pollen assemblages (McGlone, 1983; McGlone and Wilmshurst, 1999; McWethy et al., 2010). Archaeological features can be used to indicate where and to some degree how people were using the land. However, accurately determining the time of their erection or duration of use can be difficult due to the use of materials with inbuilt age in their construction or modern disturbance (Goff and McFadgen, 2001; Horrocks et al., 2007).

Lacustrine sediments serve as archives of environmental and anthropogenic change (Elliot et al., 1995; McGlone and Wilmshurst, 1999; Meyers and Ishiwatari, 1993; Sutton, 1987) and should contain continuous histories compared to many terrestrial archaeological deposits. Sediments extracted from lakes neighbouring archaeological sites can be used as a proxy and utilized to determine the timing of human settlement as well as the severity and length of landscape impact (Elliot et al., 1995; Lane et al., 2004). This has been traditionally achieved by recording the shifts in abundance of different pollen types and charcoal from both natural and man-made fires to create vegetation and fire histories from lacustrine sediments (McWethy et al., 2009; Newnham, 1999). These records have often been placed in time with a low-resolution radiocarbon chronology (Elliot et al., 1997; Elliot et al., 1995), which cannot be used to accurately date human arrival. Additionally, the environmental reconstructions created through this technique are regional in scope, since pollen can travel considerable distance on the wind (Close et al., 1978; McGlone et al., 2005). Alternatively, geochemical and elemental measurement of lake sediments can be used to identify catchment specific information about erosion and alterations of the organic and mineralogical components deposited into the lake. These proxies can be used to identify the onset of human arrival and reconstruct how the catchment environment was transformed after settlement (Cohen, 2003; Mees et al., 2003; Meyers and Lallier-Vergès, 1999). The timing and duration of these changes can be derived through the construction of a high-resolution chronology built from organic materials contained within the lacustrine sediments (Hajdas et al., 2006; McWethy et al., 2009).

Two lakes on the Aupouri Peninsula near several archaeological sites were selected for this study with the goal of determining the timing of human arrival in the region and to develop a better understanding of the severity and duration of human impact to the area through time. The first step to achieve this is to identify the most reliable target material for ^{14}C measurement. After these fractions are determined they will be measured to generate a high-resolution chronology using Bayesian statistics. The age-depth model will determine when the region was first anthropogenically altered. The results will be compared to pollen and charcoal records produced for the lakes as part of the larger study. Lastly, an environmental reconstruction will be produced from carbon and nitrogen and geochemical measurements. These proxies are catchment specific and will provide site-specific data towards the research goals of determining when humans arrived in the region and the pace of land use after arrival.

1.2 Thesis Structure

The thesis is structured into research chapters because the outcomes of the first research objective, identification of a reliable ^{14}C target, directly informed the direction undertaken to achieve the second objective. The second research goal, development of a high-resolution chronology, was required to create the environmental reconstruction for the region, which is the third research objective. Each research chapter contains a brief introduction, methods, results, and interpretation of each outcome.

Chapter Two provides the historical and theoretical framework for the project's research questions. Included is an overview of the debates regarding the timing of human settlement, duration of landscape modification and subsistence practices in New Zealand. The second part of Chapter Two covers Polynesian horticultural practices and the Polynesian cultivar suite. The third part presents a brief archaeological history of Northland and the traditional methods used to develop vegetation histories, fire regimes and identify anthropogenic impact in sediment records in New Zealand. Lastly, the research questions are presented for the project.

The study area is described in Chapter Three. Climate, geology and the vegetation histories of the study area are given. Details for the lakes selected for the research and their catchments are also covered in this chapter along with the archaeological sites currently identified near the lakes.

Chapter Four examines the reliability of pollen concentrates created from anthropogenically impacted lake sediments as ^{14}C dating targets. Sample preparation, ^{14}C methods and the results of the experiment are reported. The most reliable radiocarbon target within the sediments is identified and possible reasons for offsets in ages explored. The results were used to inform the selection of materials to produce an accurate age-depth model for the research.

The age-depth model is presented in Chapter Five where the timing of settlement for the study area is interpreted. This research chapter briefly explains how Bayesian statistics were used to build and evaluate the model. Lastly, the date of human arrival derived from the chronology is compared to previous dates from the nearby Houhora archaeological site.

Chapter Six is the final research chapter and begins with a brief explanation of how the isotopic and elemental proxies will be used to determine human impact and the pace of landscape change for the area. The methods used to prepare samples and the measurement results are then provided. The isotopic and elemental data are modelled into the research chronology to be compared to other records of land use and timing of human occupation in Northland.

A discussion of the research outcomes within the broader New Zealand environmental and archaeological context is examined in Chapter Seven. The timing of human arrival and the speed of landscape alteration identified for the region are compared to working theories in New Zealand regarding locations and timing of settlement, the subsistence methods employed and the pace of anthropogenic landscape alteration after arrival.

Finally, Chapter Eight summaries the main findings and results of the project.

2. Colonization and Environmental Impact

2.1 Introduction

Isolated deep in the southern oceans, New Zealand was the last major land mass to be discovered and settled by humans (McGlone et al., 1994). Transported along with the Polynesian colonists were their socio-cultural perspectives as well as tools, animals, cultivars and the knowledge and techniques for growing these crops (Anderson, 2018; McGlone et al., 1994). However, the timing of human settlement of New Zealand has been intensely debated and several colonization models have been proposed.

One such New Zealand settlement model has become known as the early or long prehistory model (McGlone and Wilmshurst, 1999). This settlement theory proposes that the first arrivals to New Zealand may have consisted of a small population practicing traditional horticultural methods, particularly in the warmer Far North (defined as the North Cape and consolidated dunes of the Aupouri Peninsula) (Newnham, 1999), with no obvious archaeological sites remaining to identify their presence (Sutton, 1987, 1994; Sutton et al., 2008). Sutton (1987) reported environmental research from the Bay of Islands created by Chester (1986) which identified changes in proxies of human settlement and land use. Human occupation was identified by increased charcoal abundance in conjunction with a rise of *Pteridium esculentum* (bracken fern) spores as a proxy for forest clearance (Sutton, 1987). This settlement model projected a colonization period of 0-500 A.D. (Sutton, 1987; Sutton et al., 2008) with ^{14}C dates on bone collagen from a Polynesian commensal, *Rattus exulans,* supporting a relatively long settlement chronology (Holdaway, 1996).

This model has been criticized because the context of the environmental interpretations was not archaeological and non-anthropogenic fire episodes in New Zealand's prehistory could be misidentified (McGlone and Wilmshurst, 1999). The accuracy of the dates used to build this model was also questioned, with in-washed old carbon being a possible reason for why older dates were obtained (McGlone and Wilmshurst, 1999; McGlone et al., 2005; Sutton, 1987; Wilmshurst, 1997). To address this, the full suite of dates used to support the long prehistory model was culled of measurements on materials which may have produced inaccurate results along with single dates and outliers (Spriggs, 1989; Spriggs and Anderson, 1993). The bone collagen dates were also reviewed. Wilmshurst (2008) has suggested that prior treatment methods to measure the collagen were inadequate or the diet of *R. exulans* contained ^{14}C depleted materials which affected radiocarbon measurement (Beavan and Sparks, 1997; Wilmshurst et al., 2008). Seeds with the diagnostic tooth marks of *R. exulans* were radiocarbon dated instead and yielded no calibrated age ranges earlier than the 13th century (Wilmshurst and Higham, 2004). This combined research lead to a short or late prehistory model with a post-1200 AD settlement date for New Zealand (Anderson, 1991; McGlone and Wilmshurst, 1999; Wilmshurst et al., 2011). The late settlement model is the current consensus model for colonization of New Zealand. However, Sutton et al. (1994, 2008) have argued that the late settlement model leaves little time to accommodate the array of environmental and cultural changes seen in the archaeological and environmental records. Anderson and others (Anderson, 2018; Anderson and Wallace, 1993; Jacomb et al., 2014) have suggested that some archaeological sites do not show evidence of long occupation and that the time depth allotted by the long settlement model for landscape modification and cultural development is not required. Sutton et al. (2008) also argued that the late settlement model is comprised of too few dates from the northern part of the North Island, where early colonization possibly occurred (Davidson, 1982; McGlone, 1983; Sutton, 1994). In this argument, data of greater antiquity may have been selected against and the limited surviving dates have biased the record towards the late model (Sutton et al., 2008).

In addition to the settlement history, the speed and intensity of impact to the landscape after human arrival and the subsistence methods the settlers used to establish themselves in the New Zealand landscape have also been debated (McGlone et al., 1994; Newnham et al., 2018; Sutton, 1994). A number of researchers have proposed that the New Zealand landscape was swiftly transformed by fire in a single pulse when humans first arrived (Anderson, 2002; McGlone et al., 1994; McWethy et al., 2010; McWethy et al., 2009; McWethy et al., 2014; Perry et al., 2012; Wilmshurst et al., 2011). However, much of the evidence for late settlement and rapid modification comes from the South Island (Perry et al., 2014). Significant environmental differences between the South and North Islands may have promoted different settlement patterns, pace, and intensity of landscape modification (Newnham et al., 2018) and subsistence practices. Newnham et al. (2018) have recently found evidence of a two-step anthropogenic impact history in sediments from Lake Pupuke near Auckland. Their environmental reconstruction, supported by tephrochronology, shows that at this northern location there was early (~1350 AD) human occupation and associated environmental effects, but that the initial alteration to the environment was minor compared to the large-scale anthropogenic impact seen shortly after the Rangitoto tephra around 1450 AD when the forests were quickly cleared by fire (Newnham et al., 2018). This two-phase history of anthropogenic impact at Lake Pupuke does not mirror those recorded on the South Island. Newnham suggests that the damper, less combustible environments in the northern and western regions of New Zealand may explain the different rates of human impact and land use (Newnham et al., 2018). Newnham et al. also propose that the second phase of more intense environmental impact may be in response to the cooling temperatures of the Little Ice Age (LIA). Anderson (2016) and others have argued that the LIA could have caused horticultural intensification in warmer, fertile regions, as marginal growing areas in the south were abandoned (Anderson, 2016; Leach, 1984). As Newnham's work is based on only one lake record, the broader applicability of this model is not yet clear. Additional records from the north are needed to confirm regional differences in the timing and pace of occupation. These will provide a deeper understanding of how the warmer and wetter environments in the north may have affected human settlement.

A possible reason the northern regions may have experienced different rates of anthropogenic landscape change may relate to subsistence practices. New Zealand's climate is colder and more varied than tropical Polynesia (Alloway et al., 2007; Leach, 1984; McGlone, 1989; Newnham, 1999). The landscape is also more diverse and includes a larger range of biota than found elsewhere in Polynesia (McGlone et al., 1994). The first arrivals to New Zealand may have taken advantage of the large number of animals, unused to predation, that could be easily hunted (McGlone et al., 1994) rather than focusing on the labour intensive practice of horticulture. Additionally, the climate of much of New Zealand, specifically in the deep south, would not have been conducive for the growth of tropical plants cultivated by Polynesians (Furey, 2006). Accordingly, one subsistence model for the colonization of New Zealand focuses on the importance of hunting and wild foods to the settlers (Anderson, 1997; McGlone et al., 1994). There is archaeological evidence that early settlements on the South Island were large sites located at the mouths of rivers near a variety of animal protein sources, primarily seals and the large flightless birds *Aves Dinornithiformes* or moa, which were prevalent on the South Island (Anderson, 1997; Anderson et al., 1996; Higham et al., 1999; McGlone et al., 1994; Walter et al., 2017). Habitation sites were occupied for relatively short time frames as big game hunting reduced at the location (Higham et al., 1999; Jacomb et al., 2014). Landscape clearance by fire was undertaken to clear paths for travel and to promote hunting resources and the growth of bracken fern (McGlone et al., 1994; McWethy et al., 2010). In this model, the rhizome of bracken fern was the primary source of carbohydrate for the settlers (Anderson, 1997; McGlone et al., 1994).

An alternative subsistence paradigm is a horticulture focused model which rests in comparative Polynesian sociocultural economic drivers (Kirch, 1989, 2000). This model emphasizes widespread archaeological and contact history indications of horticulture in New Zealand to the very margins of production possibility (Barber, 2004, 2010, 2013, 2017; Furey, 2006). Although New Zealand's temperate climate was unsuited for most of the tropical Polynesian crops, several were successfully transferred, as established in the archaeological and historical records, especially the hardy sweet potato *Ipomoea batatas* (Barber, 2004; Furey, 2006; Leach, 1984). The horticultural model looks at the value of these crops to the Polynesian settlers, both as a food source and as a cultural or religious connection to their Polynesian homeland, within the unique environment of New Zealand (Barber, 2004). Northland is where the widest variety of Polynesian cultivars could be grown and where horticulture practices would climatically have been the easiest to establish (Barber, 2004; Furey, 2006; Sutton, 1994). For these reasons, this region may have been selected for occupation early in New Zealand's settlement history.

The Far North is an ideal location for further research to address the limited colonization data from the North Island and understand more about the possible role that climate had on settlement patterns, intensity and speed of landscape modification and subsistence practices. The challenge, as mentioned earlier, is that the Far North, like much of New Zealand, has experienced intensive historical landscape modification, which makes accurate chronologies and environmental reconstructions difficult to build. A viable option to achieve these goals is to use lake sediment records, like Newnham and others, to develop an age-depth model and an environmental history for the region. A robustly dated chronology from this area would increase the currently limited information about the timing of settlement and length of human impact to the environment. An environmental reconstruction of these sediment records could then be used to shed light on the speed and intensity with which the colonists modified the landscape in the Far North and compared to Newnham's results from the Auckland region and the environmental histories of human impact from the South Island.

2.2 Background of Horticultural Practices

Horticulture is practiced throughout Polynesia, and tropical cultigens were brought with the settlers to New Zealand. As mentioned above, adherence to different subsistence practices may have impacted the selection of settlement locations upon arrival and possibly the pace of landscape modification. The warmest microclimate in New Zealand is found in the Far North, making this region the most attractive for growing tropical crops. To provide a background for how the landscape of this area might have been modified for horticultural practices the following section provides a brief overview of Polynesian horticultural methods, cultivars and some of the archaeological and historical records pertaining to horticultural practices in New Zealand.

The entire Polynesian cultigen suite consisted of eleven tree and eight root crops. As the islands of the Pacific were colonized, some portion of these nineteen plants were transplanted and grown on each island (Furey, 2006). Although New Zealand's temperate climate was unsuited for many tropical crops such as breadfruit, several were successfully transferred. Six Polynesian cultivars, which are discussed later, are known to have been grown in New Zealand at the time of European arrival (Furey, 2006). Other plants were likely trialled upon arrival but abandoned as they failed in the temperate climate (Furey, 2006).

Historical documents and collections of oral histories from the late 18thto the early 19th century, including reports from Cook's expeditions, provide some clues to the range and intensity of horticulture in New Zealand at that time. European depictions of Maori horticulture were of neat, weed-free gardens. The components and layout of crop production were also described by several early explorers (Beaglehole, 1963; Best, 1925; Leach, 1976). Included in these are descriptions of the range of traditional horticultural practices and the considerable landscape modification needed to grow them (Best, 1925; Colenso, 1880; Furey, 2006; Leach, 1984). The scale of garden construction that was witnessed and identified in the archaeological record may have involved considerable human effort and landscape alteration. Borrow pits were sometimes dug to add gravels and sands to mulch or lighten the gardens soils (Anderson, 2016; Barber, 2004; Gumbley et al., 2004; McFadgen, 1980). Gumbley et al. (2004) have estimated that to prepare one hectare of land for gardening would involve digging, moving (in flax baskets), and spreading of 1300 m^3 of sand and gravel. After the garden was established other elements such as stone mounding or walls may have also required construction (Leach, 1984). Some historical reports record soil mounding around sweet potatoes, (Beaglehole, 1963, 1968; Best, 1925; Leach, 2005) which is also evidenced in the archaeological record (Higham and Gumbley, 2001). Ample archaeological evidence exists to support the descriptions of garden constructions in the forms of stone structures, terraces, borrow pits and modified soils along with ditches and trenches. Examples of these structures and modifications have been recorded throughout the North Island as well as along the northern and east coasts of the South Island (Barber, 1989, 2004, 2010; Furey, 2006). The widespread distribution of seasonal storage pits to preserve tubers and seeds suggests that horticulture was important to the settlers of New Zealand across most of the land (Barber, 2004, 2010, 2013; Bassett et al., 2004; Leach, 1984).

Maori horticultural practices were noted by Europeans in many parts of New Zealand but many of the accounts come from Northland. McNab (1914) observed ditch features near the North Cape, which have been interpreted to have been used for water carriage (Barber, 1989). Gourds, sweet potatoes, and other root crops, possibly yams, were described as being cultivated in Northland by members of the ship St. Jean Baptiste (De Surville, 1982). The landscape and climate of the Far

North have provided a suitable environment to grow many of the Polynesian plants and employ traditional cultivation practices.

2.2.1 Horticultural Systems

Three types of agricultural systems are recorded in Polynesia: arboriculture, permanent dryland systems, and wetland systems, which controlled water for taro cultivation (Kirch, 1994). Only the first two types were observed in New Zealand by early Europeans (Furey, 2006). The research of Barber and Horrocks (2005) on relic ditch systems on the Aupouri Peninsula suggests that wetland horticulture may have been practiced in this region as well (Barber, 1989, 2001; Horrocks and Barber, 2005; Horrocks et al., 2007; Jones, 1994).

These various systems allow different types of land to be cultivated, which may increase yields and support intensification (Furey, 2006; Kirch, 1994; Ladefoged et al., 2009; Leach, 1976). There are advantages to both wetland and dryland horticulture depending on the environment provided by the island. Wetland systems allow for the use of fertile, already damp or swampy land to be utilized for the cultivation of wetland taro. The amount of effort needed to create wetland garden plots is initially quite high. However, once built these plots require minimal physical maintenance (Allen, 1971; McCoy et al., 2013) to achieve wetland taro's need for water reticulation to avoid rot in stagnant water (Allen, 1971). Yields from wetland fields are considered to be fairly reliable and in many parts of Polynesia this was a very successful horticultural technique (Kirch, 1994). The energy necessary to drain the land for dryland crops and maintain the plot would be considerably higher than wetland systems in many places (Vitousek et al., 2004) but does allow the use of more marginal land for production which can be important when socio-cultural or population demands in an area increase to the point that crop yields must also increase (Allen, 2004; Cauchois, 2002; Kirch, 1994; Stevenson et al., 2015). Dryland systems are ideal in areas that are naturally less swampy and for the growth of certain dry Polynesian cultivars like sweet potato, which require rainfall but will rot if the soil remains too damp (Furey, 2006). Light, well-draining soils have the disadvantage of also having lower fertility, which can affect growth rates and yields. This could be improved upon by burning the nearby forest, which would release phosphates, carbon and other nutrients into the soil (Elliot et al., 1997; Elliot et al., 1995; McWethy et al., 2010). However, these nutrients would quickly be depleted by the root crops and fallow periods as long as 25 years might have been required to improve the soil for productive gardening again in New Zealand's temperate climate (Leach, 1984).

2.2.2 Polynesian Cultivars in New Zealand

Horticulture in New Zealand was primarily built around the cultivation of Polynesian root crops (Jones, 1994). In addition to the root crops, *Lagenaria siceraria* (bottle gourd) and two tree crops, *Cordyline esculentum* (tī pore) and *Broussonetia papyrifera* (paper mulberry) were successfully transferred (Barber, 2004). The bark of the paper mulberry tree was utilized only for textiles (Furey, 2006). The taproot of tī pore was eaten as a carbohydrate but was only grown in Northland (Furey, 2006). The fruit of young bottle gourd was eaten, and mature fruits were dried and used as containers. The root crops were grown primarily as carbohydrate sources and in some cases, the leafy parts of the plants were used for greens (Barber, 2004; Horrocks et al., 2004b).

Of the three root crops, imported sweet potato was the most successful cultigen in New Zealand (Burtenshaw et al., 2003). Though not a dominant crop in the rest of Polynesia (Leach, 1984), sweet potatoes were the most important food plant in New Zealand because they had the greatest tolerance for the widest range of environmental conditions and matured sooner than the other root crops (Furey, 2006; Jones, 1994). Sweet potatoes require at least 50 cm of rainfall during the growth season (Burtenshaw et al., 2003) and are sensitive to hard frosts so soil temperature is important for propagation. Sweet potatoes prefer soils between 15-35°C and will fail in conditions below 10°C (Burtenshaw et al., 2003). The best yields are achieved in well aerated porous soils that drain easily, heat up early in the season and stay warm. Excess yields were placed in storehouses. Some sweet potato storage structures were above ground (whata or pataka) while others were semi-subterranean pits, which are seen in the archaeological record (Furey, 2006). The short growing period as well as the plant's ability to tolerate dry, cool conditions allowed sweet potato to be grown from Northland to as far south as Banks Peninsula (Bassett et al., 2004; Leach, 1984). However, the plants do not flower in New Zealand's climate, so cannot be identified in a pollen record (Harberle and Atkin, 2005; Horrocks et al., 2004a).

Colocasia esculentum (taro) also made the transition from the tropics into New Zealand's temperate climate. This plant was a staple crop throughout Polynesia and was grown both in dryland and wetland environments (Kirch, 1994). Taro requires more moisture and warmer weather than sweet potato and also reaches maturity slower (Furey, 2006). A minimum of 100mm of monthly rainfall and temperatures above 20°C are ideal for taro (Leach, 1979). Light alluvial soils near a water source are favourable to maintain soil moisture (Colenso, 1880:8). Provided these conditions are met, taro can be self-reliant and is found growing unattended in some swampy areas in New Zealand (Matthews, 1985). Unlike sweet potato, mature taro could either remain in the ground or survive stored in the open (Colenso, 1880:15) which made excess yields easier to maintain but harder to see in the archaeological record. Taro's environmental requirements for growth meant that the crop was probably not as successful in the cooler and drier regions of New Zealand. Early European reports record taro as having been grown extensively on the North Island (Colenso, 1880), most predominately on the northernmost half of the North Island to the northern end of the South Island (Leach, 1984; Matthews, 2014).

The role of *Dioscorea spp. (*yam or uwhi) to the New Zealand settlers is not well understood. Yam was quickly replaced by the post-contact potato in the 19th century due to the new crop's tolerance to a wider range of conditions and higher yields (Leach, 1984), which may be evidence of the difficulties in growing yam in New Zealand. Yams were cultivated for their starchy tubers but required roughly eight months to reach maturity (Leach, 1984). Yam prefers temperatures above 20°C and rainfall in excess of 100mm a month during the growth season (Leach, 1979). Mature tubers could be stored for three to four months in warm conditions (Leach, 1984). Yams were documented as being grown only on the North Island (Furey, 2006). The microscopic remains of yam starch granules identified in soil samples from Motutangi on the Aupouri Peninsula (Horrocks and Barber, 2005) tie their cultivation to this area.

In addition to the Polynesia crops relocated in New Zealand, three native plants, *Cordyline australis* (tī kōuka), *Corynocarpus laevigatus* (karaka) and bracken fern were cultivated or managed by the settlers as additional food sources. The lower stems and taproot of the tī kōuka tree were processed into a type of toffee (Anderson, 2018). Maori managed existing stands of karaka and trees were planted near some settlements for their edible fruit. The karaka fruit kernel was also eaten after thorough processing to remove toxins (Leach and Stowe, 2005; Maxwell et al., 2016). Bracken fern rhizomes were a carbohydrate staple for Maori (McGlone et al., 1994; McGlone et al., 2005) and the growth of bracken fern was encouraged by recurrent burning the landscape (McGlone et al., 1994; McWethy et al., 2009). Bracken fern colonizes land quickly after forest clearance and can withstand repeated burning, although soil fertility and temperature determine rhizome starch quality. Consequently, food-quality bracken rhizomes were encouraged in more arable soils (McGlone et al., 2005).

2.3 Archaeological History of Northland

For the Polynesian settlers, Northland's mild climate would have been the most suitable region in New Zealand to attempt to establish their crops (Davidson, 1982; Sutton, 1994; Walter et al., 2017). The relatively flat terrain, good harbors, and coastal fauna may have added to the appeal, as these attributes were also valued by the European immigrants who opted to settle Northland first (King, 2003). Continued land use and natural phenomenon may have destroyed some of the pre-contact archaeological evidence in Northland (Coster, 1989), however many sites and artefacts have been recorded in the region (Fig.1).

A complex archaeological site located around the entrance to Houhora Harbour at Mount Camel (N3/59) is one of the most important sites in the Far North (Anderson and Wallace, 1993; Furey, 2002). Occupation of the area was recorded by members of Cook's ship Endeavour, among other explorers, who saw settlements and garden plots in this area (Beaglehole, 1955; Dieffenbach, 1843). Early archaeological excavations at the site unearthed several artefacts that are stylistically similar to early East Polynesian assemblages (Anderson and Wallace, 1993; Furey, 2002). Midden contents from the site also contained remains of moa and other now-extinct animals (Anderson and Wallace, 1993). The artefacts and midden objects suggest that Houhora was occupied early in New Zealand settlement history (Furey, 2002). The first radiocarbon measurements from the site generally supported a late 13th to early 14th century occupation (Shawcross and Roe, 1966). More recent radiocarbon measurements on charcoal, shell, and fish bones from the site have reproduced similar ages for site habitation (Anderson and Wallace, 1993; Furey, 2002; Petchey, 2000). The dates measured on the original charcoal and moa bones recovered from Houhora are discussed in Chapter 5 more completely. Calibrations of these results with the 2013 Southern Hemisphere curve (Hogg et al., 2013) are also provided in that chapter and appendices.

Early Maori artefacts and similar midden contents were also uncovered at the Twilight Beach site (N1&2/976) (Taylor, 1984), which may suggest that this site was contemporaneous with Houhora (Taylor, 1984). The site has a single ^{14}C date obtained from a shell sample that returned a 13th century age (Coster, 1989), but it is unclear if a ΔR was applied to the measurement result. Excavation of sites at Tauroa Point (N5/301 and 302), located at the southern end of Aupouri Peninsula, also produced artefacts and radiocarbon ages from cultural layers indicating habitation of the area early in the settlement history of New Zealand. Radiocarbon dates from shell and more recently charcoal from these sites imply that occupation of the area occurred during the early 14th century (Allen, 2005, 2006; Phillipps et al., 2016).

The investigation of relic ditch systems at Motutangi (N03/639), located roughly 5km from Houhora, suggest that horticulture was practiced in the warm, fertile soils near the harbour. Comparable systems from the base of the Aupouri Peninsula were characterized as 'ancient drains' when the area was drained for pastorium in the 1920s (Barber, 1989, 2001; Wilson, 1921). A debate followed as to whether the features were constructed to drain the land for eel and bird trapping or for cultivation (Barber, 2001; Horrocks and Barber, 2005). The systems are extensive covering ~100ha with the highest feature concentrations near the mouth of the Awanui river (Barber, 1989, 2001; Horrocks and Barber, 2005). The movement of water through these linked ditches may have facilitated irrigation and provided drainage during flooding, (Barber, 2001) possibly allowing for mixed crop production with taro grown in the wetter areas and other crops grown on the drier edges (Barber, 1989, 2001). Microbotanical analysis of sediment sampled from the Motutangi ditch systems (E1613411 N6141980) produced xylem and starch granules from taro and yam that were possibly propagated by both wet and dry cultivation respectively (Horrocks and Barber, 2005; Horrocks et al., 2007). If used for wetland taro cultivation, these ditches are significant because they would represent a unique adaptation of tropical wet taro horticultural technologies at the coldest and southernmost borders of production (Barber, 2001; Jones, 1994). Radiocarbon measurement on likely, but not definitive, short-lived plant materials produced a ca. 16th century range for use of the Motutangi ditch system (Barber, 1989). Otherwise, these ditches are difficult to reliably date because of extreme mixing of sedimentary horizons from decades of intensive land use (Horrocks and Barber, 2005).

Additionally, defensive Māori earthworks or pā sites (ca. 1500 AD to European settlement) (Schmidt, 1996) have been documented densely throughout Northland, sometimes associated with horticulture features or located near prime horticultural areas (Anderson, 2018; Davidson, 1982; Jones, 1994; Kirch, 1989). In the Far North, pā sites have also been recorded in the dune fields of the west coast sometimes near lakes. Also found among the west coast sand dunes on the Aupouri Peninsula are nearly continuous middens of various and unknown ages (Coster, 1989; Jones, 1994). The archaeological evidence of the Far North suggests that once the area was settled the land remained in use, but what is not as clear is when occupation first began or the duration of each occupation phase.

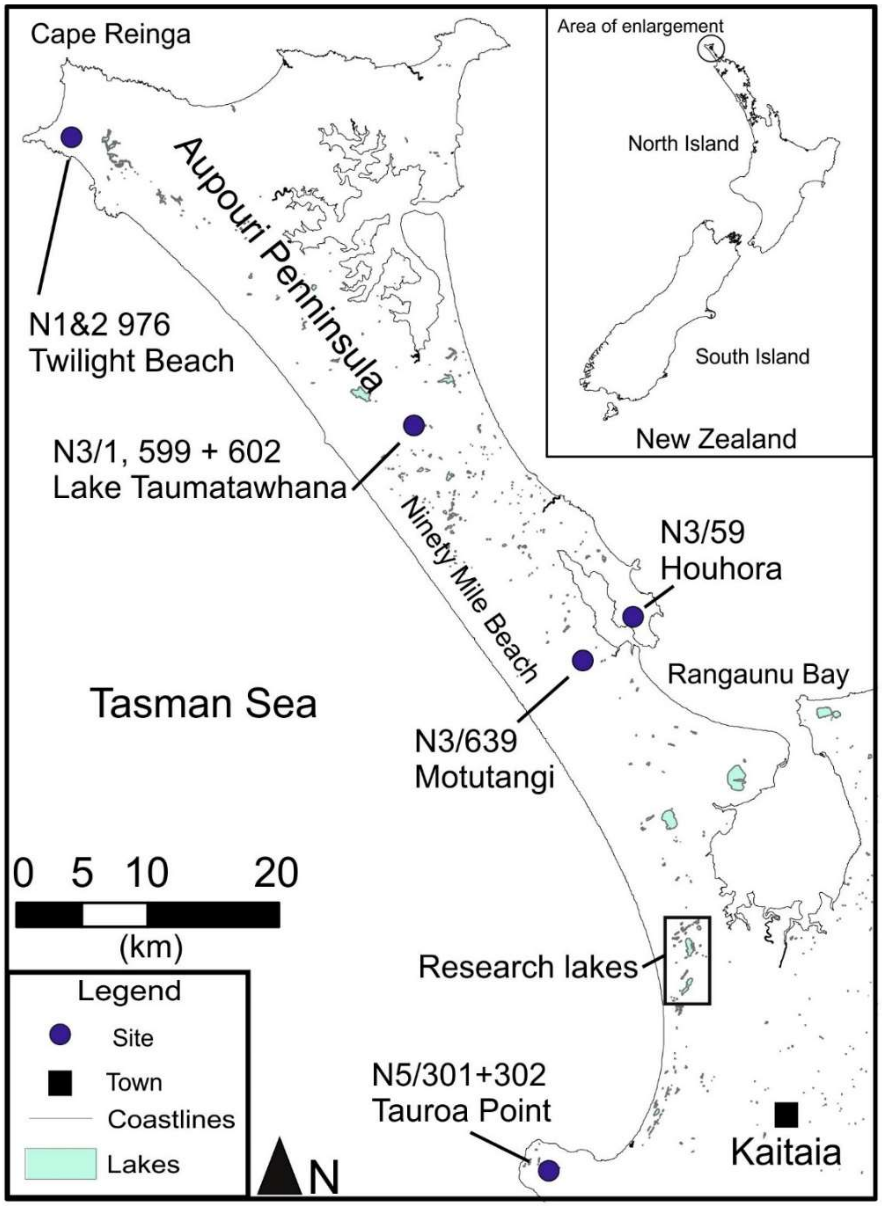

Figure 1. Map of select archaeological sites on the Aupouri Peninsula

2.4 Natural vs Anthropogenic Signals in Sediment Records

Though several archaeological sites have been identified in the Far North, directly dating these sites may not be the best way to determine when settlement occurred or for how long the landscape was used after construction. To identify initial human colonization of the region and create an accurate chronology for the pace and intensity of anthropogenic land use, lake sediments from the region provide an important research source alongside archaeology. Lakes are natural sediment traps that record both eroded and transported materials from the catchment from environmental and anthropogenic drivers (Striewski et al., 2009). Lake sediment cores have been successfully used to create paleoenvironmental and time-depth models to establish human presence and land use to answer similar questions about the timing of human arrival and intensity of human impact in northern environments (Elliot et al., 1995; Horrocks et al., 2005; Newnham et al., 2018; Newnham et al., 1998a; Striewski et al., 2009).

The main indicators of anthropogenic impact in sediment records are alterations of the pollen assemblages and charcoal abundance (McGlone and Wilmshurst, 1999). Due to the lack of specific anthropogenic markers, such as pollen from the Polynesian cultivars in New Zealand (McGlone and Wilmshurst, 1999), sediment research has become an important method for understanding human impact of an area to develop erosion, fire, vegetation and environmental histories for the research sites (McGlone and Wilmshurst, 1999). The difficulty of these methods is being able to distinguish natural from human-driven phenomenon. Currently, the most accepted method for identifying human impact in sediment records is to determine when in time the intersection of several specific changes to the environment occurred. The first proxy for human impact is fire.

Upon arrival, the Polynesian settlers burnt New Zealand's thick forests to improve travel and hunting as well as clear land for settlements and horticulture and assist in the growth of bracken fern (McGlone, 1983; McWethy et al., 2010). Both natural and anthropogenic fires are identified by charcoal within sediment records. In New Zealand large magnitude natural fires are rarer in the moister climates of the western coasts of both the North and South Islands, however soil charcoal, which indicates reoccurring natural fires took place, is found throughout both of the main islands (McGlone et al., 1997; McWethy et al., 2014; Perry et al., 2012; Wilmshurst, 1997). Therefore, evidence of significant fire in thickly forested or wetter regions (precipitation >1000mm yr^{-1}) is more likely human in origin (McGlone and Wilmshurst, 1999). Charcoal evidence of regularly reoccurring local fires is also probably anthropogenic (McGlone and Wilmshurst, 1999), and is commonly seen as evidence of anthropogenic land management. Local burn events can be identified in lake sediments by charcoal pieces >50 µm, which indicate that fire occurred near the catchment. Smaller charcoal fragments may represent regional fires (Clark and Royall, 1995). Human land management is generally identified by a sweeping change in the charcoal abundance with evidence of continued local burn events (McGlone and Wilmshurst, 1999; McWethy et al., 2014; Perry et al., 2012).

In addition to the charcoal records, several native plants in New Zealand appear to re-establish quickly after burn events. The frequency of burn events can be seen in the pollen record by a continued representation of palynomorphs from plants that re-populate rapidly after fire such as bracken fern, shrubs, and grasses in lieu of pollen from tall tree taxa (McGlone and Wilmshurst, 1999). Increases of bracken fern spores, in particular, have been used in many research projects to identify human impact because of the added subsistence benefit this plant provided (McWethy et al., 2014; Sutton et al., 2008).

The third line of evidence used to determine natural vs. anthropogenic impact is the sediment itself. Changes in the climate or vegetation around the lake may increase or limit the severity of soil erosion in the catchment (McGlone and Wilmshurst, 1999). Anthropogenic alteration such as forest burning also removes vegetation from an area and increases soil mobility (McGlone, 1989). All of these events may produce increased deposition of catchment soils in lake sediments along with changes in the texture, grain size and the geochemistry of the sediment (Elliot et al., 1997; Elliot et al., 1995; Striewski et al., 2009).

To avoid misidentification of the driver of landscape change these three proxies are often used jointly to differentiate human from natural environmental alteration. A decline in tall tree pollen in tandem with a rise in bracken fern spores and charcoal that persists through the core along with an increase in sediment deposition is used to mark the onset of human settlement and land use of an area (McGlone, 1983; McGlone, 1989; Newnham et al., 1998a). Collectively these proxies can then be modelled into a ^{14}C chronology to establish environmental and vegetative histories for an area and determine the time-scale of human arrival and land use for the area.

The disadvantages of these techniques are that they are time-consuming and require palynological expertise. Pollen and charcoal records derived from lake sediments also represent regional as well as site-specific information, which can make it hard to differentiate between signals of local and regional change. Additionally, lake systems can be subject to in-washing of both younger or older carbon than sediment deposition, impacting the usefulness of the sediment to build accurate age-depth models. Open lake systems specifically can suffer from material additions from fluvial sources (Howarth et al., 2013; Kilian et al., 2002). However, this issue could be avoided by selecting closed lake systems which should not experience this problem (Chester and Prior, 2004). Analytical techniques that require minimal material and treatment, produce results quickly, and are site-specific would be beneficial for research in the biological, anthropological and environmental sciences.

This research project is focused on developing a settlement and land use history for the Far North region. The timing of human settlement, the speed, and intensity of landscape modification post-human arrival and the possible subsistence methods that were employed will be investigated. A high-resolution ^{14}C chronology will be built which incorporates the established methods of identifying human impact and land use in sediment records. A multi-proxy approach will be undertaken to increase the resolution of the regional signal from pollen and charcoal records to a local signal by isotopic and geochemical measurement. To utilize the existing archaeological knowledge from the Far North but avoid some of the issues associated with modern alteration of the landscape, lake sediments near recorded archaeological sites will be studied. The chronology will be used firstly to provide a reliable date for human arrival in the Far North and secondly to determine the lengths of catchment specific events observed in the organic and geochemical proxy datasets. The dearth of well-dated records of Polynesian landscape modification and the potential variability between northern and southern records highlights the need for further work in the north.

2.5 Research Questions

The aim of the research is to use lacustrine sediment records to determine the timing of Polynesian settlement in the Far North to establish the timing and pace anthropogenic landscape modification in a lacustrine environment.

To address this aim, I will specifically ask:

> -Which organic materials from a lacustrine system will provide the most robust ^{14}C dates to build a reliable age-depth model to determine the timing of human settlement for the region?
>
> -When did Polynesian colonization of the Far North occur?
>
> -Can the intensity of Polynesian settlement and duration of land use be identified in lake sediments by looking at the isotopic and geochemical signals from these catchments?

In order to answer these questions, I will combine high-resolution radiocarbon chronologies with geochemical and isotopic proxies to determine the timing and intensity of local changes that occurred to the environment, compared to the regional records created by charcoal and pollen histories.

3. Study Area

3.1 Physical Environment and Climate of Northland

Northland is the northernmost region in New Zealand sitting between latitudes 34-36°South. The region is a peninsula roughly 300km long and 100km wide at its maximum with topographic relief ranging from sea level up to >600m above sea level (a.s.l.) within the volcanic ranges (Newnham, 1999) (Fig 2). Northland was not glaciated which allowed some soils to develop in the warm and humid climate since the Miocene, however, some soils have also been leached by heavy rain which created thin topsoils (Newnham, 1999).

Summers in the Northland region are warm and humid, and the winters are mild. The region is affected more so than the rest of New Zealand by the subtropical high-pressure belt (Chappel, 2013). Northland's climate is also moderated by the ocean so few temperature extremes are seen (Newnham, 1999). Only a few light frosts are typically recorded each year and are generally not strong enough to affect vegetation (Newnham, 1999).

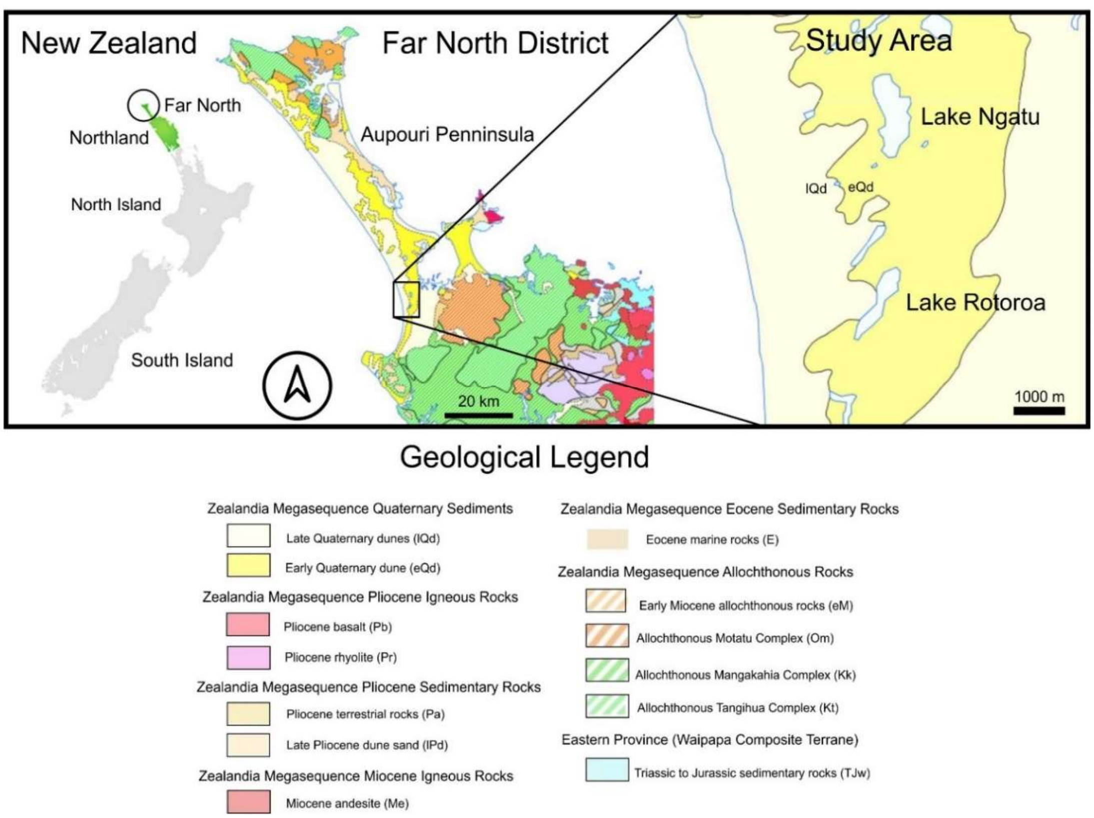

Figure 2. Geological map of the Far North District with placement of study lakes

The endemic vegetation of Northland during the Holocene consisted mainly of a dense podocarp forest. *Agathis australis* (kauri) dominated some areas, while steeper sections developed conifer forests and the lower and more fertile slopes contained more angiosperm vegetation such as *Beilschmiedia tarairi* (taraire). Swamp forests with *Dacrycarpus dacrydioides* (kahikatea) were common in moister areas and within alluvial floodplains. However, by European colonization, much of the lower elevations were occupied by *Leptospermum scoparium* (manuka) and bracken fern (Horrocks et al., 2007; Newnham, 1999) both of which regenerate quickly on cleared land (McGlone and Wilmshurst, 1999). Modern land use and pastoralism have currently limited forests mainly to steeper areas in Northland (Newnham, 1999).

3.2 Description of Study Area

For this study, lacustrine systems located on the Aupouri Peninsula in the Far North District of Northland (Fig. 2) were targeted. The Aupouri Peninsula is a narrow sand tombolo formed by several rock outcrops and connected to the mainland by Pleistocene and Holocene sands (Furey, 2002). The peninsula has low elevation and is only 10-60km wide. Situated on the west side of the peninsula at 35°S, only a few kilometres inland from the sea, Lakes Ngatu and Rotoroa were selected for the research project.

The area around the lakes can experience quite strong winds, primarily in exposed coastal areas, often associated with tropical storms. However, sunshine hours are also relatively high with parts of the Aupouri Peninsula getting over 2100 hours annually (Chappel, 2013). Likewise, the study area receives ample rainfall with 30-40% of the rain falling between June to August and a median of 1200mm rainfall per year (Chappel, 2013). Air temperatures recorded at Kaitaia Observatory ranged annually from the low single digits to the upper 20s degrees Celsius. Soil temperatures recorded at 9 am at 10cm depth varied from 10°-21°C annually. Ground frosts are very rare within the study area (Chappel, 2013).

Lakes Ngatu and Rotoroa are freshwater dune lakes located about 20km north of Kaitaia. Lake Ngatu sits at an elevation of about 32m a.s.l. and has a catchment size of roughly 1.73km^2 with the surrounding catchment ranging from 32m to greater than 80m a.s.l. Lake Rotoroa sits at approximately 28m a.s.l. with a steeper catchment of 1.15km^2 (Fig.3). The surrounding landscape ranges from 50-60m a.s.l. and includes a small pā (N04/7) recorded on a hill on the southwestern shore, overlooking the lake.

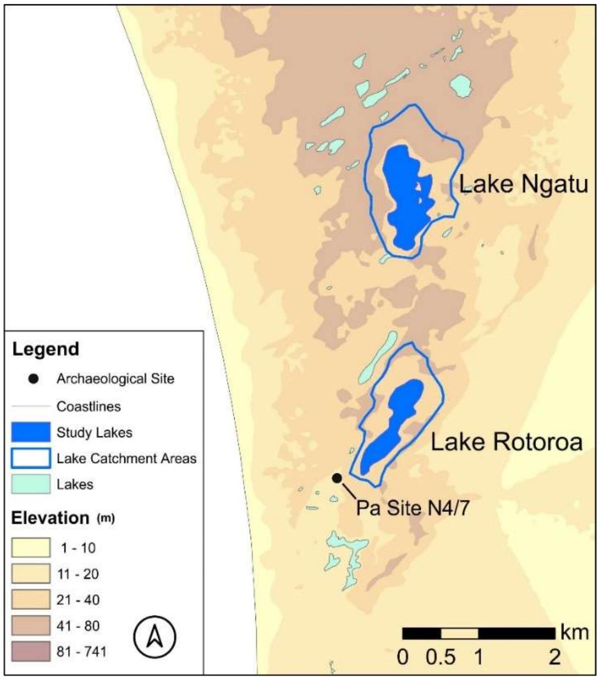

Figure 3. Basic elevation and catchment map for Lakes Ngatu and Rotoroa

3.3 Geology and Vegetation of Study Area

The soils surrounding Lake Ngatu and Lake Rotoroa are categorized as part of the Parabolic Dune sequence in the Karioitahi soil group (Isaac, 1996). The 1996 QMAP shows Lake Ngatu's catchment composed entirely within the soil category of Early Quaternary dunes (eQd), which is described as uncemented to weakly cemented or partly consolidated sand that could include muds, peats, and clay-rich sandy soils. Lake Rotoroa is also mapped within this soil unit along with a short section mapped in Late Quaternary dune (lQd) soil along the western shore. lQd is termed loose to poorly consolidated sand with possible additions of mud and peat from swamp or lake deposits (Isaac, 1996). The right third of Figure 2 shows the geological catchment soils of the lakes.

Prior to settlement, a mixed coastal broadleaf forest grew in the study area. The forest consisted of angiosperm and podocarp trees such as rimu *(Dacrydium cupressium*), kauri *(Agathis australis)* and beech (*Nothofagus*) amongst others (Horrocks et al., 2007; Newnham et al., 2004; Maxwell, 2017 personal communication). Kauri tree remnants can still be found submerged in Lake Rotoroa. Grasses and ferns increased after settlement due to burning. Manuka and bracken fern scrub dominated the low-lying areas in the early 1800s when initial European settlement began (Elliot et al., 1997). Today the area around the lakes primarily supports shrubs such as manuka and exotic European species along with many wetland plants.

3.4 Archaeology Recorded in the Study Area

There are many archaeological sites currently recorded within a few kilometre radius of Lakes Ngatu and Rotoroa. Sites were located using ArchSite, a GIS-based inventory of the New Zealand Archaeological Association (NZAA) Site Recording Scheme. The number and type of sites catalogued excludes historical sites and is based solely on what was available in the ArchSite record system and will not represent unreported or undiscovered archaeological sites at the time of publication. Particularly in the case of these lakes, archaeological data may have been lost either to environmental or historical modification of the environment (Allen, 2006; Coster, 1989; Horrocks and Barber, 2005). The types of sites recorded in the vicinity of the lakes can be broken broadly into four groups. The first are middens and ovens, the second is taro, the third are pits and terraces and lastly, the fourth is pā. Additionally, an extensive ditch system is recorded within a few kilometres of the lakes.

Clustered along the coast, west of Lake Rotoroa, many midden and, oven sites have been documented, suggesting this stretch of coast was popularly used to process marine foods. Curiously though, there are no midden sites listed as located along the coast north of Lake Rotoroa. A few other middens were also distributed inland north of Lake Ngatu (Fig. 4). Though none of the midden or oven sites near the lakes have been dated or appear to have contained items that could be linked back to a specific period, the evidence indicates that the colonists were utilizing aquatic protein in their diets and processing this food locally either at a certain point or through time.

In addition to the evidence that marine sourced foods were utilized by the colonists, the ditch system recorded to the northeast of the lakes (N04/237) and the three separate taro plant records (O04/455-7), also imply that horticultural practices were regionally employed. The taro plants were growing at the time of recording and could be relics of historic plantings (Matthews, 2014). Many of the pits and terraces documented near the lakes may also support the view that horticulture was practiced in the area. The pits were likely used to store surplus harvests (Best, 1916) and the terraces possibly to grow crops upon. Some of these features are also associated with pā sites. Many of the pā near the lakes have limited information recorded about them, making it difficult to assign them to a specific time period, however, a few of the pā (O04/198, 207 and 549) were noted as being large and well-fortified, sometimes including structures and pits within their boundaries. Sites O04/516 and 517 consist of pits and terraces located outside of the pā proper but appear associated with a pā. The pits and terraces recorded at site O04/198, which cover an extensive area of ~1000m^2, are recorded as belonging with pā O04/198, though these features are a short distance from the limits of the pā. O04/486 was recorded as a large pā with a historic European grave and associated orchard nearby as well as a taro plant (O04/455). These four pā and related features could suggest that they are somewhat younger than some of the other smaller, less fortified pā recorded in the area and were constructed for defensive purposes for a larger group of people. Additionally, as previously mentioned, along the southwestern shore of Lake Rotoroa a pā was recorded (N04/7) (Fig.4).

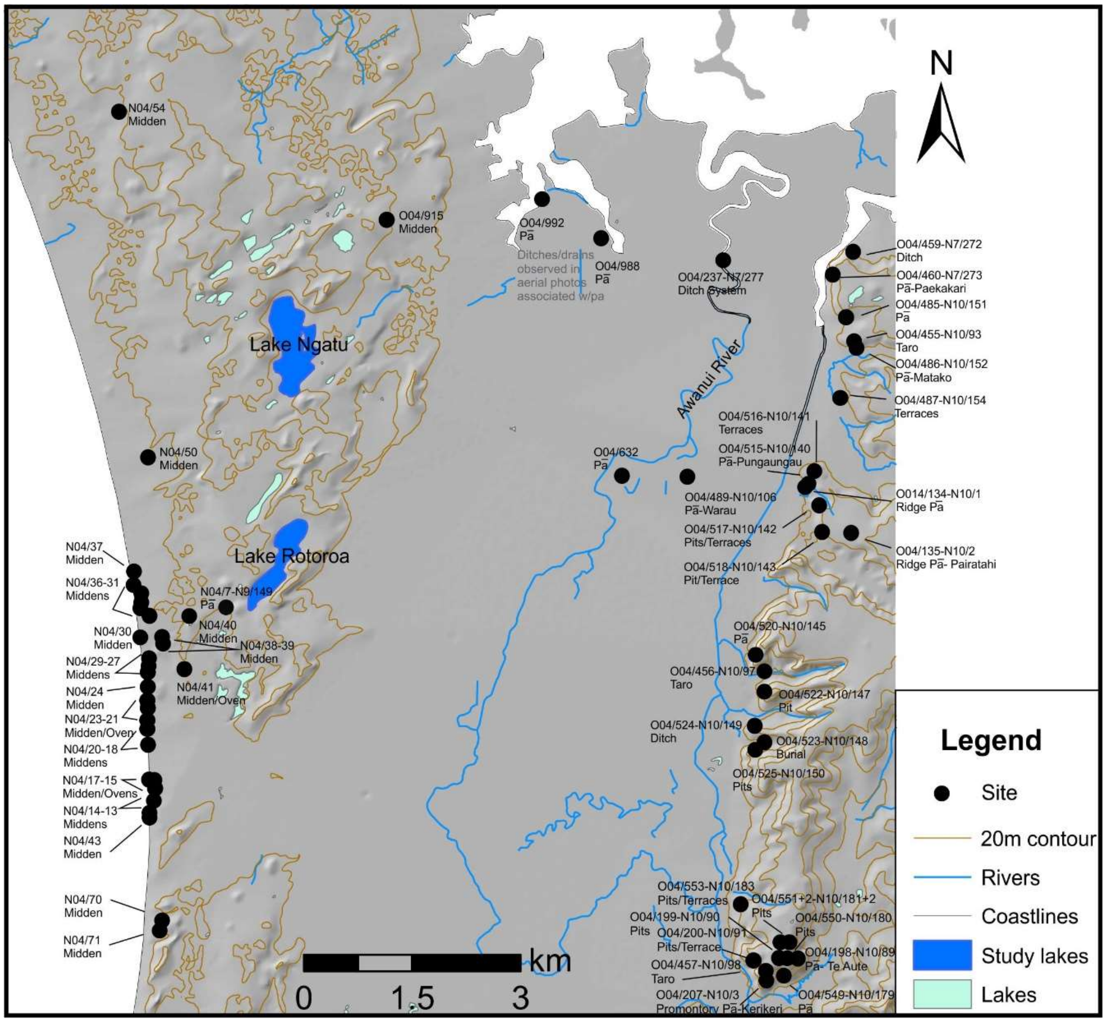

Figure 4. Archaeological sites recorded at the time of this study in the vicinity of the Lakes Ngatu and Rotoroa

This pā is possibly even younger in construction, or re-purposed, as the site records suggest that this pā might contain 'musket features'. This implies that the pā was a functioning site after European contact. A copy of the site form for N04/7 is available in the appendices. Comparatively, pā sites O04/992, 988 and 632 are recorded as being located near garden systems in the area but are not described as large or heavily fortified. O04/489 is listed as a small swamp pā with pits, which may have been used by a small group of people (Jones, 1994). The remaining pā recorded in the area (O04/460, 485, 134, 135, 515, 520) have site forms that contain very limited information but are frequently described as having been already modified or partly destroyed when documented. These pā are recorded as being built prior to 1769 AD, but it is difficult to say how or when they were used since the sites may simply not have been built as large defensive structures or that portions of the sites have been destroyed over time.

However, these sites (Fig.4) imply that the landscape was utilized for a variety of purposes through time. Archaeological evidence (Anderson and Wallace, 1993; Furey, 2002; Petchey, 2000) from Houhora suggests that the Far North was occupied early in the settlement history of New Zealand and the pā and other archaeological features recorded in the vicinity of the lakes indicate that area was not only utilized during the early years of settlement but that human occupation and land use continued through time.

4. Radiocarbon Materials Experiment

4.1 Introduction

To obtain an accurate age range for initial human impact in the Far North and develop a precise chronology of anthropogenic land use for the area, the materials selected to build the age-depth model must precisely represent sediment deposition. Before samples were selected to construct the age-depth model, a dating experiment was undertaken to ensure that the most robust materials were later chosen for radiocarbon measurement. The background for and design of the experiment is presented in section 4.2. The methods used to prepare materials for the investigation are explained in section 4.3. The results from the test are provided in section 4.4 with interpretations of the outcomes following in section 4.5. A brief summary of the experiment in section 4.6 advises how the results impacted sample selection for construction of the age-depth model.

4.2. Background to the Experiment

A common technique for constructing age-depth models in lacustrine environments involves the radiocarbon measurement of organic materials preserved throughout lake sediment cores (McWethy et al., 2014; Meyers and Lallier-Vergès, 1999; Newnham et al., 2004). Radiocarbon was selected to build the catchment chronologies for the Lake Ngatu and Rotoroa sediment cores because they were expected to contain organic materials and sediment deposition should be in stratigraphic order. Lastly, high-resolution radiocarbon measurement combined with age-depth modelling generally provides results with greater precision than many other chrono-methods through the last 1000 years, which is the time depth of the research question.

Short-lived terrestrial plant macrofossils are considered ideal targets for radiocarbon measurement to develop age-depth models in lacustrine environments (Howarth et al., 2013; Turney et al., 2000). These materials should produce reliable ^{14}C ages for sediment deposition because they originate from outside of the lake and are fragile, thus lowering the probability of their being reworked from catchment soils into lake basins (Birks, 2001) or having reservoir ages like aquatic plants (Turney et al., 2000). ^{14}C ages from discrete macrofossils can also yield tightly defined dates unlike bulk sediment, which contains a mixture of organic content (Vandergoes and Prior, 2003). Leaf and twig macrofossils also represent a short lifespan, unlike larger pieces of wood or charcoal which may suffer from inbuilt age (Gavin, 2001; Wilmshurst et al., 2011). Though macrofossils can provide useful results they can be quite rare, and some lake sediments lack enough of these materials to build high-resolution chronologies (Kilian et al., 2002; Li et al., 2014). When the quantity of dating targets required to build a high-resolution age-depth model is not matched in number by identified macrofossils other reliable dating materials must be sought.

Pollen concentrated from lake sediments can be radiocarbon dated to assist in building an age-depth model when macrofossils are limited (Chester and Prior, 2004; Howarth et al., 2013; Moy et al., 2011; Newnham et al., 2007). Pollen is considered a reliable dating material because it generally originates from terrestrial sources and settles into the lake sediment with regularity through constant pollen rain, making pollen fairly abundant in lake sediments even when macrofossils are scarce (Vandergoes and Prior, 2003). Previous research has found that ages obtained from well-purified pollen concentrates were concurrent with lake sedimentation (Brown et al., 1989; Vandergoes et al., 2005; Vandergoes and Prior, 2003). An additional benefit of using pollen concentrates to develop the age model is that pollen and charcoal have traditionally been used to reconstruct regional vegetation and fire histories from lake sediments (Chester and Prior, 2004; Newnham et al., 1998a; Vandergoes et al., 2005). Transitions of these materials may denote environmental shifts or human modification associated with additions of exotic taxa or forest clearance (McGlone et al., 1994; McGlone and Wilmshurst, 1999; McWethy et al., 2010; Wilmshurst, 1997). Utilizing palynological concentrates as dating targets allow for a direct match between the material used for dating and the interpreted environmental events (Chester and Prior, 2004). Pollen, however, can suffer from re-working; particularly in lake systems, by transportation of catchment soils yielding potentially older ages than actual sediment deposition (Kilian et al., 2002; Mensing and Southon, 1999). Fluvial processes have been proposed as the main mechanism for fossil pollen to enter a lake basin (Mensing and Southon, 1999). Pollen concentrate dates from lakes with fluvial systems have produced ages that are consistently older than expected compared to independent age markers (Howarth et al., 2013; Kilian et al., 2002). Sediments from closed lake systems should not suffer from this type of re-working and pollen concentrates measured from closed lakes have overall produced reliable ^{14}C ages (Chester and Prior, 2004). However, anthropogenic drivers could initiate soil movement or erosion in closed lake basins (McGlone and Wilmshurst, 1999). Currently no research has investigated the specific effect of human-instigated erosion on the ^{14}C content of pollen in closed lake systems.

4.2.1 Experimental Design and Pollen Records

The sediment cores obtained from Lakes Ngatu and Rotoroa did not contain a great number of identifiable terrestrial macrofossils through all depths. However, pollen concentrates could be produced at regular intervals to provide more continuous data for construction of the age-depth model. Since Lakes Ngatu and Rotoroa are not impacted by fluvial systems, these lakes should provide good testing grounds to determine if anthropogenic landscape modification of the catchments eroded fossil pollen into the lake basins. If this proved to be the case, then pollen concentrates, at least after human impact, would produce inaccurate ages and should not be used to build the model.

Palynomorph and charcoal analysis are the traditional methods for determining anthropomorphic alteration of the landscape and environmental change (McWethy et al., 2014). These records were created and used to identify pre- and post-initial human modification depths in the lake sediments for sample selection for the dating experiment. This analysis was performed by Dr. Justin Maxwell (University of Otago and International Archaeology LLC) as part of the larger project with the full results of those analyses to be published separately. Figure 5 provides abridged pollen and charcoal records for the lakes. The pollen analysis is presented as concentration data. Values on the x-axis for key taxa are presented as the number of grains per cubic centimetre. Human arrival was identified at approximately 27cm depth in Lake Ngatu and 38cm in Lake Rotoroa (Fig. 5).

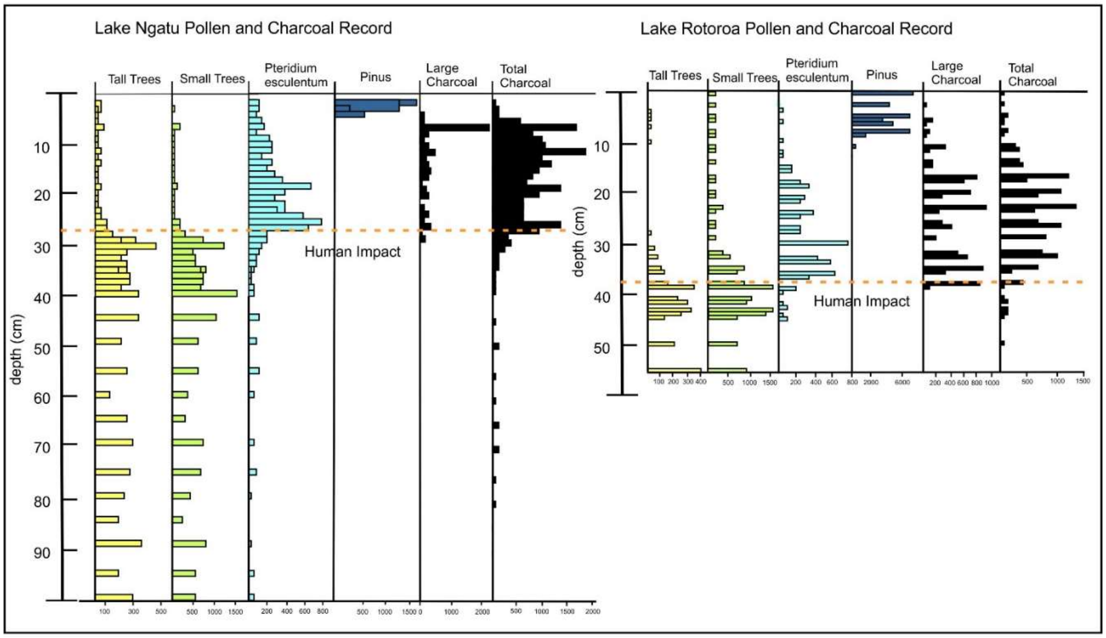

Figure 5. Simplified pollen, spore and charcoal identification for the 2017 Lakes Ngatu and Rotoroa sediment cores (unpublished data supplied by J. Maxwell). Tall and small tree pollen is represented entirely by New Zealand indigenous taxa. X axes are pollen concentration values.

For the test, both identifiable terrestrial macrofossils were radiocarbon dated along with concentrated pollen from the same depth. Sample sets were obtained from both above and below sediment markers of initial human alteration of the landscape in both lakes (see section 2.4 for a discussion of how human impact is identified in sediment records). Six sample sets in total were selected, three from each lake and at least one sample from above and one from below human impact in each lake. Samples from before initial human impact will henceforth be called 'pre-impact' and samples isolated after initial human impact will be called 'post-impact' throughout the rest of the thesis.

Additionally, the purity of the pollen concentrate was judged, allowing the contamination within the pollen concentrate to be corrected for. Isolating pollen away from extraneous substances within the sediment for measurement can be challenging and very time-consuming. Lithic, algae and fine cellular plant materials are also present in the sediment but can be separated from palynomorph grains through multiple sieving and density separation steps. Provided that the abundance of pollen is not too low, it is possible to produce a concentrate that is ≥ 80% palynomorph with enough mass for measurement by accelerator mass spectrometer (AMS) from ½ cm (~2g) of cored sediment.

The purity of the pollen concentrate is important because it may affect the accuracy of measurement. Prior research indicates that pollen concentrates containing larger amounts of contaminating material produce ages which are older than deposition (Chester and Prior, 2004; Kilian et al., 2002). The incorporation of algae and other aquatic materials is of particular concern because these organisms photosynthesize sub-aqueously and may be depleted in ^{14}C (MacDonald et al., 1987; Vandergoes and Prior, 2003). Cellular material observed in the final measurement concentrations could also derive from aquatic sources and suffer from similar ^{14}C depletion. Since the residual contaminate materials might impact the ^{14}C age of the concentrates, great care was taken to produce pollen concentrates with the highest ratio of pollen possible. However, to be able to distinguish between the effects of the included contaminating materials in the pollen concentrates from the possible effects from human modification of the environment, algae and cellular materials from matching depths were also concentrated and measured.

Measurement of the contaminating fractions allowed for a mixing model to be built that could then provide age ranges for the pollen concentrates without the ^{14}C activities of the contaminates included. Separating the contamination values from the pollen helps to distinguish not only how the incorporation of these materials affected the ^{14}C age of the concentrated pollen but also if reworked pollen was entering the lake basin either before or after human impact.

4.3 Methods

4.3.1 Fieldwork and Core Recovery

Coring was undertaken at Lakes Ngatu and Rotoroa in March 2016 with a modified Livingston corer operated from an inflatable cataraft equipped with a small working platform. The depocentres of the lakes were cored to avoid the effects of wind-induced mixing of the sediment-water interface. Coring pipe was percussion-pounded into the lake sediment until no more depth could be achieved, with one complete core obtained per lake. PVC pipe 3m long and 70mm in diameter was used for coring and the core total length ranged from 3m to 5m. An overlap of ½ metre depth was taken when a second 3m length of core was needed for comparative and continuous records. Gravity cores were also taken from each lake in May 2017 to a depth of 60cm to accurately preserve the sediment-water interface.

The 2016 cores were cut into 1 ½ m sections and housed in refrigerated storage at the University of Otago, Dunedin and GNS Science, Avalon. One gram of sediment was sampled at 1 cm increments throughout the lake cores for pollen and charcoal analysis.

4.3.2. Core Sampling and Sample Preparation for ^{14}C Dating

After splitting and imaging, the cores were sampled continuously at ½ cm and one cm resolution for Lake Ngatu and Rotoroa respectively. Approximately 2-3mm of sediment that was in contact with the coring pipe was removed and discarded to eliminate the chances of contamination by vertical travel. Each sampled depth (n=>500) was sieved to 90µm and a small number of terrestrial macrofossils were isolated. Of these, six were selected, three from each lake at varying depths, for the experiment. Processing of paired pollen, algae, and cellular concentrates began after the six macrofossils were selected for dating.

4.3.3 Macrofossil Pre-treatment

Isolated terrestrial macrofossils were prepared for ^{14}C dating by mechanically cleaning the sample followed by the standard Rafter Radiocarbon Lab protocol for acid-alkali-acid (A-A-A) treatment. This treatment removes calcium carbonate, humic and other mobile carbon contaminants from the macrofossil. The last acid step breaks any bonds the sample has created with atmospheric CO_2 during the alkali step. Chemical treatment was individualized for each sample based on fragility and sample mass by adjusting the molarity, temperature or length of treatment to avoid sample mass loss.

4.3.4 Microbotanic Concentration

Pollen concentrates were created using a modified method developed by Newnham et al. (2007) and Howarth et al. (2013). Pollen was isolated using a combination of sieving and density separation with sodium polytungstate (SPT) along with chemical treatment to remove organic and inorganic contaminants (Fig. 6). During each sieving and density separation step both the greater and less than sample fractions were checked under magnification for pollen abundance. All samples underwent identical treatment up to density separation at $1.3 \geq X \geq 1.17$ specific gravity (s.g.). At this step, each sample was individually checked for sample mass and pollen abundance. Further separation at decreasing densities and/or oxidation was performed if sample mass allowed with the aim of preparing concentrates with higher ratios of pollen relative to non-pollen materials. Final pollen concentration was calculated individually for each sample before measurement. A slide was made from a subsample of the final fraction and concentration was determined by counting grains of pollen, cellular, algae, and other materials to 300 particles under magnification along a transect on that slide.

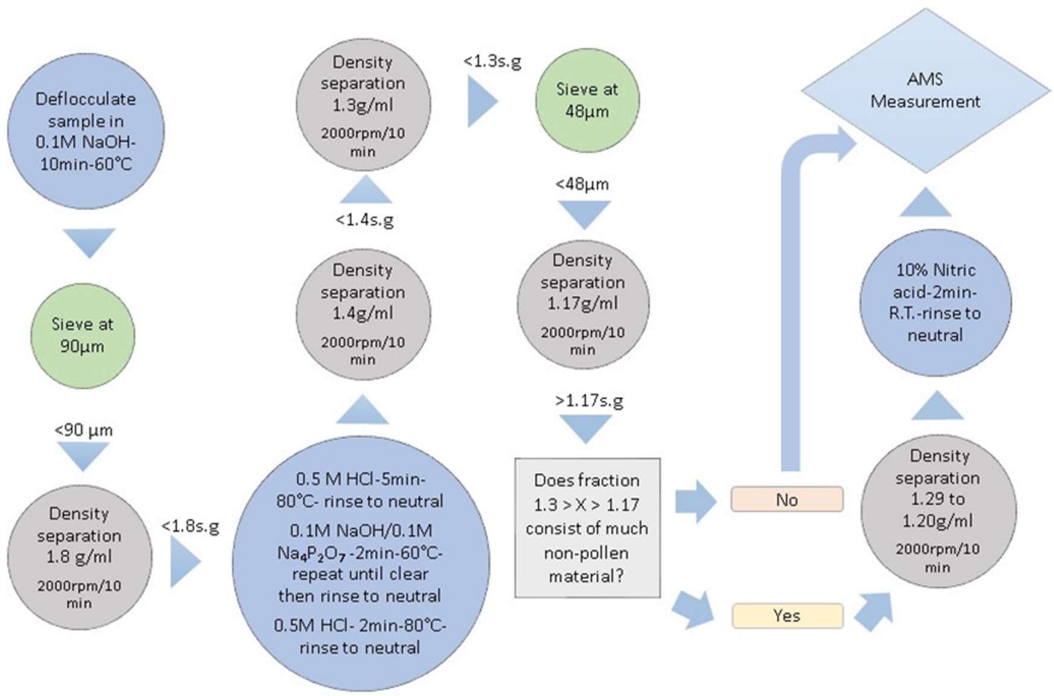

Figure 6. Flow diagram describing concentration of pollen. Method modified from Howarth et al. (2013).

Algae concentrates were created from the 1.8 > X > 1.4s.g. sample fractions. Further sieving and hand picking with tweezers were often required to remove larger cellular materials. Palynomorphs had already been removed from this fraction during pollen concentration. The concentrated algae had undergone chemical treatment during pollen concentration so an additional acid wash to remove any physically introduced contaminates was the only chemical treatment required. The algae *Botryococcus braunii* dominated the two lakes and composed the bulk of the concentrated algae for measurement. Botryococcus grows as a colony and has a flexible structure which can make microscopic counting for concentration percentage difficult. However, the percentage of isolated algae was in all cases >95% in each algal concentrate.

Cellular concentrates came from sample materials that were >90µm. This sample fraction was often contaminated with algae, so further sieving and hand picking was required. Cellular concentrates were a mixture of thin, translucent cellular sheets, seed fragments, and casing along with small flakes of unidentified organic detritus. These materials had not yet received chemical treatment so cellular concentrates underwent A-A-A treatment to remove environmental contamination. Cellular concentrates were well sieved and picked through so concentrations were quite pure, ranging from >95-100% (Fig. 7).

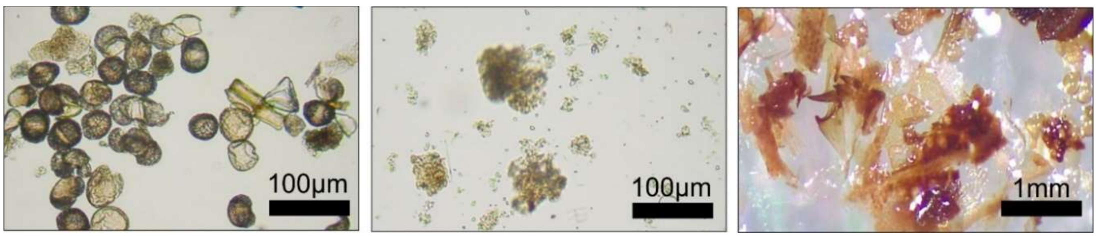

Figure 7. Images of final pollen, algae, and cellular material concentrates

4.3.5 CO2 Extraction, Graphitization, Measurement and Calibration

Samples prepared for ^{14}C measurement were loaded into quartz tubes and carbon dioxide was generated by sealed tube combustion and converted to graphite by reduction with hydrogen over an iron catalyst (Turnbull et al., 2015). $\delta\ ^{13}C$ was measured offline on samples with sufficient mass using a continuous flow isotope-ratio mass spectrometer (EA-IRMS) in the Stable Isotope Laboratory at GNS Science. Radiocarbon dating was performed at Rafter Radiocarbon Laboratory, GNS Science on the 0.5 MV XCAMS AMS. Results were produced using the measurement of all three carbon isotopes provided by XCAMS which corrects for any mass-dependent fractionation that may have occurred before or during measurement (Zondervan et al., 2015). Results were normalized against the NIST standard Oxalic Acid I. Blank correction was applied to the results using a process blank target of matching mass which was included in measurement with the experimental samples and normalized to $\delta^{13}C$ of -25‰ (Donahue et al., 1990). Radiocarbon results are reported as ^{14}C ages (yr BP) with a 1-sigma error. Samples were calibrated using OxCal calibration program version 4.3 with the SHCal13 calibration curve (Bronk Ramsey, 2008; Hogg et al., 2013).

4.3.6 ^{14}C Correction for Pollen Concentrates

For the purposes of the experiment, the conventional radiocarbon age (CRA) of all six pollen concentrates were corrected with the formula below. This was used to remove the ^{14}C activities of the contaminating materials from that of the pollen, which then supplied a ^{14}C age for each pollen concentrate as if the sample were pure pollen.

$$(P_{CRA} - A_{CRA} \times A\% - CM_{CRA} \times CM\%) \div P\% = 100\% P_{CRA}$$

In this formula, 'P' stands for pollen, 'A' for algae and 'CM' for cellular material. 'CRA' represents the measured CRA of each fraction. '%' values stand for the percent of each material type in a single pollen concentration. The calibrated age ranges subsequently produced from this model can be seen in Figure 8.

4.3.7 Chi-Squared and Pseudo-Bayesian Tests

The age distribution for the different target fractions was compared with that of the macrofossil for the same depth horizon using the combine function in OxCal. The combine function performs a two-phase test, first, a chi-squared test is performed which tests the statistical difference between the age probability density functions (PDFs). Secondly, a pseudo-Bayesian test provides an agreement index which is a measure of how much the two age distributions agree (Bronk Ramsey, 1995). The agreement index is tested by comparison to the critical value which is produced by using the formula, $1/\sqrt{(2n)}$ (Table 2).

4.4 Results

In both lakes, the results from below initial human impact were distinctly different from the samples isolated above human modification. Pre-impact pollen concentrates all returned calibrated age ranges that were close to or statistically contemporaneous in age with the associated macrofossil. In comparison, pollen concentrates isolated after human impact returned ages that were hundreds to a thousand years older than the associated macrofossil. The ^{14}C results for the six sample sets are provided in Table 1 along with the percentage counts of pollen, algae and cellular materials for each sample.

The algae and cellular concentrates for all samples returned, to varying degrees, ^{14}C ages that were older than the macrofossils, showing that these materials are partly ^{14}C depleted. Therefore, the ^{14}C values of the pollen concentrates were influenced by the radiocarbon ages of these contaminating materials. A mixing model was used to understand how the inclusion of algae and cellular materials affected the ^{14}C ages of the pollen concentrates and how the corrected pollen concentrate calibrated ages would appear compared to the macrofossil without these effects.

Table 1. Radiocarbon results, calibrated age ranges, and microbotanical concentrations.

Lake Core	Depth [1]	Sample material measured	NZA [2]	CRA[3] [yBP]	CRA error	$d^{13}C$ [4] [‰]	$d^{13}C$ error	Fraction modern [5]	Fraction modern error	Calibrated age ranges cal BC/AD (95.4%) [6]	Microbotancal ratios (%)
Lake Ngatu 2016	5-5.5cm	*Leptospermum scoparium* leaf	62585	207	19			0.9746	0.0023	1662-1697 (21.4%), 1725-1808 (72.7%), 1872-1876 AD (0.5%)	
Lake Ngatu 2016	5.5-6.5cm	pollen concentrate	62579	1369	20	-25.6	0.2	0.8433	0.0021	653-692 (49.4%), 700-723 (6.7%), 731-766 AD (38.8%)	Pollen 51, Algae 16, Cellular 33
Lake Ngatu 2016	5.5-6.5cm	algae concentrate	62580	584	19	-21.3	0.2	0.9298	0.0022	1393-1431 AD	Algae 96
Lake Ngatu 2016	5.5-6.5cm	cellular concentrate	62581	463	64			0.9440	0.0075	1407-1627 AD	Cellular 99
Lake Ngatu 2016	10-10.5cm	*Leptospermum scoparium* leaf	62587	253	47			0.9689	0.0057	1510-1579 (7.2%), 1622-1813 (81.7%), 1837-1849 AD (1.2%), 1856-1881 (2.5%), 1926-1950 (2.3%)	
Lake Ngatu 2016	9.5-10.5cm	pollen concentrate	62586	1749	20			0.8043	0.0020	249-310 (43.4%), 319-389 AD (51.7%)	Pollen 55, Algae 12, Cellular 33
Lake Ngatu 2016	10-10.5cm	algae concentrate	62588	787	19	-20.1	0.2	0.9067	0.0021	1229-1252(22.2%), 1259-1291 AD (72.4%)	Algae 98
Lake Ngatu 2016	10-10.5cm	cellular concentrate	62589	617	19	-17.4	0.2	0.9260	0.0022	1320-1350 (42.6%), 1386-1411 AD (52.4%)	Cellular 100
Lake Ngatu 2017	43-43.5cm	flax or lake margin plant *	64141	3344	102			0.6595	0.0084	1878-1391 BC	
Lake Ngatu 2017	43-43.5cm	pollen concentrate	63956	3499	23	-28.0	0.2	0.6469	0.0019	1878-1689 BC	Pollen 88, Algae 2, Cellular 10
Lake Ngatu 2017	43-43.5cm	algae concentrate	63957	3462	23	-28.1	0.2	0.6499	0.0019	1870-1843 (5.9%), 1812-1799 (1.8%), 1776-1628 BC (87.4%)	Algae 98
Lake Ngatu 2017	43-43.5cm	cellular concentrate	63958	3447	24			0.6511	0.0020	1862-1849 (1.7%), 1771-1620 BC (93.4%)	Cellular 100

Table 1. continued

Lake Core	Depth [1]	Sample material measured	NZA [2]	CRA[3] [yBP]	CRA error	$d^{13}C$ [4] [‰]	$d^{13}C$ error	Fraction modern [5]	Fraction modern error	Calibrated age ranges cal BC/AD (95.4%) [6]	Microbotancal ratios (%)
Lake Rotora 2017	27-28cm	reed (unidentified)	63829	270	34			0.967	0.0041	1512-1550 (6.2%), 1562-1571 (0.9%), 1623-1682 (48.3%), 1731-1801 AD (39.7%)	
Lake Rotora 2017	28-29cm	twig (unidentified)	63457	324	20	-25.0	0.2	0.9604	0.0023	1508-1585 (59.8%), 1620-1651 AD (34.8%)	
Lake Rotora 2017	26-29cm	pollen concentrate	64145	550	20	-17.4	0.2	0.9338	0.0023	1401-1441 AD	Pollen 49, Algae 28, Cellular 23
Lake Rotora 2017	26-29cm	algae concentrate	64146	324	20	-19.1	0.2	0.9605	0.0024	1508-1585 (59.8%), 1620-1651 AD (34.8%)	Algae 97
Lake Rotora 2017	26-29cm	cellular concentrate	64144	358	20			0.9564	0.0024	1497-1637 AD	Cellular 99
Lake Rotoroa 2016	48-49cm	twig (unidentified)	63022	2265	21	-29.3	0.2	0.7543	0.0019	377-206 BC	
Lake Rotoroa 2016	48-49cm	pollen concentrate	63023	2356	21	-27.6	0.2	0.7458	0.0019	411-355 (92%), 277-257 BC (3%)	Pollen 80, Algae 2, Cellular 18
Lake Rotoroa 2016	48-49cm	algae concentrate	63025	2425	21	-28.4	0.2	0.7395	0.0019	725-716 (1.1%), 703-693 (1.3%), 540-393 (92.6%)	Algae 98
Lake Rotoroa 2016	48-49cm	cellular concentrate	63024	2512	21	-26.2	0.2	0.7315	0.0019	765-429 BC	Cellular 99
Lake Rotoroa 2016	59.5-60cm	*Dacrydium cupressinum* leaf	61839	2299	21			0.7511	0.0020	396-346 (42.8%), 315-227 (51.2%), 217-213 BC (0.8%)	
Lake Rotoroa 2016	59-60cm	pollen concentrate	62582	2471	20	-28.1	0.2	0.7352	0.0018	747-682 (18.7%), 665-638 (6.1%), 588-403 BC (70.3%)	Pollen 85, Algae 6, Cellular 9
Lake Rotoroa 2016	59-60cm	algae concentrate	62584	2611	20	-30.6	0.2	0.7225	0.0018	805-747 (75.1%), 682-666 (5.3%), 638-586 (11.6%), 579-557 BC (3%)	Algae 99
Lake Rotoroa 2016	59-60cm	cellular concentrate	62583	2712	21	-26.8	0.2	0.7134	0.0018	893-797 BC	Cellular 100

[1] Refers to depth in cm below individual core liner

[2] Laboratory code: Rafter Radiocarbon Laboratory (NZA), Institute of Geological and Nuclear Sciences, Ltd., Lower Hutt, New Zealand

[3] Uncalibrated years before present (BP; ie. before 1950) is the conventional radiocarbon age as defined in Stuiver and Polach, 1977.

[4] δ13C normalization performed using δ13C measured by AMS, accounting for AMS fractionation. Environmental δ13C measured offline by IRMS and reported if sufficient material available.

[5] Fraction modern (F) is the blank corrected fraction modern normalized to δ13C of -25‰, defined in Donahue et al., 1990.

[6] Calibrated with OxCal version 4.3 (Bronk Ramsey, 2017 with SHCal13 atmospheric curve (Hogg et al., 2013).

* Indictes samples that contained <0.3 mg carbon. These samples are sensitive to contamination which was corrected for using concurrently measured size-matched modern and 14C-free blank material
This correction and the lower number of 14C counts obtained produces lower precision. Nonetheless, measurement of known-age materials shows that the results are accurate within the reported preci

4.4.1 Mixing Model

Two distinct patterns appear again following correction in samples sets before and after initial human impact. The calibrated age ranges of the corrected pre-impact pollen concentrates from Rotoroa both shift slightly more towards those of the terrestrial macrofossils, while the 43.5cm sample from Ngatu remains statistically unchanged by correction. In comparison, the corrected ^{14}C age distributions for all corrected post-impact pollen concentrates moved further away from those of the matching macrofossils by thousands of years (Fig. 8).

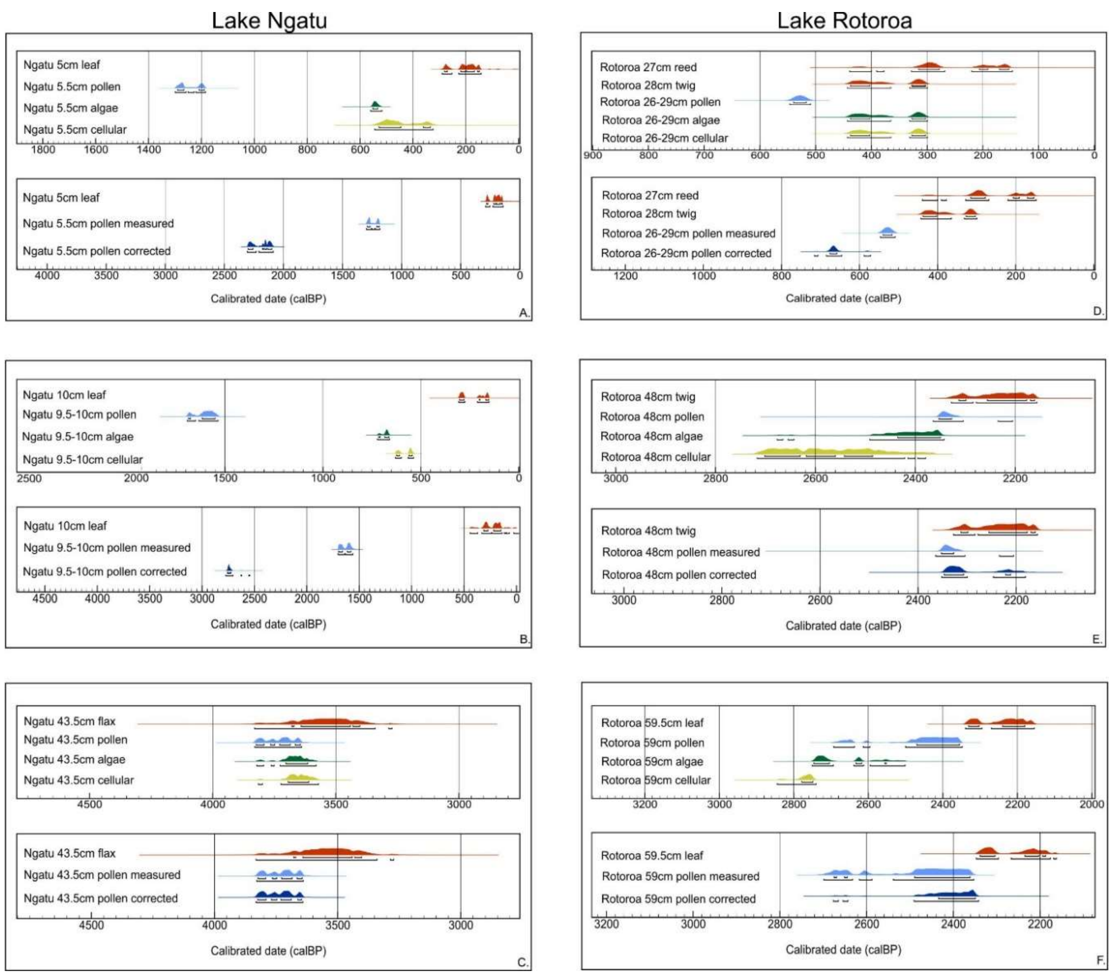

Figure 8. Calibration plots for all sample sets- before and after correction

A. Ngatu 5.5cm, B. Ngatu 10 and 9.5-10cm, C. Ngatu 43.5cm, D. Rotoroa 27,28 and 26-29cm, E. Rotoroa 48cm, F. Rotoroa 59 and 59.5cm. Images created with OxCal V4.32 Bronk Ramsey (2017); r:5 SHCal13 atmospheric curve (Hogg et al., 2013).

All three pre-impact corrected pollen samples were tested using the combine function in OxCal. The results of the chi-squared test and agreement index produced from this function show that after correction for contamination the PDFs of the pollen concentrates from the samples at Lake Ngatu 43.5cm and Lake Rotoroa 48cm produced a statistical overlap with their respective macrofossils (see T and A values in Table 2). The results of the test for the sample from 59cm in Lake Rotoroa shows that there is a statistical difference the age distributions. These tests were not undertaken on corrected post-impact samples because the calibrated ranges did not show any statistical overlap to evaluate.

Table 2. Results of the combine function test in OxCal showing the statistical fit between corrected pre-impact pollen concentrates and their matching macrofossils.

Lake	depth (cm)	Corrected CRA	X2 test T value	T critical value	A combined value	A critical value	Calibrated ranges (BC) at 2 sigma
Ngatu	43.5	3505 ± 21	2.061	3.841	61.10%	50%	1880 to 1685 (95.4%)
Rotoroa	48	2319 ± 21	1.557	3.841	81.80%	50%	392-350 (43%), 300-23 (52.4%)
Rotoroa	59	2424 ± 21	14.258	3.841	7.40%	50%	464-459 (0.6%), 454-447 (0.9%), (428-392 (93.9%)

degrees of freedom=1
alpha level =0.5%
CRA error= 1 sigma

4.5 Interpretation of Results

4.5.1 Comparison of Macrofossil and Measured Pollen Concentrate Results

The calibrated age ranges for all six of the macrofossils measured are stratigraphically consistent with each other and fit within the consensus New Zealand settlement chronology, with an approximate 1300 AD settlement date (Anderson, 2002; Wilmshurst et al., 2008; Wilmshurst et al., 2011). This suggests that the macrofossils did not suffer from any serious reworking and that these materials should produce accurate ages for sediment deposition for the chronology and can be used to analyse the pollen concentrates measured at depths matching them.

Palynomorph concentrates isolated from before human impact returned calibrated age ranges within (Ngatu 43.5cm) or near to those of the associated macrofossils and also fit the consensus chronology. However, the three pollen samples created from post-impact sediments were significantly older than the paired macrofossils. The two post-impact pollen concentrates isolated from Lake Ngatu were hundreds to a thousand years older than the matching macrofossils with calibrated age ranges spanning from the earliest timeframe of expected settlement of New Zealand to several hundreds of years before settlement is considered to have occurred. The age ranges of these two post-impact pollen samples, even without the macrofossil date to compare to, are noticeability off-target. The calibrated age ranges of these samples fall nearer to those expected from pre-impact depths rather than post-impact.

However, this was not the case for the post-impact pollen concentrate isolated from Lake Rotoroa. This sample also returned an age that was a few hundred years older than the associated macrofossil, but for this sample, the calibrated age ranges fall within the consensus age range for human settlement of New Zealand. This suggests that radiocarbon dates on post-impact pollen in Lake Rotoroa could produce ages that are older than deposition, but not so substantially that the erroneous ages would be obvious without other lines of evidence to support or reject the palynomorph age. This implies that pollen concentrated from post-impact sediment could be a problematic dating target to use to build an age-depth model, but that inaccuracies may not be obvious upon first inspection.

4.5.2 Measurement of Aquatic Sources of Contamination within the Pollen Concentrate

The algal and cellular concentrates showed evidence of being ^{14}C depleted compared to the macrofossils measured at the same depth. Correction of the ^{14}C values for the pre-impact pollen concentrate samples calculated through the mixing models suggests that the inclusion of these contaminants did influence the radiocarbon ages of the pollen concentrates, particularly in Lake Rotoroa. The pre-impact pollen samples contained the highest abundance of pollen in the series, with extraneous materials making up < 20% of the sample matrix. Despite the relative purity of these concentrates, the algal and cellular materials contained within them still appear to account for a portion of the offset between the reported results for the macrofossil and the pre-human settlement pollen (Fig. 8). This supports prior research which has suggested that the purity of the pollen sample can significantly alter the reported age of the sample (Chester and Prior, 2004; Kilian et al., 2002).

Though the incorporation of these materials has affected the accuracy of the Lake Rotoroa pre-impact pollen samples it doesn’t appear to be the sole cause of the erroneously older measured ages in Rotoroa 59cm. This sample still showed isotopic evidence of containing ^{14}C depleted materials after correction, and the results of the chi-square test did not show significant statistical overlap with the calibrated age ranges of the macrofossil after correction either. Possible reasons for this offset are discussed further below.

The post-impact sample series shift in the opposite direction when corrected with the mixing model. These three samples suffered the most from the inclusion of contaminants due to the low abundance of pollen at these depths. The limited pollen was likely due to increases of clastic material entering the basin in tandem with reduced vegetation around the catchment after a series of burn events when anthropogenic impact occurred. Despite these samples having the greatest abundance of contaminating material contained within them, after the ^{14}C activities of the contaminating materials were removed, the two post-impact pollen samples from Lake Ngatu show increased differences of +~1000 yrs between their corrected calibrated age ranges and the matching macrofossil. The post-impact pollen concentrate from Lake Rotoroa was affected in the same way after correction, but not as severely. This sample only shifted ~100 years further away from the age ranges of the macrofossil. This occurred to these three samples because though the aquatic materials measured at the same depths were ^{14}C depleted, the algae and cellular material concentrates had younger ages than the associated pollen concentrates did. When the isotopic effects of the contaminate materials were removed from the post-impact pollen concentrates the corrected age ranges 'aged' several hundred years. The post-impact pollen sample from Lake Rotoroa doesn't suffer as much aging after correction because the aquatic samples from that depth returned similar ages to the uncorrected pollen (Fig. 8). Increased deployment of fossil pollen into the lake basin is a possible reason for the post-impact pollen concentrates to diverge from the age ranges of their associated macrofossils. Fossil pollen could be derived from catchment soils being stripped by wave actions, heightened aeolian transport due to increased dune mobility following deforestation, or possibly human-induced erosion of the catchment soils with land use.

4.5.3 Contamination Estimation for Corrected Pollen Sample- Rotoroa 59cm

Rotoroa 59cm was the only pre-impact sample set that did not show statistical overlap in the age distributions of the corrected pollen concentrate and macrofossil after correction for aquatic contamination. To estimate how much entirely ^{14}C depleted material would be required to be contained within this pollen sample to account for the continued offset, calculations for ^{14}C dead contamination were made. The formula for correction is below.

$$\%dead\ ^{14}C contamination = \left(e^{\left(CRA_C/_{-8033}\right)} - e^{\left(CRA_T/_{-8033}\right)}\right) \div \left(e^{\left(50000/_{-8033}\right)} - e^{\left(CRA_T/_{-80}\quad\right)}\right) \times 100$$

CRA_c is the corrected conventional radiocarbon age of the sample and CRA_T is the true age of the sample, based on the CRA of the macrofossil. 50000 is the value used for completely radiocarbon depleted material. The remaining functions and values in the formula for calculating conventional radiocarbon ages are derived from Stuiver and Polach (1977). Corrected CRA for the sample is reported in Table 2.

The result of the calculation suggests that only 1.70% (mean) of totally ^{14}C depleted material within the pollen concentrate would be required to explain the offset between the corrected CRA of the pollen- 2424±21 yrBP from that of the matching macrofossil- 2299±21 yrBP (1-sigma). This calculation only provides an estimate of the minimum amount of possible contaminating materials. If the included materials were not entirely radiocarbon depleted more mass would be required to achieve the observed offset. However, Rotoroa's catchment soils were formed during the Pleistocene to late Holocene (Isaac, 1996; Petty, 1981), so any re-worked palynomorphs could have low ^{14}C values, and the amount of contaminating old carbon required for the offset could be quite small (Caughley, 1988).

One possible reason for this offset is that prior to human impact a small amount of fossil pollen was irregularly mobilized into the lake basin through natural processes like wave action. A second possibility could be related to biases in the ratios developed for each pollen concentrate. The percentages for each material were obtained by counting grains, not by individual material mass. This could have led to misrepresentations of how much mass of each material type existed in the sample compared to the total number of grains of that sample type. Uncertainties in the normalisations of the ratios of the materials represented in the pollen concentrates are likely similarly small in value. Since the amount of ^{14}C depleted carbon needed to explain the offset is probably similar to the error in ratio calculations it is not possible to distinguish which of these scenarios is the more plausible explanation for the offsets. However, despite the uncertainties, the analysis demonstrates that small quantities 14C depleted pollen can significantly influence the radiocarbon ages.

4.5.4 Anthropogenic Impact of the Catchment

Prior studies have suggested that the selection of a closed lake and care in achieving pure pollen concentrates should produce ^{14}C ages that are accurate for sediment deposition (Chester and Prior, 2004; Vandergoes and Prior, 2003). This test indicates that the purity of the pollen concentrate may not affect the age of the sample as much as the historical and environmental context of when deposition occurred. The offset observed in this experiment between pollen and macrofossil sample sets can't be explained by contamination from ^{14}C depleted aquatic materials or through fluvial processes. Since the significant differences in sample arrays occur after human landscape modification the results suggest that the offsets between the post-impact pollen concentrate dates and macrofossils ages are caused by mobilization of fossil pollen, especially of peats within the catchment soils, primarily by human modification of the landscape. Consequently, pollen concentrates isolated after anthropogenic landscape modification could produce ^{14}C ages that are much older than sediment deposition. Prior to anthropogenic land use pollen concentrates might be an appropriate dating target when macrofossils are not available. Similar impacts may be seen in lake settings where other types of significant landscape disturbances affect the lake margin environment. These results may have broader implications for other types of research and concentrated pollens from closed lakes impacted by earthquakes, natural loss of forest due to lightning strike, blowdown or substantial vegetation loss from storms may cause similar issues. The outcomes of the test suggest that palynomorphs utilized for dating from lake deposits formed during periods of either natural or anthropogenic landscape disturbance should be used with caution. These issues may only be apparent after experimental validation, such as those undertaken as part of this project, to identify the materials that could reliably be used to build the age-depth model.

4.6 Summary

A dating test was undertaken to determine which organic materials from two closed lake systems in the Far North would produce the most reliable ages for sediment deposition. Since the focus of the research project is to identify the timing of human settlement for the region and develop a duration record of land use, it was important to build a very precise chronology from sediments which had been affected by anthropogenic modification over time. With concerns that human alteration of the environment could cause the mobilization of fossil pollen (McGlone and Wilmshurst, 1999; Newnham et al., 1998b), three macrofossils from each lake were radiocarbon dated along with pollen, algal, and cellular material concentrates from the same depth. This was done to determine if pollen concentrates would return reliable ages for deposition and could be used as materials to build the age-depth model and if the contaminating materials were responsible for any offsets seen.

The test found that prior to human occupation concentrated pollen produced radiocarbon ages that were comparable to those of the matching macrofossil. Contamination correction improved these results. On the other hand, post-impact pollen concentrates produced ^{14}C calibrated ages that were hundreds of years older than terrestrial macrofossils from the same depths. The offset between the pollen concentrates and macrofossil samples could not be explained by the inclusions of ^{14}C depleted materials from aquatic sources within the pollen concentrates, which were found to be younger in age than the matching pollen concentrates. The old carbon contamination within the post-impact pollen concentrates was likely derived from fossil pollen transported from catchment soils into the lake basins. This was probably due to increased local erosion after deforestation by Polynesian settlers to New Zealand (McGlone and Wilmshurst, 1999; McWethy et al., 2010; McWethy et al., 2014; Perry et al., 2012). The pollen concentrates isolated from depths above obvious signs of intense alteration to a landscape produced spurious radiocarbon ages that were significantly older than deposition and could not be used to develop the age-depth model for the research project.

5. Developing a Chronology for Human Settlement and Land-use

5.1 Introduction

To constrain when human settlement first occurred in the Far North it is necessary to create a precise chronology. To generate a high-resolution chronology, a dense series of samples would need to be obtained for measurement from a master sequence of the sediment cores. The results of the experiment, discussed in Chapter 4, informed the selection of the most appropriate samples to build the model. Section 5.2 introduces core imaging, Bayesian modelling and the methods used to build the age-depth model. The chronology for the lakes and the accuracy of the age-depth model are presented in 5.3. This is followed by a discussion on the timing of human arrival in the Far North as determined by the model and then compared to previous ^{14}C dates from Houhora in 5.4. Finally, section 5.5 summarizes the outcomes of the model.

5.2 Methods

The dark-coloured and homogenous nature of the sediment in all the cores rendered any features or changes in sediment density visually indiscernible. CT scanning is rapidly becoming an indispensable tool for sediment core assessment (Boyle 2000). Figure 9 shows a visual comparison of the cores as imaged by a line scanner and CT. Instead of visually correlating the 2016 and 2017 cores for each lake, CT data in conjunction with palynomorph and charcoal records were used to identify coring related issues and create a master sequence for each lake. CT imaging is a non-destructive technique that reveals the internal structure of the scanned object (Mees et al., 2003) and produces bulk density values for that object. CT values of the cores were plotted against each other and correlated by patterns in the CT numbers. Pollen and charcoal records were also correlated between the 2016 and 2017 cores for both lakes by common changes in the abundance of various pollen taxa and charcoal to build the master sequence. It was critical to establish a master sequence for each lake because radiocarbon and other proxy materials would be isolated from all core materials. Therefore, the sampling depths between the separate cores needed to be fitted together to construct an accurate chronology.

5.2.1 Imaging

Line scanning and X-ray computed tomography (CT) were used to identify physical properties within the cores. CT imaging was performed on a GE BrightSpeed medical CT scanner set to 120 kV, 250 mA, pitch of 0.625 mm and a 100 cm^2 window. CT tomography data were analysed with Imagej software to produce sagittal slice images and down-core Hounsfield/CT number values. Denser areas with higher CT values appeared lighter and lower density areas with smaller values were darker. CT images can be rendered in either 2-D or 3-D, allowing features and structures within the sediment cores to be observed that would not be seen through visual core logging (Fig. 9).

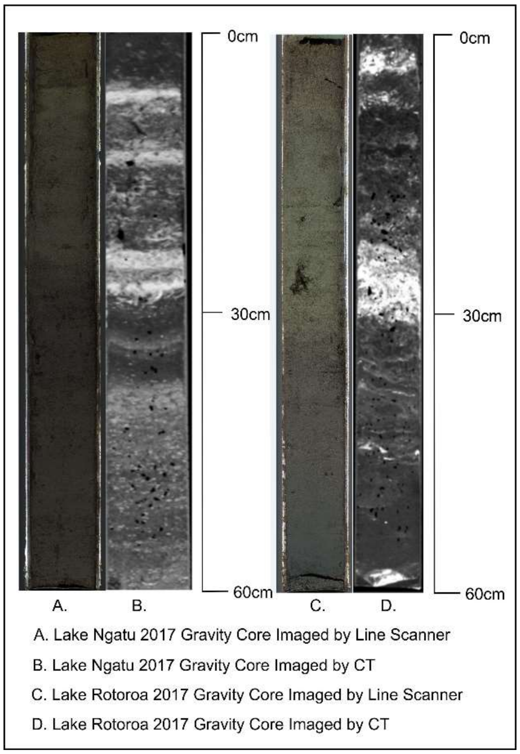

Figure 9. Lake core images by line scanner and CT

5.2.2 Radiocarbon sample selection

To build the age-depth model twelve identifiable terrestrial macrofossils with enough mass for measurement were isolated from the Lake Rotoroa master sequence (three of which were included in the dating experiment). Of these twelve, nine were situated after or just at human arrival according to the CT data and pollen records, with three samples located below evidence of human arrival (Fig. 10). In Lake Ngatu however, only four dateable macrofossils were recovered, with only one sample identified as coming from pre-settlement depths. Four samples are not enough to create a high-resolution ^{14}C chronology and the targets available were not evenly distributed between pre- and post-impact sediments. The results of the dating test suggested that pollen isolated in this lake from depths prior to human impact or other disturbances were suitable, though not ideal dating targets (see Chapter 4). To increase the distribution of radiocarbon dates in Lake Ngatu and to create a better bridge between the post-settlement and the single pre-settlement target, four pre-settlement pollen concentrates from Lake Ngatu were also processed and measured. Radiocarbon sample treatment and measurement details are provided in Chapter 4 section 3.

5.2.3 Bayesian Modelling

Following AMS measurement, radiocarbon dates were calibrated using the SHCal1 13 and Bomb 13SH3 calibration curves (Hogg et al., 2013; Hua et al., 2013). The Southern Calibration Curve 2013 (SHCal1 13) suffers from plateaus during the late Holocene, the timeframe of the research (Hogg et al., 2013), which can render wide probability distributions on individual radiocarbon dates. Bayesian statistics were used to integrate numerical ages from ^{14}C dating and biostratigraphy in conjunction with stratigraphy to better constrain the ages of sediment deposition (Bronk Ramsey, 2008, 2009). There are three components to a Bayesian age-depth model based on Bayes theorem- the prior, likelihood and posterior. The prior is additional data for the model outside of the observed data (depth/stratigraphic order), the likelihood is the observed data within the parameters of the model (e.g.-pine pollen, tephra or ^{14}C ages) and the posterior is the given probability of all observations including the prior (Bronk Ramsey, 2008, 2009).

OxCal 4.3 software was used to run a P_Sequence prior model which combines the prior and likelihood probability distributions using a Markov Chain Monte Carlo (MCMC) algorithm to test all outcomes possible with the given prior and likelihood probabilities (Bronk Ramsey, 2008; Howarth et al., 2013). The P_Sequence prior uses a Poisson counting process with the assumption that the accumulation of layers in the model are random and distributes events according to depth (z). Increments within the model correspond proportionally to the variability of actual deposition using a parameter (k) to estimate the number of accumulation events over depth (Bronk Ramsey, 2008). A flexible or variable k value was employed for this project which allowed the model to average over different k values and find the most appropriate value for k with depth (Bronk Ramsey and Lee, 2013). This is useful because it limits the number of defined assumptions in the model (Bronk Ramsey and Lee, 2013).

Boundaries were placed into the model for human impact observed at 27cm in the 2016 Lake Ngatu sediment record and at 38.5cm in Lake Rotoroa and European establishment of pine plantations was entered as likelihood parameters into both models at 1920±20 (1-sigma) to coincide with the first European pine plantations in the region (Roche, 1990; Thode, 1983). The tops of the sediment cores were given the calendar year of 2017±3 (1-sigma) as additional likelihoods to identify when collection occurred and finally, to complete the model the bases of the cores were prescribed a depth ½ cm below the last likelihood distribution measured in each lake. The models for the two lakes were cross-referenced together by initial Polynesian impact, the exotic pine pollen age, and core top likelihood parameters. These marker beds, which represent coeval regional signals, were built into the model prior which allows the two chronologies to inform each other and thus strengthen both chronologies.

The fit of the age-depth model to the posterior and likelihood data were assessed to determine if the model produced accurate results. An agreement index (AI) was calculated for the overall fit of how well the posterior model agrees with the prior distribution. Indices were created for the model as well as for all observational data individually. It is important to test the fit because it is easy to build a model which deviates from the likelihood data and does not accurately represent the observational record (Bronk Ramsey, 2009). The results of the OxCal model were used to establish the timing of human impact. The chronology that was developed was used with the elemental and isotopic data to develop duration rates for the area.

5.3 Results

5.3.1 Identification of Coring Problems

The CT data showed that the 2016 Lake Ngatu long core experienced an issue which produced sediment sucking through 30-50cm, possibly caused by a jammed piston during percussion coring (Fig. 10). Approximately 5cm of the sediment to water interface was identified as missing from the Ngatu long core by the lack of exotic plant species in the pollen record despite European plants currently growing near the lake. The 2016 Lake Rotoroa long core also suffered from coring issues and was disturbed during storage, which caused sediment mixing and expansion, rendering the top 40cm of the core unusable. The 2017 Rotoroa pollen record identified that the top 15cm was absent in the 2016 Rotoroa core. These issues were not apparent during coring, splitting or visual inspection but were only observed in the palynomorph and CT data.

5.3.2 Master Sequence

Master sequences were successfully constructed from the 2016 and 2017 cores for both lakes (Fig. 11) and provide a single continuous sediment record for the proxy data to be placed against. Coring related issues and impacted depths were avoided in the construction of the master sequence. The master sequence for Lake Ngatu was constructed from seven tie points identified in the CT images and values as well as matching abundances in the pollen and charcoal records (Fig 10). The Ngatu master sequence contains depths 0-5cm from the 2017 core and continues with depths 0-50cm from the 2016 core. In Lake Rotoroa three tie points identified in the CT data were used to correlate sediment depths along with the pollen and charcoal records. The Rotoroa master sequence was composed of 0-59cm from the 2017 core and then 60-100cm from the 2016 core.

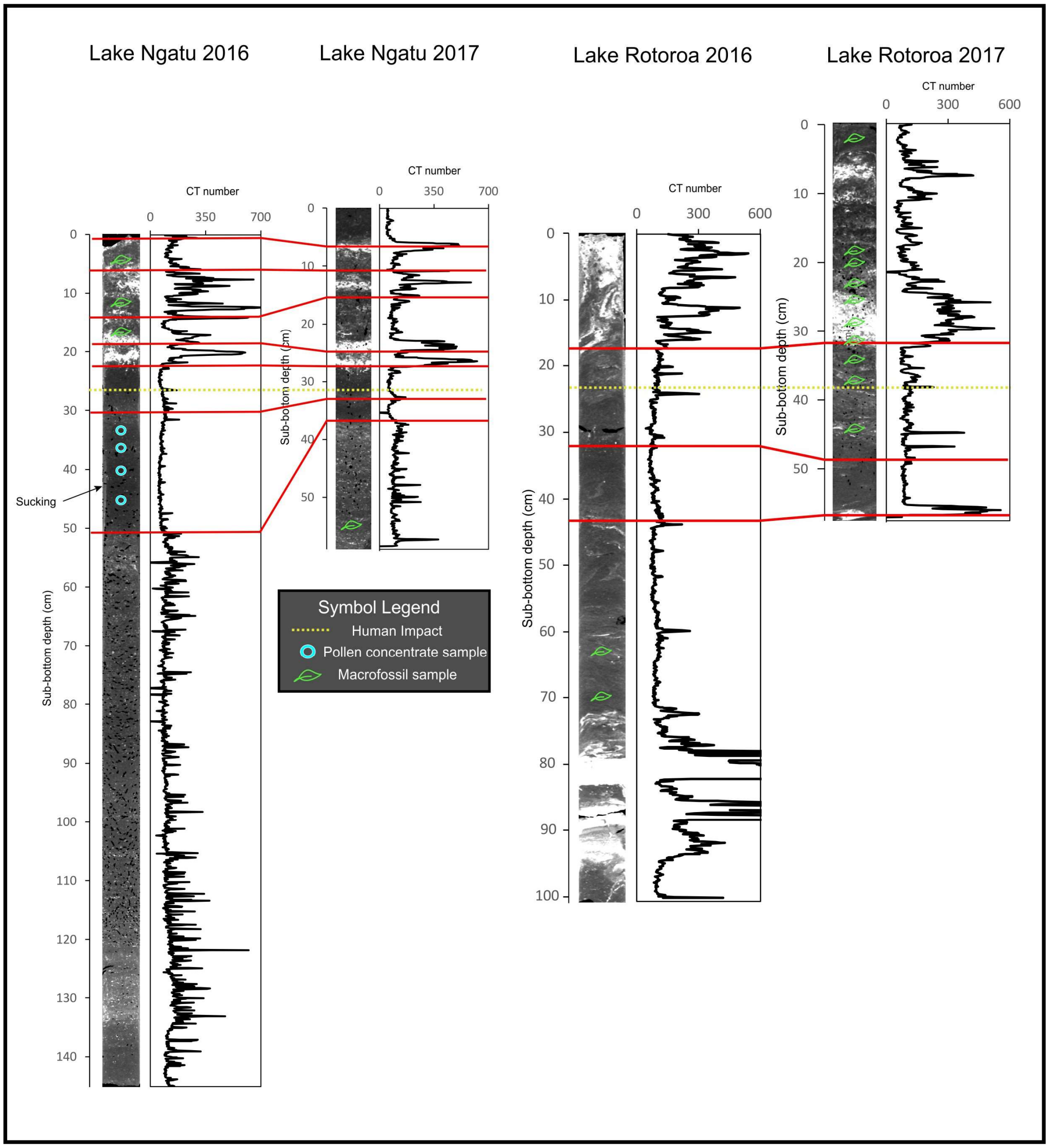

Figure 10. CT images and correlation of sediment depths from Lakes Ngatu and Rotoroa

Higher CT values indicate denser sediments and smaller values represent lower densities. Position of radiocarbon samples selected for measurement as well as demarcation of Polynesian settlement based on pollen and charcoal analysis.

5.3.3 Radiocarbon and Modelling Results

Radiocarbon measurement on 20 total targets was used to develop the age-depth model. Table 3 provides the non-modelled radiocarbon results and associated calibration age ranges for the samples. The model had an AI index of 78.4%; above the 60% required to measure an agreement between the model and the observational data (Bronk Ramsey, 2008). This indicates that the model had a good fit between the posterior and the likelihood distributions. Additionally, no inverted dates or outliers were identified in the model. The age-depth model for the lakes is presented in Figure 12.

The Ngatu portion of the age-depth model from the bottom of the core up to human impact (purple section of Fig. 12) was built from six likelihoods. The core bottom at 70.1cm has a modelled calibrated age range of 1948 to 1439 BC (average 1704±140 BC) (all errors are reported at 1-sigma). At the top of this section was NZA 63954 at 33cm with a modelled age range of 263-428 AD (average 385±29 AD). These six likelihoods had an average modelled standard deviation of 70 years. This value is poor primarily due to the lack of constraint in the model between NZA 64141 at 70cm and NZA 61666 at 46cm which alone has an average standard deviation of 80 years. This explains the wider probability bands seen between the bottom of the Ngatu core and NZA 61666 (Fig.12).

The Ngatu section from initial human impact to prior to European arrival was built from four likelihoods. Modelled human impact was from 1164-1278 AD (average 1231±34 AD) at 27cm. The top of this section was constrained by NZA 63828 at 5.5cm with a modelled age of 1835-1940 AD (average 1880±28 AD) (teal section of Fig. 12). The average modelled standard deviation of likelihoods from this section showed a good fit with a value of 39 years. The final section from European arrival to the top of the core was built from only two likelihoods. The first was the European marker bed at 5cm with a modelled calibrated age of 1875-1937 AD (average 1904± 17 AD). The core top at 0cm was the last with a modelled range of 2011 to 2023 AD (average 2016±3). The average standard deviation for likelihood data from this section was 10 years.

The construction of the Rotoroa age-model from core bottom to before human impact was built from four likelihoods. The bottom of the core at 70cm had a modelled age between 419 BC and 253 BC (average 367±48 BC), while at the top of the section NZA 64147 at 45.5cm had a modelled age range of 773 AD to 966 AD (average 873±53 AD). The average standard deviation of this section is 42 years (dark blue portion of Fig. 12). The upper part of this section suffers from poorer constraint and plateaus in the calibration curve between NZA 63022 at 62.5cm and NZA 64147 at 45.5cm. The average standard deviation between these two samples was 42.5 years. The modelled section from human impact to before European arrival in Rotoroa was built from nine likelihoods. This section starts at 38.5cm with the modelled age range for human arrival, which is the same here for Rotoroa as reported above for Ngatu, and ends with NZA 63829 at 19cm. Sample 63829 has a modelled calibration range of 1624-1793 AD (average 1657±32 AD). This section was well constrained with an average standard deviation of 29 years for all likelihood data (green section of Fig. 12). The final section from European arrival to the top of the core was composed of three likelihoods. This section spans from the marker bed for European arrival at 12cm, with the same modelled calibrated ages reported above for Ngatu, to the core top at 0cm with a modelled range for 2010-2022 AD (average 2016±3). This final section has an average standard deviation of 7 years on all likelihood results.

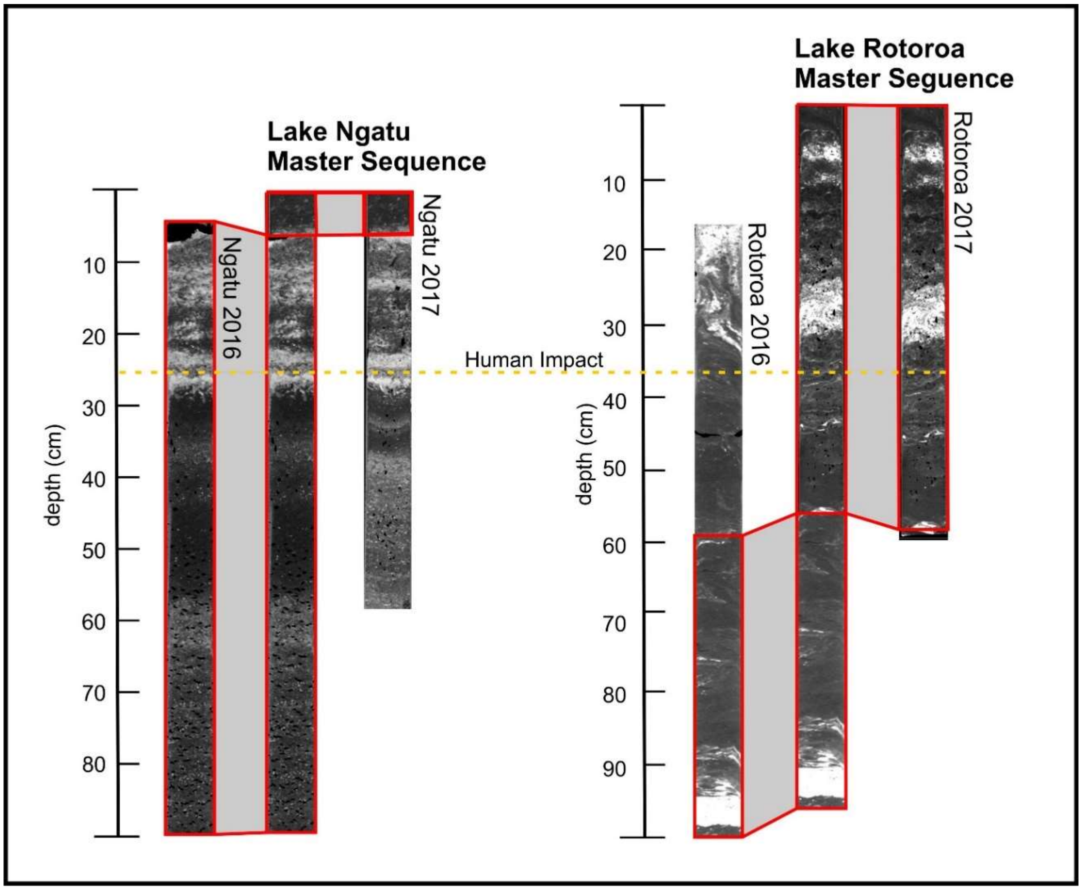

Figure 11. Master sequence sediment core depths for Lake Ngatu and Rotoroa

Table 3. Radiocarbon results and calibrated age ranges.

NZA	Sample ID	Description	Depth[1]	Rafter ID [2]	CRA [3]	CRA error	$d^{13}C$ [4]	$d^{13}C$ error	F [5]	F error	Calibrated age ranges cal BC/AD [6]
			(cm)		[yBP]		[‰]		[ ]		95.40%
Lake Ngatu Measurements											
63828*	NGAT-2016-5.5cm	Manuka leaves	5.5	40960/47	157	28			0.9807	0.0035	1677-1735 (26.4%), 1799-present (68.6%)
62585	NGAT-2016-11cm	Manuka leaf	11	40960/43	207	19			0.9746	0.0023	1662-1697 (21.4%), 1725-1808 (72.8%), 1872-1876 AD (0.5%)
62587	NGAT-2016-16cm	Manuka leaf	16	40960/6	253	47			0.9689	0.0057	1510-1579 (7.2%), 1622-1813 (81.7), 1837-1849 (1.2%), 1856-1881 (2.5%), 1926-present (2.3%), 1925- present (2.5%)
63954	NGAT-2016-33cm	pollen concentrate	33	40960/19	1703	21	-28.07	0.2	0.809	0.0021	340-427 AD (95%)
61665	NGAT-2016-36cm	pollen concentrate	36	40934/1	2100	23	-27.92	0.2	0.7699	0.0022	145-42 BC (85.3%), 17 BC-17 AD (9.6%)
63955	NGAT-2016-40cm	pollen concentrate	40	40960/35	2418	22	-27.91	0.2	0.7401	0.0020	725-719 (0.6%), 702-694 (0.9%), 539-388 BC
61666	NGAT-2016-46cm	pollen concentrate	46	40934/2	2783	24	-27.72	0.2	0.7072	0.0021	971-956 (3.3%), 938-813 BC (91.8%)
64141*	NGAT-2017-56cm	Flax or lake margin plant	56	40960/46	3344	102			0.6595	0.0084	1878-1391 BC (94.4%)
Lake Rotoroa Measurements											
63458	ROTO-2017-1cm	Gorse twig	1	40960/52	Modern		-31.67	0.2	1.0557	0.0025	Calendar yr 1995.5 +/- 0.5
63829*	ROTO-2017-19cm	reed	19	40960/50	270	34			0.9670	0.0041	1512-1550 (6.2%), 1562-1571 (0.9%), 1623-1682 (48.3%), 1731-1802 AD (39.7%)
63457	ROTO-2017-20cm	twig, unknown terrestial	20	40960/49	324	20	-24.99	0.2	0.9604	0.0023	1508-1585 (59.8%), 1620-1651 AD (34.8%)
63960	ROTO-2017-23cm	Flax or lake margin plant	23	40960/54	327	21			0.9601	0.0025	1507-1588 (63.6%), 1618-1650 AD (31.3%)
64142	ROTO-2017-25cm	Flax or lake margin plant	25	40960/55	339	20	-18.7	0.2	0.9587	0.0023	1504-1592 (72.6%), 1615-1646 AD (22.6%)
64143*	ROTO-2017-29cm	Flax or lake margin plant	29	40960/56	281	29			0.9656	0.0035	1512-1550 (9.6%), 1561-1572 (1.5%), 1623-1675 (61.4%), 1738-1798 AD (22.3%)
63830*	ROTO-2017-31.5cm	leaf, charred	31.5	40960/51	441	50			0.9466	0.0059	1429-1627 AD (95%)
63831*	ROTO-2017-34.5cm	charred plant material	34.5	40960/53	738	30			0.9122	0.0034	1271-1321 (62.2%), 1350-1386 AD (32.9%)
63959	ROTO-2017-38cm	charcoal from monocot	38	40960/48	845	21	-24.56	0.2	0.9002	0.0023	1209-1274 AD (94.8%)
64147	ROTO-2017-45.5cm	bark	45.5	40960/61	1215	21			0.8596	0.0022	774-821 (22%), 834-903 (50.4%), 923-967
63022	ROTO-2016-62.5cm	twig, unknown terrestial	62.5	40960/44	2265	21	-29.3	0.2	0.7543	0.0019	377-206 BC (95.2%)
61839	ROTO-2016-70cm	Rimu leaf	70	40934/3	2299	21			0.7511	0.0020	396-346 (42.8%), 315-227 (51.2%), 217-213 BC (0.8%)

[1] Refers to depth in cm below individual core liner
[2] Laboratory code: Rafter Radiocarbon Laboratory (NZA), Institute of Geological and Nuclear Sciences, Ltd., Lower Hutt, New Zealand
[3] Uncalibrated years before present (BP; ie. before 1950) is the conventional radiocarbon age as defined in Stuiver and Polach, 1977.
[4] δ13C normalization performed using δ13C measured by AMS, accounting for AMS fractionation. Environmental δ13C measured offline by IRMS and reported if sufficient material available.
[5] Fraction modern (F) is the blank corrected fraction modern normalized to δ13C of -25‰, defined in Donahue et al., 1990.
[6] Calibrated with OxCal version 4.3 (Bronk Ramsey, 2017 with SHCal13 atmospheric curve (Hogg et al., 2013).
* Indictes samples that contained <0.3 mg carbon. These samples are sensitive to contamination which was corrected for using concurrently measured size-matched modern and 14C-free blank materials.
This correction and the lower number of 14C counts obtained produces lower precision. Nonetheless, measurement of known-age materials shows that the results are accurate within the reported precision.

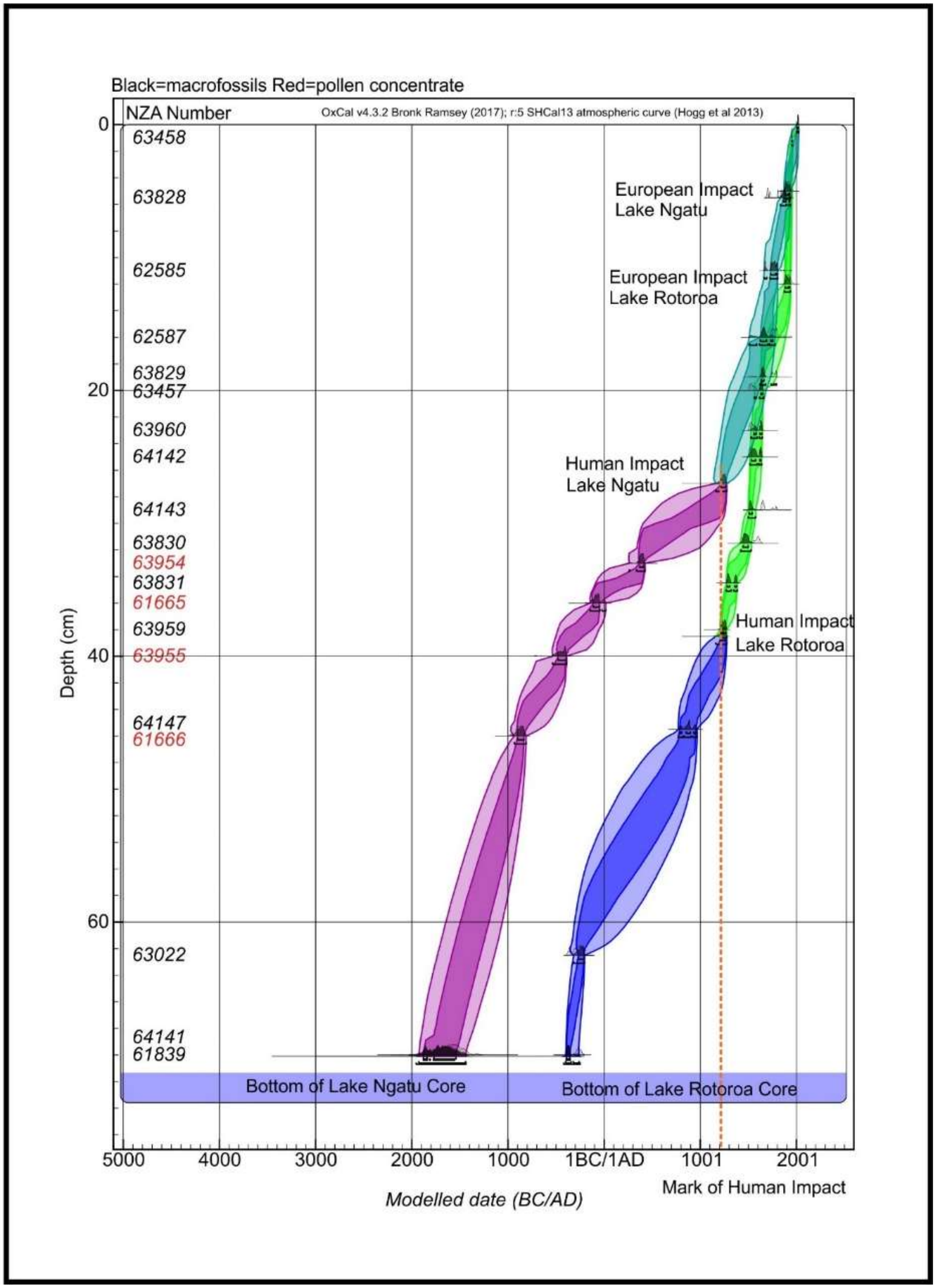

Figure 12. Calendar year age model built from ^{14}C measured pollen concentrates and macrofossils isolated from Lakes Ngatu and Rotoroa

5.3.4 Modelled Timing of Initial Human Impact in the Region

The calibrated age range for initial anthropogenic impact of the study (Fig. 13) supplied by the model falls between 1164-1277 cal. AD (95.4%). Probability distribution function (PDF) for all likelihood data supplied by the model are reported in the appendices.

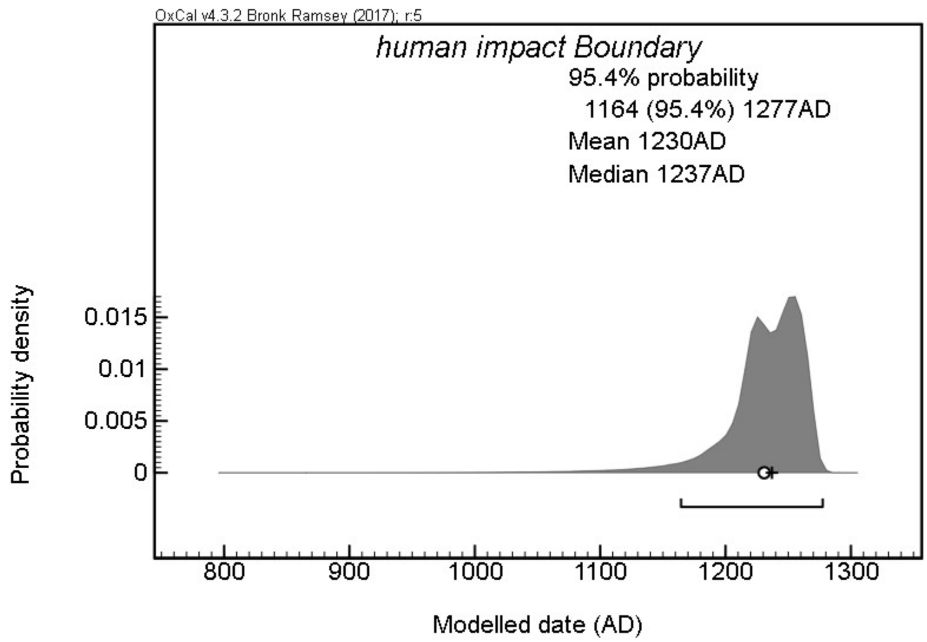

Figure 13. Calibration age range of human impact produced by the P_Sequence model

5.4 Interpretation- Timing of Human Settlement to the Far North

5.4.1 Establishment Human Impact in the Age-Depth Model

The high-resolution of likelihood data through the period of interest (Polynesian arrival and settlement) in the model provides good constraint for determining the timing of events and the duration of those events. The modelled age-range of initial human impact of the study region suggests that anthropogenic modification of the area began early in the settlement history of New Zealand. This result is directly supported by several ^{14}C measurements and the CT, pollen, and charcoal records.

Depths 27cm and 38.5cm in Lakes Ngatu and Rotoroa, where the human impact marker beds are situated in the model, are tightly bound by radiocarbon dates, particularly in Rotorua. A small and very fragile piece of charcoal at 38cm in Lake Rotoroa (NZA 63959) (Fig. 14), identified as having come from a monocot twig was measured to help accurately constrain the timing of human impact to the area. The delicate nature of this target, obtained from lake sediments that showed no evidence of mixing, makes this sample highly unlikely to have been reworked. The charcoal sample was identified as having come from a short-lived lake margin plant (Maxwell, 2017 personal communication).

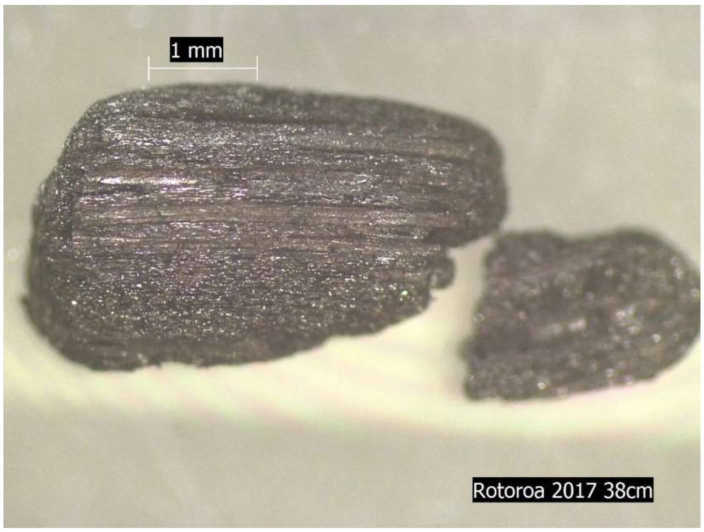

Figure 14. Photograph of charred monocot plant macrofossil from Lake Rotoroa 38cm

The modelled calibration range for NZA 63959 is 1210-1274 AD (94.5%) (Fig.15). Since this sample was obtained just 0.5cm above the Rotoroa human impact marker bed in the model, the statistical overlap in the age range between this sample and the modelled range for human arrival is significant for testing the validity of the modelled age initial human impact.

The accuracy is further supported by samples measured both above and below NZA 63959. Samples below 38cm showed no signs of charring, however, two of the samples measured directly above NZA 63959 at 34.5 and 31.5cm were also burnt. This suggests that the fire history of the area had altered at these depths and that continued burning of the area occurred. This pattern was also observed in the charcoal record. The modelled calibrated age range of NZA 63959 at 38.5cm was 1210-1275 AD. The modelled calibrated age distributions for the macrofossil at 34.5cm (NZA 63831) were between 1271-1320 and 1350-1387 AD and the sample at 45.5cm (NZA 64147) had calibrated age ranges between 773- 820, 833-903 and 922-966 AD (probability for all calibrations reported is 95.4%).

With support from the regional and local charcoal records, the samples have supplied not only reliable radiocarbon dates, which help confirm the accuracy of the modelled date for initial human impact, but the sample condition (burnt/unburnt) also provide archaeological context to the chronology. The results of the age-depth model suggest that initial human impact of the area is earlier than the chronology of any other dated archaeological site on the Aupouri Peninsula (Coster, 1989; Furey, 2002).

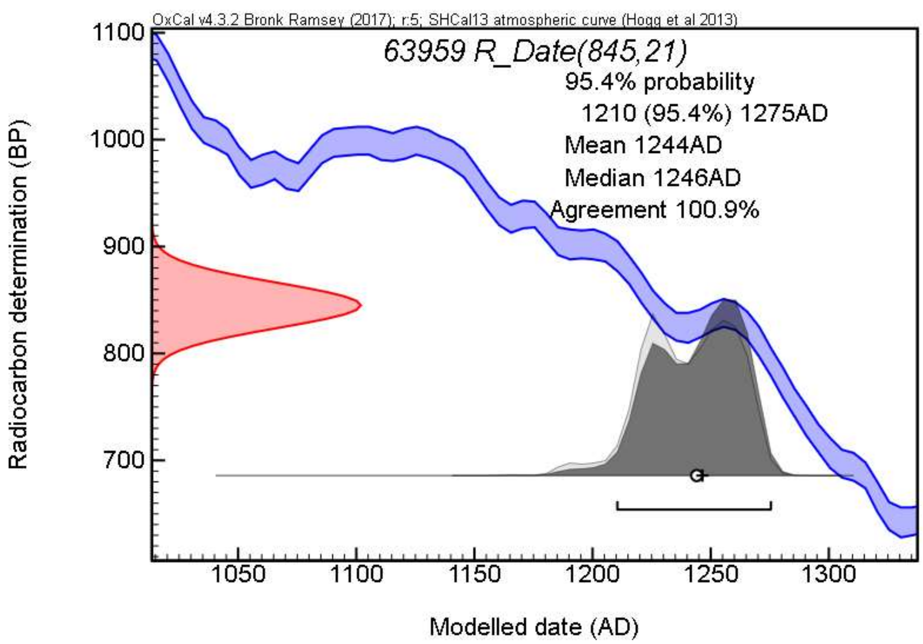

Figure 15. Calibration distribution of NZA 6959 on a piece of monocot charcoal derived from the P_ Sequence Model. Unmodelled calibration for sample available in Table 3

5.4.2 Comparison of Modelled Timeframe of Human Settlement to Previous Radiocarbon Measurements from Houhora

To determine how the outcomes of the age-depth model compare to the earliest dated archaeological site in the region, earlier measurements from Houhora were re-assessed. Shawcross and Roe submitted three charcoal pieces for radiocarbon measurement from archaeological investigations of Houhora in the 1960s (NZ 914, 915 and 916)(Furey, 2002; Roe, 1967). At that time ^{14}C measurement by AMS was not available, therefore these dates were produced by traditional gas counting. The amount of sample material required for gas-counting was significantly larger than the mass needed for AMS measurement. For example, approximately 180-255g of materials was submitted per originally submitted charcoal date compared to the ~1mg of material used for NZA 63959. The large mass of these charcoals could mean that either the pieces were quite large or that the mass incorporated a wide variety of materials. The historical sample submission documents reviewed did not identify this or the type of plant the charcoal came from. The lack of identification and the large mass of these samples increases the probability that they suffer from inbuilt age (Petchey, 2000; Wilmshurst et al., 2011), potentially affecting their accuracy. Also, according to the submission information for these samples, the dates produced an inverted age compared to the site stratigraphic information, casting further doubts on the reliability of the ages. Moa bones collected from this site were also dated in the early 1980s (NZ 5007 and 5008). The submission information for these samples suggests that they should be contemporaneous with the previously dated charcoal. To assess these previous dates against those from the current research project the original raw gas counting measurements were re-calculated against the standard material Oxalic Acid I and reported as a Conventional Radiocarbon Age (CRA) with 1 sigma error (Stuiver and Polach, 1977). The samples were then re-calibrated with the most recent Southern Hemisphere calibration curve (Hogg et al., 2013) (Table 3).

Additionally, dates for Houhora which were procured from rubber latex pulls taken from the original excavation and remaining bagged materials from excavation were dated in the early 1990s. These materials were identified as charcoal from short-lived plants and dateable marine shells. The researchers could not provenance the pulls to the original excavation maps and there was a small possibility that the samples selected might not be in situ but were from sections re-touched in the pulls to complete the pulls for display (Anderson and Wallace, 1993). Four of these samples (NZA 2391, 2436-8) were measured by AMS, but two samples (NZ 7920-1) were measured by gas counting. The geographic ΔR correction for shells NZA 2391 and 7920 was set to -30 ± 13 as given in Anderson and Wallace (1993) and calibrated with the Marine13 calibration curve (Reimer et al., 2013; Stuiver et al., 1986) and presented in Table 4. Calibration was also attempted with no ΔR correction for these two samples which produced and exact same calibrated age-ranges for the shell samples. The local ΔR would be required to accurately evaluate the shell results.

Table 4. Calibrated age-ranges for the 5 original and 6 more recent samples measured from Houhora.

NZ	Material	CRA	CRA	Calibrated age ranges	NZ	Material	CRA	CRA	Calibrated age ranges
		yBP	error	cal BC/AD (95.4%)			yBP	error	cal BC/AD (95.4%)
914	Charcoal	698	49	1276-1400	7920	Marine Shell	812	37	1430-1580
915	Charcoal	563	61	1300-1464 (95.1%)	7921	Charcoal	300	54	1477-1683 (78.2%)
				1472-1476 (0.3%)					1730-1803 (17.2%)
916	Charcoal	775	61	1185-1326 (77.3%)	NZA				
				1341-1390 (18.1%)	2391	Marine Shell	675	80	1470-1820
5007	Moa Bone	563	56	1305-1362 (19.3%)	2436	Charcoal	632	85	1238-1241 (0.2%)
				1377-1460 (76.1%)					1266-1458 (95.2%)
5008	Moa Bone	586	46	1311-1360 (26.2%)	2437	Charcoal	774	85	1072-1076 (0.3%)
				1379-1449 (69.2%)					1149-1406 (95.1%)
					2438	Charcoal	727	85	1189-1419

Most recently four gelatine samples (Wk-4920,4921, 4968 and 4969), two shell samples (Wk- 5034-5) and one charcoal sample (Wk-5484) were measured from remaining contents of the Houhora excavations. All samples produced calibrated age ranges from late 1200 to early 1400 AD (Petchey, 2000).

Though materials dated earlier from Houhora have associated problems and their accuracy cannot be entirely relied upon, the Polynesian style of some of the material culture found at the site and the moa content incorporated in site middens (Furey, 2002) suggests that early site settlement is not inconsistent with initial landscape alteration or occupation of the region between 1164-1277cal AD (95.4%), as modelled in this research. This is backed up as well by more recent ^{14}C measurements on twig charcoal, shell, and bone from the site which should not suffer from inbuilt age. The age-range produced by the model is probably the most accurate estimate for the timing of human-induced alteration of the environment in the Far North currently available owing to the large number of samples measured and modelled and the care taken to measure short-lived materials which had been tested to produce accurate ages for deposition.

5.5 Summary

The CT data and pollen and charcoal records were invaluable tools to correlate the lake cores, identify coring issues and for building a master sequence for the cores. These data sets were also used to build the age-depth model and determine when human settlement of the region began. The dating targets themselves contributed to the anthropogenic signal, seen also in the charcoal records, which supports the timing of anthropogenic burning in the chronology. Finally, the P_Sequence model used to develop the ^{14}C chronologies for the lakes has provided one of the highest-resolution models for anthropogenic impact in the Far North of New Zealand and suggests that human occupation of the area occurred between 1164-1277 cal. AD, as early if not earlier than anywhere else in New Zealand.

6. Environmental Reconstruction

6.1 Introduction

The construction of a robust age-depth model allows for the carbon, nitrogen and XRF proxy data from the lake sediments to be placed in time and utilized to determine the timing and duration of landscape use through time. The first part of this chapter discusses how organic matter influences sediment formation and how carbon, nitrogen and XRF measurement will be used to examine the organic and geochemical make up the sediment. Section 6.3 covers the preparation and measurement of samples for C:N and XRF analysis. In section 6.4 the proxy results are described against time and C:N results for the modern analogue samples are given. 6.5 begins with a section that explains the impact that the algae concentrate results had on the wider interpretation. An interpretation of all proxy results broken into four temporal zones follows. Lastly, a summary of the environmental reconstruction is presented in section 6.6.

6.2 Overview of Selected Proxies

6.2.1 Carbon and Nitrogen

Organic matter plays a critical role in the formation of lake sediments and is primarily sourced from the remnants of plants within the lake and the catchment (Chepstow-Lusty et al., 2009). Organic materials may experience many processes during sediment formation such as diagenesis and degradation which affect the geochemical makeup of the sedimentary materials. However, elemental and stable isotope measurement of bulk organic lake sediments can be used as a proxy for landscape modification of that system (Li et al., 2006; Meyers, 1994). Measurement of the isotopic ratios of carbon and nitrogen can be used to understand the paleoenvironment histories of lacustrine environments and identify the effects humans have had on the watershed (Meyers and Lallier-Vergès, 1999). Changes in the origin of the carbon being deposited into the lake can be used to reconstruct lake productivity and environmental fluxes around the catchment (Meyers, 1994). Human alterations to catchments have been identified in shifts in the C:N ratios in lake sediments (Kaushal and Binford, 1999; O'Reilly et al., 2005; Schmidt et al., 2002).

Carbon and nitrogen measurement were selected for the research project because the lake sediments were rich in organic material and may show significant changes in these values through time. Additionally, since the organic material in lake sediment is largely derived from within the lake and catchment, these measurements provide catchment specific information about both environmental and anthropogenic change. These results were compared with the regional pollen and charcoal records and used to identify the drivers of environmental change and estimate the duration of these changes.

In addition to carbon and nitrogen measurement on the lake sediment, modern analogue samples were also collected and measured. C:N analysis of the modern materials provided the isotopic signatures from different carbon sources in and around the lake prior to deposition. The results from the modern materials were used to help interpret the sediment results.

6.2.2 XRF Data

XRF measurement was performed on the lake sediments in this study to provide a rapid, inorganic and catchment specific proxy for human settlement and land-use for the area to help establish the duration of change the sediments underwent. X-ray fluorescence (XRF) is a technique that can be used to record changes in the elemental and chemical composition of a material by measuring the fluorescent (secondary) X-rays emitted from a sample when it is bombarded by a primary X-ray source. Each element present in a sample produces a set of unique fluorescent X-rays specific to that element. XRF measurement is a non-destructive technique (Boyle, 2000), providing total concentrations values for important environmental elements such as silicon (Si), titanium (Ti), calcium (Ca), potassium (K), iron (Fe), manganese (Mn), phosphorus (P), and zirconium (Zr), among others, in soils and sediments and can be used in combination with other proxies (Boyle, 2000).

Many elements have multiple potential sources. Calcium has been used to identify carbonate precipitation, changes in evaporative concentration and calcium input from lithic sources into lake sediments (Brown et al., 2007; Mueller et al., 2009). Silicon can also enter the lake system from quartz or autochthonous diatom production (Balascio et al., 2011; Brown et al., 2007). To better determine the origins of Ca and Si these two elements can be compared to corresponding titanium values over time. Ti is a conservative element and should be indicative of primary mineral inputs (Davies et al., 2015). If transitions in Ca and Si correlate with an erosional elemental proxy such as Ti, this would suggest a minerogenic origin of these elements (Boyle, 2002). If not, they might be more related to, in case of Ca, increased evaporative concentration, and increased Si might be related to biogenic silica production or a mix of biogenic and lithic input (Brown et al., 2007; Davies et al., 2015).

Iron can enter lakes as ferrous Fe in detrital sediment or as dissolved ferric iron depending on redox condition (Boyle, 2002; Mackereth, 1966). Fe to Mn ratios can be used to help identify redox conditions (Burn and Palmer, 2014; Davison, 1993; Haberzettl et al., 2007). In reducing conditions Fe and Mn become soluble, but manganese is more affected, so higher Fe/Mn ratios may suggest that an anaerobic environment existed (Boyle, 2002; Davies et al., 2015). Ti/Zr ratios are a grain size proxy (Shala et al., 2014). Titanium generally represents finer grains like clay, and zirconium is more common in silts and fine sand grains (Cuven et al., 2010).

Additionally, a rise in elemental potassium has been used to signify increased detrital input in sediment records (Aufgebauer et al., 2012; Elliot et al., 1997; Moreno et al., 2011) while increased phosphorus has been used to identify periods of nutrient enrichment (Corella et al., 2012). Ratios of the above elements and elemental curves for K and P will be created and examined to aid in interpreting these elements in through the core.

6.3 Methods

6.3.1 Sampling for Stable Isotope Measurement

Sediment samples for carbon and nitrogen isotopic and elemental measurement were cut from the master sequences of the cores from selected depths at ½cm resolution for Lake Ngatu and 1cm for Lake Rotoroa. Samples were freeze-dried then sieved to 425µm to remove larger lithic materials and isolate any macrofossils contained within the material. The <425µm fraction was ground by mortar and pestle to homogenise and powder the sediment for measurement.

Modern sample materials were collected from in and around the lake margins. Included in these samples were soils under leaf litter from less disturbed Northland podocarp forests outside of the catchment. These were obtained to measure soils with compositions more akin to those that could have been transported into the lake in the 12-13th centuries and prior to human arrival. Catchment soil samples were also taken from soil horizons dug from shorts pits near the lakes. One lake margin plant per lake and two charophyte plant specimens were collected for Lake Ngatu. Algae samples were extracted and concentrated for both lakes. Three algae concentrates were created per lake from sediments horizons that were from before human impact, after initial human impact and from the tops of the sediment cores.

6.3.2 Sample Treatment for Elemental and Stable Isotope Measurement

Both chemically treated and untreated sediments were analysed. Acidification is recommended for lake sediments before %C and $\delta^{13}C$ measurement to remove inorganic carbon derived from calcium carbonate in the sediment without eliminating the organic carbon within the sample matrix (Komada et al., 2008; Lane et al., 2008). Between 5-10mg of sediment was weighed out into 5 X 9mm Ag capsules, depending on the carbon content of the sediment. A repeat treated sample from the same depth every 3-5cm was also measured to test material homogeneity and machine linearity. Treated samples were acidified using modified methods from Verardo et al. (1990) and Komada et al. (2008) (Fig. 16). Treatment was as follows: samples were wetted with 2µL of deionized water before acidification by 2µl of 10% hydrochloric acid (HCl), then dried at 40°. Once dry 10µl of acid was added and again and the samples were dried down. This was continued twice more with the amount of acid increasing to 60µl in the final step (Komada et al., 2008). Once acidification was complete and the samples were dry the Ag capsules were folded down, placed into Sn capsules and rolled up for combustion.

Modern analogue samples taken from catchment soils and leaf litters in podocarp forests were prepared by freeze drying and sieving to <425µm. Once sieved the soil was powdered and prepared for combustion and measurement as described for the untreated lake sediments. Treatment with acid was not required as carbonate was unlikely to have contaminated the sample material.

Modern analogue flora samples were identified to genus or species, photographed, subsampled and cleaned with DI water and sonification if required. Clean subsamples were then dried in a vacuum oven and prepared for measurement like the untreated sediments described above.

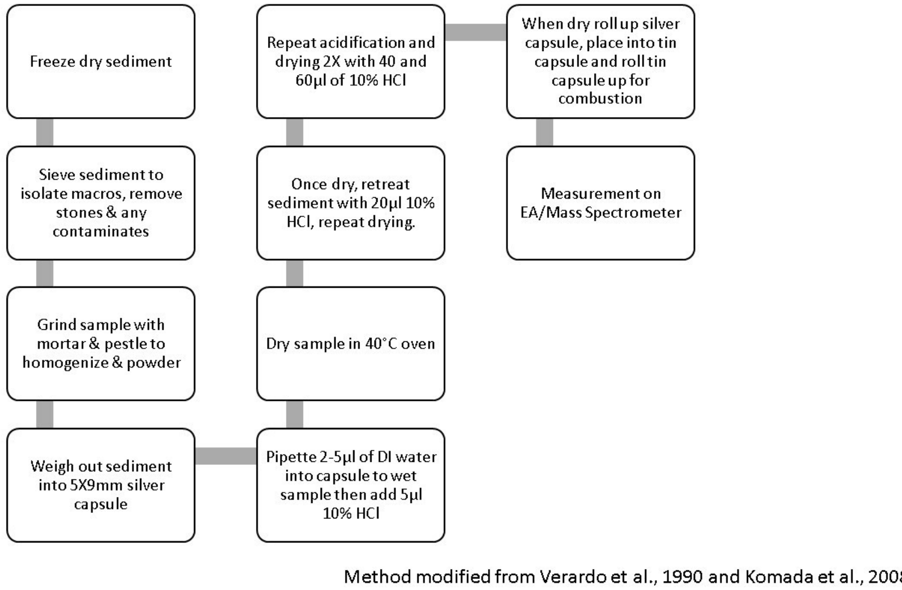

Figure 16. Preparation and treatment of sediment for carbon and nitrogen isotopic measurement

Untreated sediments from the same depths were also weighed out to similar masses as treated counterparts into 5 X 9mm Sn capsules to be run for %TC, %N, total carbon $\delta^{13}C$, and $\delta^{15}N$. Acidification has been shown to affect the reliable measurement of %N and $\delta^{15}N$ (Brodie et al., 2011) therefore, the C:N ratios were derived from the treated %C to the untreated %N value to avoid offsets in the ratio by carbonate contamination in the carbon and acid poisoning of nitrogen (Komada et al., 2008).

6.3.3 EA-Mass Spectrometer Measurement

Elemental and stable isotope measurements were run at GNS Science Stable Isotope Laboratory on a continuous flow GVI Isoprime mass spectrometer. Samples were measured along with pre-weighted internal standards on an EA-IRMS (Elemental Analyser isotope ratio mass spectrometry). The EA is a combustion device used for solid samples that converts organic matter into CO_2. Unwanted bioproducts and gases created during combustion are removed as they pass through a reduction tube and water trap while the carbon and nitrogen flow into a mass spectrometer for isotopic analysis. Combustion takes place in a He atmosphere inside a quartz reactor at a temperature of 1010 °C. Results were corrected to internationally established values for VPDB (Vienna Pee Dee Belemnite) and Air N_{-2} (atmospheric nitrogen) with a machine error of 0.2and 0.3‰ respectively.

6.3.4 Preparation and XRF Measurement

Sampling for XRF measurement was done at 1cm resolution from each master sequence. Samples were freeze-dried, sieved to <425µm to screen for large organics or stones, and then ground with a mortar and pestle to homogenize grain size. A minimum of one gram of sediment per sample was transferred into vials with 5µm polypropylene thin film covers for measurement.

XRF analysis of the sediments was undertaken at the Victoria University of Wellington by a handheld Olympus Vanta M series XRF analyser. Heavy elements were measured for 30 seconds at 40 keV and light elements were measured for one minute at 10 keV. Results were corrected against international standards measured along with the lake sediments. Since total organic carbon was not measured for each sample, the data were normalized to the lightest element measured, aluminium, to correct for the organic component within the sediments which can dampen the accuracy of measurement (Boyle, 2000; Löwemark et al., 2011). Aluminium will be reported in parts per million (ppm) in this study. All other elements are reported as a ratio to aluminium (Löwemark et al., 2011) (Appendix D).

6.3.5 Proxy Record Zoning and Calculation of Zoned Duration in OxCal

All proxy data were plotted against time and then broken into different zones based on concurrent changes in the proxy values. The pollen and charcoal data were primarily used to identify boundaries for Polynesian and European arrival. Subzones were primarily derived from the geochemical results. Temporal ranges were calculated for each identified zone in OxCal with the duration function which provides a probability distribution that represents the difference in age between the first and last core depths identified in each zone (Bronk Ramsey, 1995).

6.4 Results

6.4.1 Proxy Data Relative to Time

The following section describes the pollen, charcoal, CT, carbon, nitrogen and geochemical proxy data relative to time in each lake. The results are broken into four temporal zones per lake based on alterations in the proxy data. Carbon and nitrogen results plotted against depth are shown in Appendix C and XRF results against depth are presented in Appendix D.

Lake Ngatu

Zone 1 – 1000 BC to 1100 AD

This zone stretches from 70cm to 27cm depths. Tall and small tree pollen abundance is high and variable through this time, while bracken fern spores are limited and >50µm charcoal particles are absent. Overall, elemental and isotopic carbon and nitrogen are steady through this period though carbon increases from 20% to nearly 30% from 0 to 1100 AD. The C:N ratio is high with values of 19-20. The CT values are low and constant. Ti/Zr and Si/Ti show variability through the high end of their measured range through this time. Elemental trends for P and K as well as Ca/Ti and Fe/Mn are stable and low (Fig. 23).

Zone 2 – 1100 to 1500 AD

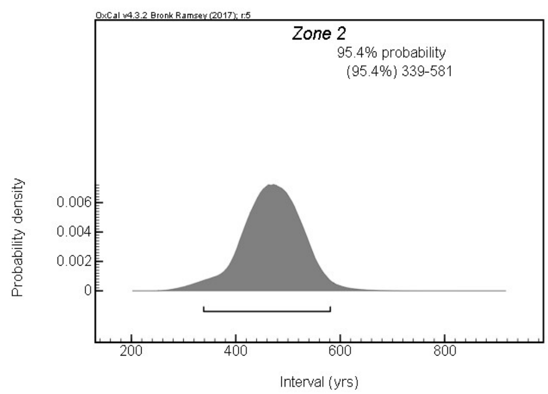

Figure 17. Duration PDF of Zone 2 Ngatu

This zone ranges from 27 to 13.5cm depths and the modelled duration of the zone is 339-581 years (Fig.17). This zone sees a sharp decline in tall and small tree pollen and an increase of over 400% in the abundance of bracken fern spores. Charcoal first appears at about 1300 AD. Elemental carbon drops to just 5% while isotopic carbon becomes ~9‰ heavier. Nitrogen lowers for the first time to below 1% and $\delta^{15}N$ become ~3‰ lighter. CT units increase also roughly at 1300 AD along with a strong shift to low Ti/Zr, and Si/Ti values. K values increase at this time while P slightly decreases.

The Ca/Ti ratio lowers then begins to increase again around 1500 AD. The Fe/Mn results show a strong, sharp increase between 1250-1400 AD (Fig. 23).

Zone 3 – 1500 to 1750 AD

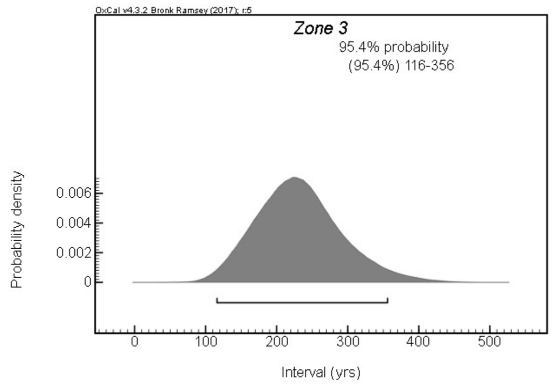

Figure 18. Duration PDF of Zone 3 Ngatu

This zone is from depths 13.5cm to 3.5cm and has a modelled duration of 116 to 356 years (Fig.18). Tree pollen abundance remains low during this time while a second increase in bracken fern spores is seen between 1600-1700 AD. Charcoal abundance also increases slightly. The percentage concentration of carbon and nitrogen in this zone are in phase which is reflected in steady, low C:N ratios of between 10-11. Isotopic carbon slightly shifts towards heavier values while ^{15}N becomes slightly lighter by 1750 AD. The CT values are low for a brief period from 1500-1600 AD followed again by high values from 1600-1750 AD. Ti/Zr and K values vary through this zone but remain low. P and Ca/Ti increase rapidly through this zone, while Si/Ti results are erratic but also increased to values similar to those in Zone 1. The Fe/Mn ratio drops below detection limits during this period.

Zone 4 – 1800 AD to present

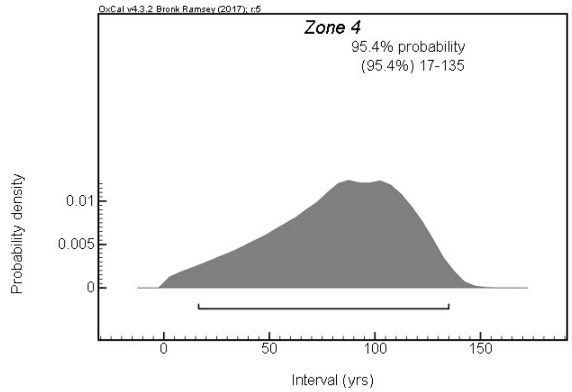

Figure 19. Duration PDF of Zone 4 Ngatu

This zone is from 3.5cm depth to the top of the core and primarily represents the post-contact timeframe, as evidenced by the pine pollen observed in the record. The duration of this zone is modelled as lasting 17-135 years (Fig. 19). There is limited proxy data for this period, but the CT data continues to show high values. Tree pollen makes a very modest recovery during this period and charcoal is at its highest abundance. The C:N ratio drops to its lowest value (10) (Fig. 23) and elemental carbon and nitrogen return to or pass pre-impact concentrations. Isotopically carbon remains similar to zone 3 while nitrogen becomes heavier. All geochemical data in this period returned low values.

Lake Rotoroa

Zone 1 - 1000 BC to 1100 AD

This zone starts at 70cm and ends at 38.5cm. CT values in Lake Rotoroa during this time show more variability and higher values than Zone 1 Ngatu. Pollen records begin at ~800 AD and show that tall and small tree pollen is well represented until about 1100 AD while abundance of bracken fern and large charcoal particles are minimal. Elemental and isotopic results are overall steady during this period except for a significant event represented by a drop in most values from 500 BC to 250 AD. The geochemical data show variable but high Ti/Zr and Ca/Ti values. The Fe/Mn ratio and elemental K were low and constant while the Si/Ti ratio displayed the greatest variability. P shifted from high to low values slowly but consistently through this time.

Zone 2 - 1100 to 1500 AD

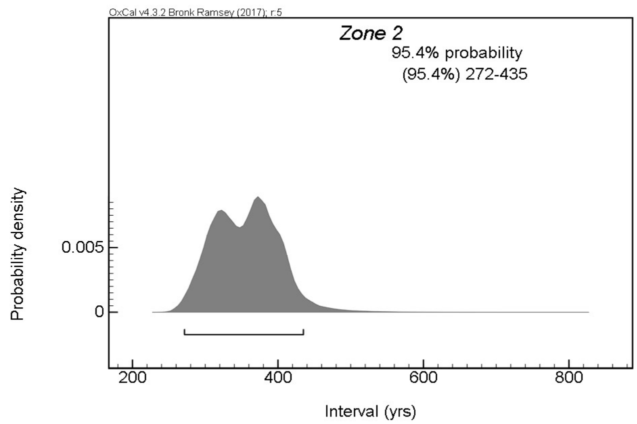

Figure 20. Duration PDF of Zone 2 Rotoroa

The zone ranges from 38.5cm to 23.5 cm depth and modelled duration is 272 to 435 years (Fig.20). Tree pollen dramatically declines through this period, but bracken fern increases by over 500 counts with its highest recorded values reached by about 1400 AD. Carbon, nitrogen and the C:N ratio drop to their lowest recorded values by 1300 AD. The value of the $\delta^{13}C$ became 5‰ heavier and $\delta^{15}N$ dropped to its lightest recorded value of -0.5‰. CT units increase by 300 (Fig. 23) in Lake Rotoroa from 1100 to 1500 AD while Ti/Zr decreases. The ratios Ca/Ti and Si/Ti both drop to lower values during this period. K remains steady in a mid-range value for the element while P significantly increases from 1100 to 1300 AD. The Fe/Mn ratio is low and static.

Zone 3 - 1500 to 1800 AD

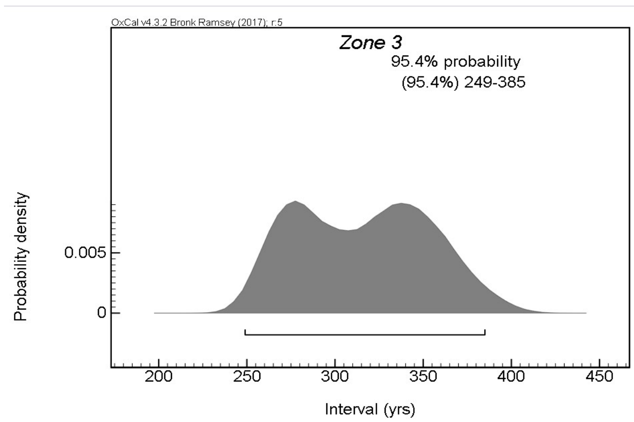

Figure 21. Duration PDF of Zone 3 Rotoroa

This zone ranges from 23.5cm to 10cm and has modelled duration of 229-385 years (Fig. 21). This zone sees both tree pollen and bracken fern spore abundance decrease. Charcoal reaches its maximum recorded values and the CT numbers fall to a low, steady value. K increases while Ti/Zr remains low and steady. The $\delta^{13}C$ lightened from -18 to -22‰ (Fig. 23) while the other elemental and isotopic data remained relatively constant, with a low C:N and about 18-19% elemental carbon. Phosphorus and Si/Ti values are erratic over Zone 3 but are overall low. Ca/Ti increases over this time as does Fe/Mn.

Zone 4 - 1800 AD to present

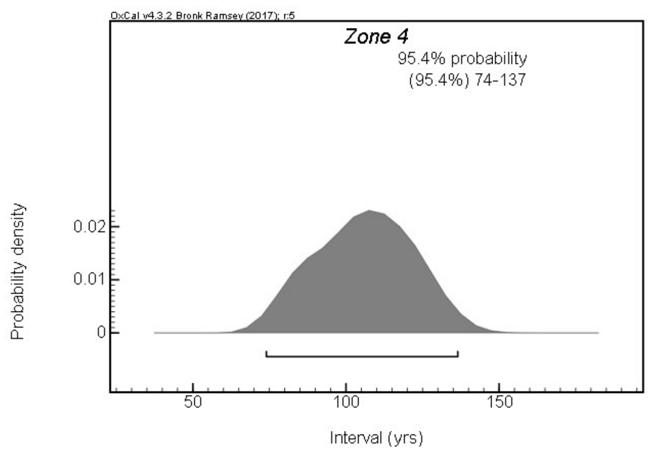

Figure 22. Duration PDF Zone 4 Rotoroa

This zone is from 10cm depth to the top of the core and has a modelled duration of 74 to 137 years (Fig. 22). This final zone also has limited data, but during this time the CT numbers again increase, and tree pollen makes a small recovery. Pine pollen becomes very abundant while charcoal reduces to nearly Zone 1 levels. Elemental and isotopic carbon values and $\delta^{15}N$ began to shift back towards basal values while nitrogen increases further away from lower core values and reaches its maximum of 2% (Fig. 23). The Ti/Zr results are low and static and K drops to basal levels. Elemental P continues to increase as does Ca/Ti while Si/Ti remains low and steady. The Fe/Mn ratio returns to pre-impact values.

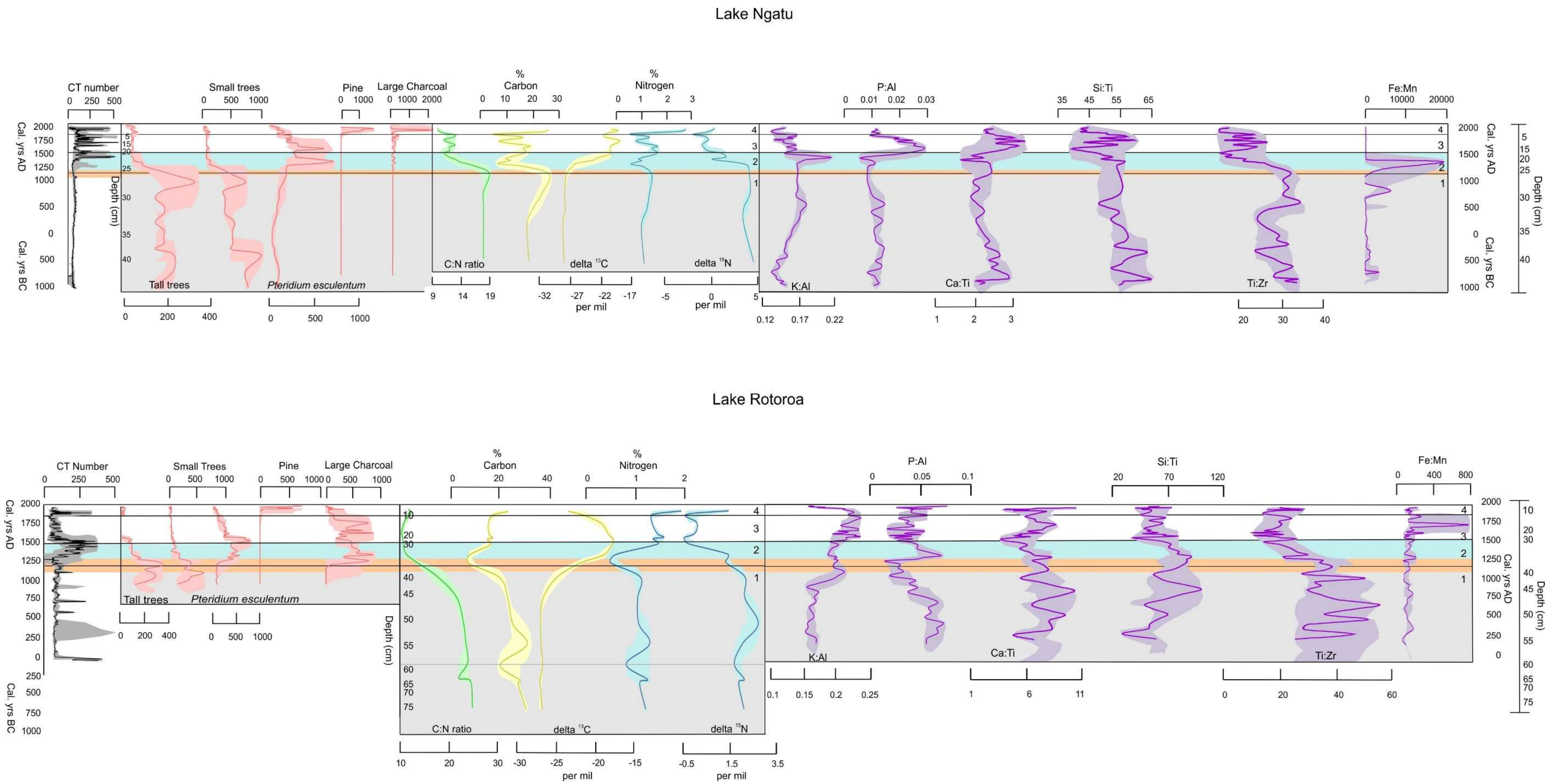

Figure 23. Proxy data reported against time

Calibrated age range for human settlement of the area determined by age-depth mode represented by orange band

IBP represented by blue band. Error bands around all indices are 2 sigma from calibrated age of datum

6.4.2 Isotopic and Elemental Results of Modern Analogues

<u>Algae</u>

Concentrated algae from the top of the Lake Ngatu core and from the post-impact sediment produced very similar delta ^{13}C results of around -19.5‰ and small C:N ratios of around 11. Elemental carbon was low in the post-impact algae sample but was higher (19%) at the top of the core. The algae concentrate from sediments prior to human arrival had a higher C:N ratio of around 18, but elemental carbon was lower than the other two algae samples and δ^{13} C was lighter at -28.5‰ (Fig. 24).

The concentrated algae in Rotoroa produced similar results to those in Lake Ngatu, with the samples from the top of the core and post-impact generating results that were different from that of the pre-impact sample. The pre-impact sample had only 9% elemental carbon compared to the 17-20% of the other two Rotoroa algae samples.

<u>Soils</u>

The modern catchment soils from Lake Ngatu produced a wide range of elemental carbon and isotopic values from 0.5-22% and -20 to -40 ‰ respectively. C:N values plotted between 15 to 26, while elemental nitrogen was generally low at ~0.1-1%.

The modern catchment soils in Lake Rotoroa are overall lighter in carbon and nitrogen than the Ngatu soils but have higher C:N ratios (Table 5). Delta ^{13} C values ranged from -19 to -30‰.

The results from the forest soils ranged from having as low as 3% elemental carbon to as high as 46%, while C:N values shifted from 25 to 31. Delta ^{13} C values were similar between the four samples at about -28‰ (Fig. 24).

<u>Flora</u>

The charophytes measured from Lake Ngatu were carbon and nitrogen-rich at ~38% and ~3% respectively. The δ^{13} C values ranged between those measured on the three algae samples. These samples had smaller C:N values of 11-17.

The *Eleocharis sphacelata* (kuta) sample from Lake Ngatu had a high C:N ratio (25) and was also high in carbon (42%). The δ^{13} C was in the range of some of the catchment and forest soils, but heavier than the pre-impact algae sample and lighter than the other two algae samples at -26.5‰ (Fig. 24). The kuta sample from Lake Rotoroa had a similar amount of carbon as the Ngatu sample but produced a very high C:N ratio of 57. Measurement on this sample material was repeated to double check the results, which were replicated in the second measurement. Table 5 provides the mean values and standard error for all modern sample sets that had more than one sample in the series.

Table 5. Mean values and standard errors on elemental and isotopic values for modern analogue samples.

Lake Ngatu Modern Analogue Samples (n=>1)

Charophyte	%C	δ13C	%N	δ15N	C:N ratio
Mean	38.32	-23.24	2.90	-6.50	13.82
Standard Error	0.41	2.25	0.45	1.33	1.98
Catchment Soils					
Mean	7.14	-26.83	0.34	0.48	19.88
Standard Error	4.07	3.17	0.18	0.91	2.24

Lake Rotoroa Modern Analogue Samples (n=>1)

Catchment Soils	%C	δ13C	%N	δ15N	C:N ratio
Mean	3.01	-23.35	0.17	1.11	22.28
Stardard Error	1.02	1.98	0.06	0.67	9.15

Podocarp Forest Soils (compared to catchment soils in both lakes)					
Mean	27.61	-28.38	0.93	0.28	28.30
Standard Error	9.19	0.45	0.30	1.06	1.44

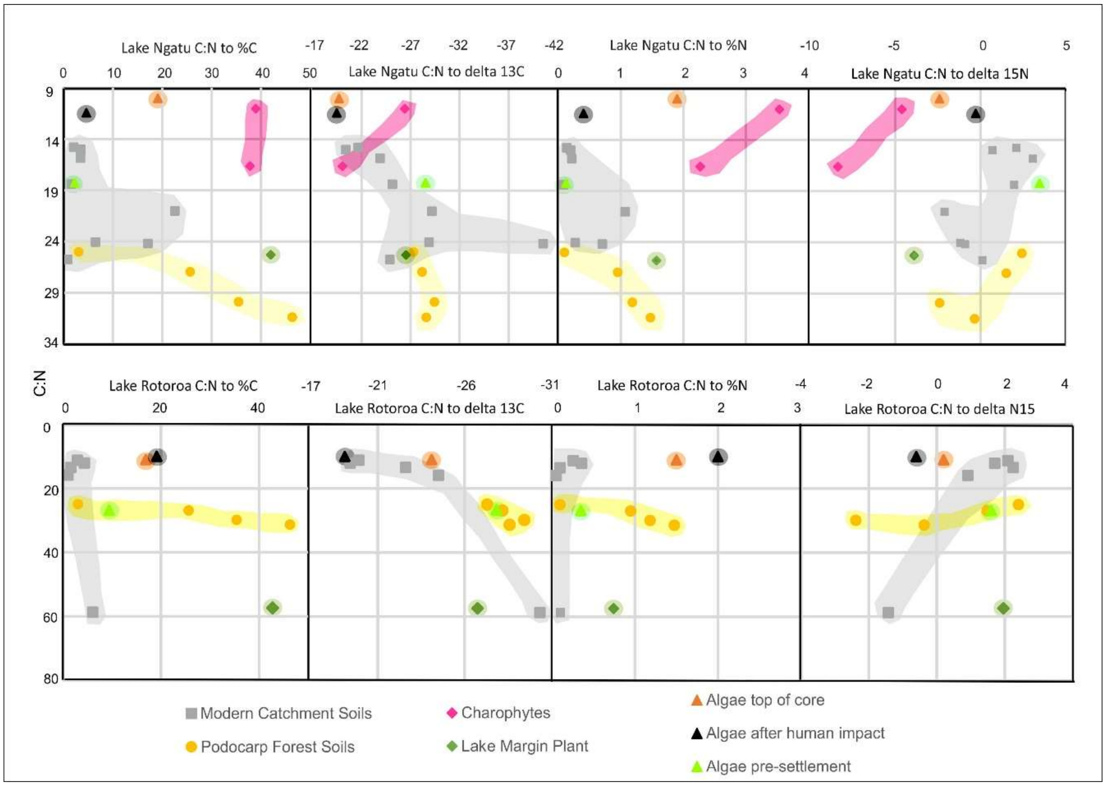

Figure 24. C:N ratios, elemental percentages and isotope data for modern analogue samples plotted with value fields

6.5 Interpretation

6.5.1 Geochemical Results from the Algae Concentrates and the Impact on Interpretation of the C:N Sediment Data

The elemental and isotopic results from the six concentrated algae samples directly affect the interpretation of the carbon and nitrogen results of the lake sediments. Algae normally have a C:N ratio of between 4-10 while terrestrial materials should exhibit ratios of >20 (Meyers and Lallier-Vergès, 1999), with values between 10 and 20 considered a mixture of the two sources. Prior to human settlement the C:N ratios (avg. 19 in Ngatu and 25 in Rotoroa) of the lake sediments suggest that their organic composition was heavily influenced by allochthonous sources (Fig. 25). Terrestrial pollen and other organic materials such as macrofossils identified in these sediments support the C:N ratios and show that some terrestrial material was contained within the matrix of these sediments. However, the C:N ratios (18 in Ngatu and 27 in Rotoroa) and isotopic values of the pre-impact sediment and algae concentrated also from this time are analogous. Additionally, after impact, when the C:N ratios of the lake sediments became smaller and the $\delta^{13}C$ values heavier, so did the those of the post-impact and core top algae samples in both lakes. This suggests that algae were a major organic contributor to sediment formation in both lakes through time and that the C:N and isotopic values of the algae can change with time and also produce C:N results that would be expected for terrestrial materials.

There is, however, a significant difference in the results of the pre-impact sediments and algae compared to the post-impact samples. The carbon content of the pre-impact algae is low (2.3% in Ngatu and 9.4% in Rotoroa) compared to the average carbon content percentages from pre-impact sediments (22% in Ngatu and 26.7% in Rotoroa). Carbon percentages of post-impact sediments are much closer to those measured on post-impact and core top algae (Fig. 25). The high carbon percentages measured on the pre-impact sediments must contain non-algae material to have achieved these results, and therefore must contain more allochthonous carbon compared to sediments post-impact.

The algae *Botryococcus braunii* was the primary organism isolated for measurement and was observed in large quantities throughout both lake cores. *B. braunii* has the ability to produce hydrocarbons (Maxwell et al., 1968); which in turn can create C:N ratios as high as ~36. However, this algae is also easily impacted by environmental change (Huang et al., 1999; Smittenberg et al., 2005) and can adjust its composition and carbon uptake to cope with environmental change (Huang et al., 1999; Street-Perrott et al., 2004). These adjustments impact the elemental and isotopic composition of the organism and C:N ratios ranging between 10-27 and periods of enriched $\delta^{13}C$ (~-15‰) from a lake containing *B. braunii* have been documented (Huang et al., 1999; Street-Perrott et al., 2004). These authors attribute the high isotopic values to regular landscape burns and reduced terrestrial input which lead to limited carbon entering in the lake. Consequently, this promoted the utilization of HCO_3 (bicarbonate), which *B. braunii* can process (Street-Perrott et al., 2004), enriching the $\delta^{13}C$ values (Huang et al., 1999) with the uptake of this carbon source. Results from these studies suggest that this is a possible reason for the elemental and isotopic values that were obtained from the Lake Ngatu and Rotoroa sediments and algae samples.

Since *B. braunii* was ubiquitous through the sediment cores and can produce a wide range of C:N ratios and $\delta^{13}C$ concentrations, it is difficult to determine if the alterations observed in the sediment samples were driven by changes in the sources of carbon input. However, the sensitivity of the algae to environmental change and its isotopic flexibility to adjust to these changes allows the algae to be used as a proxy for environmental change. The interpretation of the C:N ratios and isotopic values of the sediments will be viewed with these results in mind.

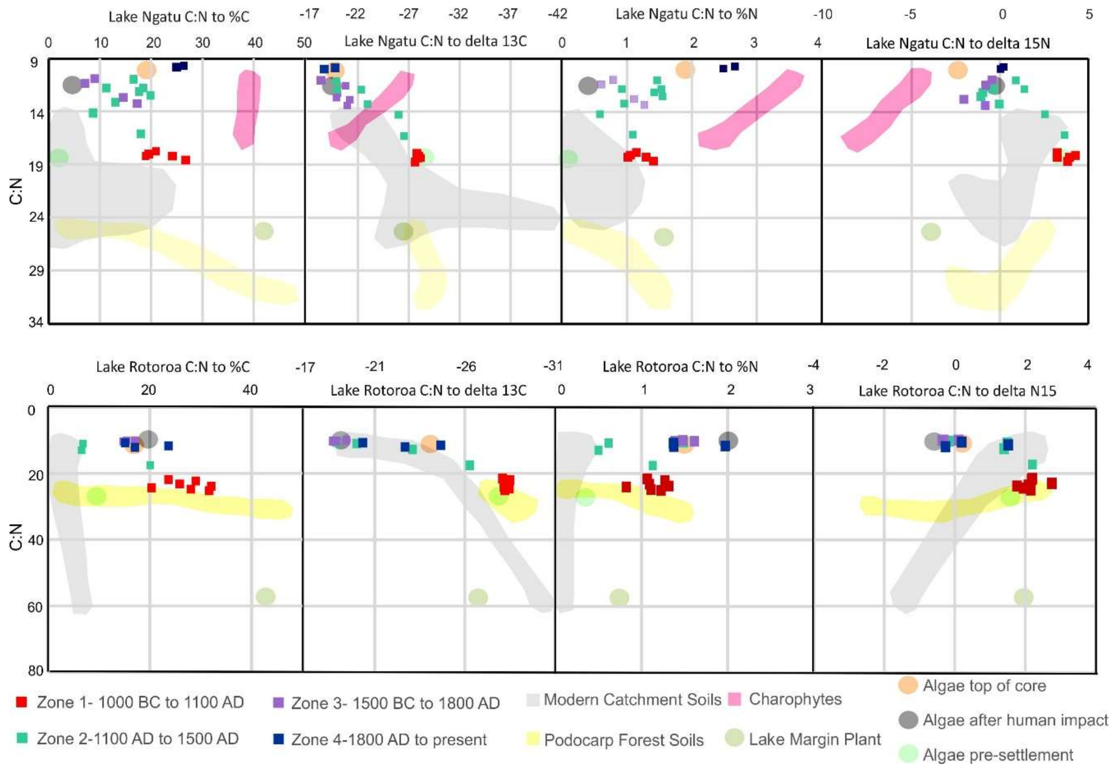

Figure 25. Lake sediment elemental and isotopic results by zone and modern analogue samples

6.5.2 Interpretation of the Proxy Data Through Time

Zone 1 – 1000 BC to 1100 AD - Pre-Impact

Tall and small tree pollen abundance in this zone indicates that established forests with limited bracken fern were growing in the region. The small amount of >50µm charcoal in the sediment records also implies that natural fires were rare and that the forests may have continually grown in the region during this period (Newnham, 1999).

Elemental and isotopic carbon, nitrogen and the C:N ratios from each lake differ slightly but both indicate that, with the exception of an occasional environmental disruption event, lake productivity was steady, and few drastic or long-term changes occurred in the organic input into the lakes through this time. The high C:N ratios prior to human settlement in Lakes Ngatu and Rotoroa are probably derived from a combination of terrestrial sourced carbon and *B. braunii* when the organisms were synthesising hydrocarbons (Maxwell et al., 1968) which are produced when specific nitrogen, sunlight and temperature conditions for growth are achieved (Qin, 2010). As indicated above, additions of terrestrial carbon explain the differences observed between the carbon depleted concentrated algae compared to the more carbon-rich lake sediments in this zone (Fig 25).

The CT and geochemical data are distinctly different in each lake. The CT values, which are a proxy for bulk density and therefore allochthonous flux, show that transport of clastic materials was low and steady into each basin except for an occasional minor environmental event in both lakes from 1000 BC to 1100 AD. This is also evident in the geochemical data. These events are likely related to storm activity rather than natural burn events due to the lack of accompanying charcoal in the record. The larger amount of variation in the Lake Rotoroa CT data compared to Lake Ngatu in this zone suggest that prior to impact the catchments behaved differently which is probably due to the steeper catchment morphology of Lake Rotoroa. The Ti/Zr values for both lakes support this with results from Lake Rotoroa showing significantly more variability and higher amplitude in that variability than Lake Ngatu. However, overall the high Ti/Zr ratios from both lakes indicate that finer grained materials were entering the lakes, which were likely derived from clays in the catchment soils.

Elemental K and P in Ngatu show minimal change through this zone, which supports the carbon and nitrogen and CT results, and indicate that only minor alterations in nutrient and detrital inputs occurred. Again, there is more variability in Rotoroa with potassium shifting from steady values to increasing values around 800 AD. Phosphorus in Rotoroa on the other hand, reduces slowly through time, reaching its second lowest recorded value around 1000 AD.

Ca/Ti and Si/Ti in Ngatu show overall high, stable values with only minor variation through time, which also suggests minimal erosion. The minor variation may imply that the source of Ca and Si alternated slightly between more detrital and in-lake production or changes in the detrital sources of these elements through this time (Balascio et al., 2011; Haberzettl et al., 2007). The larger amplitude of change seen in Ca/Ti and Si/Ti in Rotoroa through this period implies that this lake was reacting to the same environmental drivers differently (Fig. 23).

To understand why the two lakes were reacting differently, the carbon and nitrogen results from sediments in both lakes from this zone were compared to the modern analogue soil samples from the catchments and the podocarp forest (Fig. 25). Lake Ngatu sediments correlate better to the values measured on the modern catchment soils than to the podocarp forest. Conversely, in Lake Rotoroa the heavier C:N ratios and lighter isotopic values in Zone 1 are more similar to those of the podocarp forest soils rather than the modern catchment soils. The differences between the two lakes could be related to catchment morphology and soil types. Rotoroa may have been more affected by hillslope erosion of its catchment soils due to its steeper western bank, e.g. (Gilbert, 1909), while Ngatu was less impacted with its shallower slopes. This theory is supported by the CT data in Rotoroa, which indicates more erosional events occurred in Rotoroa than Ngatu over this time. This is also suggested in the higher sedimentation rates in Rotoroa, based on the age-depth model (Fig.12). Ngatu's flatter catchment and associated wetlands are also limited to eQd soils while Rotoroa's slightly steeper catchment additionally contains lQd soils which are richer in peats and organics than the sandier eQd soils. While they were not measured, it is possible that the lQd soils are more akin to the forest soils. If this is the case, then the lQd soil type was likely naturally entering the basin through surface erosion prior to settlement in Rotoroa. This interpretation is supported by the findings from Chapter 4 which showed that fossil pollen at 59cm depth was entering Lake Rotoroa in greater abundance compared to Zone 1 pollen concentrates from Ngatu. Differences of soil type and amount of detrital input into the lakes likely contributed to the differences observed in the isotopic and geochemical data between the lakes through Zone 1. This interpretation highlights that, although the lakes neighbour each other and their regional pollen and charcoal records are similar, catchment specific proxies such as carbon and nitrogen measurement can identify local signals of change.

Zone 2 - 1100-1500 AD – Initial Burn Period -Human Arrival and Anthropogenic Alteration of the Landscape

This zone is marked by a change in nearly all indices. Within the modelled age-range for human settlement (1160-1280 AD) both lakes show distinct alterations in their proxy datasets. The patterns of these changes show that this zone contains the initial burn period for these lakes. The period of the IBP was identified by the reduction of tree pollen with increased bracken spores and charcoal along with concurrent changes in all other proxy data. More refinement of this period may be produced with the complete pollen and charcoal based environmental reconstructions, but for this project, the modelled duration of the IBP is 339-581 years in length in Ngatu and 116-356 years in Rotoroa at the 95.4% confidence interval. There are significant differences in the proxy values between the lakes in this zone so each lake will be described separately below for clarity.

Lake Ngatu

From 1100-1500 AD in Lake Ngatu the tree pollen, bracken fern spore, and charcoal data show that the original forest was removed by fire and that bracken fern instead began to grow in the area. The carbon and nitrogen data in Zone 2 suggest that there was a considerable reduction in organic input which is supported by the pollen records. The loss of catchment vegetation lowered the levels of elemental carbon and C:N while the $\delta^{13}C$ values became heavier from 1100 to 1500 AD. Reduced carbon content could also be the result of dilution from increased sediment flux with erosion

(Fisher et al., 2003), but overall low CT values at the start of this zone don't support dilution. A change in the origin of the carbon entering the lake can also be observed when comparing the carbon and nitrogen results of the Zone 2 sediments to the post-impact algae sample. The carbon content of the post-impact algae sample matches those of the Zone 2 sediments. This shows that the Zone 2 sediments are more dominantly composed of algae (Fig.25) compared to sediments from Zone 1, which had more terrestrial carbon content. As mentioned above, the sensitivity of the algae to environmental change indicates that these catchments experienced an alteration to the quantities of nutrients entering the lakes at this time, probably through forest clearance, which altered the elemental and isotopic values of the algae and consequently, the sediment (Huang et al., 1999; Street-Perrott et al., 2004).

CT values do not dramatically change until 1400-1450 AD, then quickly increase to a high value of nearly 500 (Fig. 23). This suggests there was a delay in clastic input into the lake despite the pollen, charcoal, and C:N data showing environmental change earlier. Elemental K supports the timing of this with increased abundance from 1300-1400 AD, suggesting that soil was washed into the lake at this time (Aufgebauer et al., 2012; Elliot et al., 1997; Moreno et al., 2011). Concurrent lower Si/Ti and Ca/Ti values also indicate that erosion increased (Haberzettl et al., 2007). Ti/Zr values change more immediately and show a dramatic increase of course materials entering the lake from the start of this zone.

The Fe/Mn results suggest that the lake experienced reducing conditions from ~1250-1350 AD. Reduced conditions may be driven by eutrophication and redox processes due to increased surface runoff from the mobilization of soils through anthropogenic land use (Corella et al., 2012; Davies et al., 2015; Haberzettl et al., 2007). In reducing conditions phosphorus can be released from the sediment and enter the water column (Søndergaard et al., 2003) which may result in lower P values in the sediment. In Ngatu during this time phosphorus at first slightly drops in Zone 2, then quickly increases from about 1400-1500 AD, when reducing conditions in the lake end. Likely, anthropogenic alteration of the catchment introduced more P into the lake during all of Zone 2, but this is only observable in the sediment when the lake is not anoxic. Increased levels of phosphorus would change the nutrient supply in the lake and might have contributed to the alteration of the carbon and nitrogen values observed in the algae and also the sediments (Qin, 2010).

Lake Rotoroa

The pollen and charcoal records for Lake Rotoroa through this zone also show that the native forest was removed by fire. The carbon and nitrogen results follow the patterns observed in Ngatu which support that the catchments were cleared of vegetation which in turn increased erosion. This is seen in lower C:N values and heavier isotopes, however, these trends appear to have begun prior to impact, at around 750 AD. The changes in these proxies also do not appear as intense as those recorded in Ngatu. In spite of differing initiation times, the C:N and carbon content of the sediment between the two lakes is quite similar through this zone.

The CT data show a slow but steady increase of denser materials starting at 1100 AD, peaking at 1400-1450 AD, but reaching only a Hounsfield value range of 300-350, compared to the ~500 seen in Ngatu. The Ti/Zr results follow the trend in the CT data and show a gradual but persistent shift to more coarse-grained materials entering the lake. The sandier eQd catchment soils may have been mobilized at this time due to dune activation after forest clearance. The Ca/Ti and Si/Ti ratios also slowly shift towards low values and support increased detrital input over this time.

Elemental K is steady in this zone, unlike Ngatu, which might suggest that less soil was being mobilized into Rotoroa comparatively (Aufgebauer et al., 2012). On the other hand, there is a strong, immediate increase of P in this zone compared to Ngatu Zone 2. This suggests that anthropogenic impact increased the abundance of phosphorus in the lake. The additions might be related to detrital input or organic content such as the large amount of charcoal that entered the lake at this time (McColl and Grigal, 1975). In oxidizing conditions, when Fe/Mn values are low, phosphorus may become bound to sediment (Søndergaard et al., 2003) producing higher P values in the sediment. The Fe/Mn values in this zone support this and suggest that the lake had higher oxygen levels compared to Ngatu, and therefore more of the introduced P became bound to the sediment.

Overall, during Zone 2 the CT and geochemical data imply soil transport probably occurred more intensely in Lake Ngatu than Lake Rotoroa with larger Hounsfield values and a strong, linear reduction in the Ti/Zr ratio and increased elemental potassium. However, the impact of this change was not immediate and the geochemical and CT data show more evidence of sustained soil erosion around 1400 AD. The CT, Ti/Zr and other geochemical proxy data in Rotoroa shows overall a more immediate but milder signal of increased erosion in Zone 2 compared to Ngatu. The Zone 1 histories of the lakes, which showed more detrital input into Rotoroa compared to Ngatu, appear to have altered in Zone 2. The pattern observed in Zone 2 may suggest that the lakes have different land use histories.

One potential explanation for Lake Rotoroa to have a lower CT and elemental response in Zone 2 is that the steeper catchment made this lake initially less desirable to the Polynesian settlers to attempt horticulture practices than the flatter topography and extensive wetlands afforded by nearby Lake Ngatu. As mentioned in Chapter 2 regarding wetland horticulture, existing damp locations were utilized throughout Polynesia to grow wetland taro (Allen, 1971; Kirch, 1994). As Barber (1989, 2001, 2004) and Horrocks and Barber (2005) have located possible evidence of wetland horticultural practices from ditch systems on the Aupouri Peninsula, horticultural utility provides a theoretical explanation for the differences observed in these measurements and potentially in the differences in the timing of these changes between the lakes.

In summary, the geochemical proxy data support the modelled human arrival age range from 1160 to 1280 AD and suggest that from 1100 to 1500 AD the landscape around both lakes was drastically altered. Soil erosion increased as a result of forest removal by fire and possibly other land management. In Rotoroa this change was more immediate, but impact overall appears milder compared to Ngatu. In Ngatu the effects of landscape change were delayed but more intense compared to Rotoroa. The CT, elemental and geochemical differences between the two lakes, despite their proximity and similar pollen and charcoal histories, suggest the that either the topography of Lake Ngatu was more prone to erosion, which does not follow the environmental histories of Zone 1 and seems unlikely since the catchment is flatter, or that Ngatu's catchment was considered a more viable location to trial Polynesian horticultural practices compared to Lake Rotoroa.

Zone 3 - 1500 to 1750-1800 AD- Continued Land Use

Lake Ngatu

The proxy data in this zone again suggest that different responses to change occurred in each lake. In Ngatu, after a decrease in bracken fern spores around 1400 AD there is another strong pulse of spores around 1600 AD suggesting that fire had again cleared the landscape (McGlone et al., 2005). Bracken fern spores travel easily on the wind and the increase observed here is probably a regional signal (McGlone et al., 2005). Charcoal abundance slightly increases as well, suggesting that this secondary burn period primarily eliminated second growth vegetation, which does not produce as much charcoal (McWethy et al., 2014; Perry et al., 2014). This pattern has also been observed in environmental reconstructions on the South Island (McWethy et al., 2014) which recorded limited charcoal from burn events after the IBP.

The C:N ratio remains steady and low in this zone while the other elemental and isotopic values vary, but no longer experience the sweeping changes in their concentrations. After the increase in bracken at roughly 1600 AD there is a slight decrease in elemental carbon and the $\delta^{13}C$ values become a little heavier. These changes were seen in Zone 2 with anthropogenic environmental modification and may support the theory that renewed activity occurred at this time along with the increase in bracken spores and charcoal.

The CT data show some fluctuation but overall has high values, indicating continued and sustained erosion. Ti/Zr values remain lower than those measured in Zone 1 and stabilize, suggesting that course-grained soils continued to be deposited during this zone. The Ti/Zr values in Zone 3 are slightly larger than some of Zone 2, which might imply that some finer clays were also entering the lake during this period. However, elemental K also produced low values, in keeping with results for this element from Zone 1, which suggests that well-developed soils were no longer eroding into the lake. Ca/Ti increases in this zone suggesting that Ca delivery during this period was less related to erosional processes and driven more by carbonate production (Haberzettl et al., 2007). However, both treated and untreated $\delta^{13}C$ results for these sediments (see section 6.3.2) showed no evidence of containing carbonate materials (Meyers, 1994). The oscillation of Ca/Ti through Zone 3 appears then to be correlated to Ti/Zr and may suggest that increased Ca was driven by changes in the abundance of detrital calcium now eroding into the lake (Balascio et al., 2011). These proxies together may imply that after removal of the native forests in Zone 2 much of the organic-rich catchment soil had already eroded into the lake and that in Zone 3 sand or larger grained catchment soils containing detrital calcium were now the primary sources of clastic input. We know that older soils were still entering the lake during this time from the outcomes of the dating experiment (see Chapter 4), which implies that it wasn't just newly formed soils that were now being mobilized.

Fe/Mn decreases in Zone 3 suggesting that the lake had higher oxygen content. Phosphorous increases during this time which suggests that more P was being bound to the sediment (Søndergaard et al., 2003). The Si/Ti ratio returns to Zone 1 values, which might suggest increased diatom productivity (Balascio et al., 2011), possibly related to oxygen-rich lake conditions and a nutrient supply.

Lake Rotoroa

The second phase of increased bracken fern spores observed in Ngatu was not recorded in Rotoroa. Large charcoal particle abundance reduced from 1500-1600 AD then increased again to Zone 2 values from 1600-1700 AD, suggesting that the area continued to be burnt during this time. This increase of Rotoroa charcoal occurs at roughly the same time that bracken fern spore abundance increases at Ngatu. Further reductions of tall tree pollen support continued fire activity during this zone. The carbon and nitrogen indices suggest a period of relative uniformity compared to Zone 2. Over this period these values remain low and almost constant except for $\delta^{13}C$ which continues to become heavier. This suggests that after the removal of the native forest in Zone 2, the landscape did not recover and was likely burned repeatedly.

The CT values in this zone drop back to almost pre-impact levels and the Ti/Zr remains fairly low, implying slow, steady erosion of primarily larger-grained materials (Davies et al., 2015). Elemental K increases a little through this zone which is likely related to some increased soil input, but the steady overall values still suggest minimal erosion. Ca/Ti and Si/Ti generally appear to be in phase with Ti/Zr, suggesting that increased abundance of Ca and Si are probably mostly from detrital sources. These proxies may also indicate that after landscape clearance in Zone 2, sand and older catchment soils higher in calcium comprised much of the materials that were eroded into Zone 3. The Fe/Mn ratio suggests a minor reducing period in the lake around 1750 AD, however, the ratio reaches a value of only 800 compared to the 20,000 seen in Zone 2 Ngatu. As seen elsewhere in the cores, phosphorus abundance in the sediment reduces around the same time Fe/Mn increases, as P will release or stay in suspension in the water during reducing conditions.

A synthesis of the proxy data implies that both catchments were still being impacted by anthropogenic land use during this period, but that continued modification affected the lakes differently. The Lake Ngatu carbon, nitrogen and bracken fern record indicate a possible second phase of land use during this period. The CT and geochemical data support this and show sustained erosion.

In Rotoroa, the pollen records and elemental data do not suggest that a second phase of intensive landscape modification was attempted, however, charcoal abundance is high, indicating that the local landscape continued to be burnt. The CT data, K, and Ti/Zr results imply that erosion continued but much more limitedly, with CT values now as low as those recorded in Zone 1, but even less sporadic. Wilmshurst (1997) has found that soil erosion can be limited after initial human impact by the root structure of bracken fern forests that replaced the original forests and that this could be maintained even with repeat burning, which might be the case at Rotoroa.

The different erosional proxies and environmental histories between the lakes through this period could be related to preferential use of Ngatu's catchment to practice horticulture. This could be explained by an effort to intensify horticulture around Ngatu during this time which drove continued erosion of catchment soils. This interpretation is supported by the findings of Wilmshurst (1997) and suggest that Ngatu's catchment was not protected from erosion by bracken fern root structure. The steadiness of the CT data in Rotoroa, even compared to pre-anthropogenic impact depths, suggest that erosion was quite limited through this zone. Since this catchment is steeper, it should suffer more from natural erosion, as seen in the Zone 1 data. The differences observed in the proxy data between the two lakes is more easily explained by widespread bracken fern growth at Lake Rotoroa rather than by crop production at Lake Ngatu.

Zone 4- European Settlement - 1800 to present

This final period in the catchment histories of Lakes Ngatu and Rotoroa is not composed of many data but European influence on the landscape can be seen in the strong elemental shifts in both lakes, particularly in nitrogen. Additions of nitrogen from fertilization for modern agriculture and pastoralism are possible causes for this enrichment (Fenn et al., 2003; Wolfe et al., 2001). The CT data suggest erosion occurred, but weathered catchment soils were likely already removed, so the erosional signal inferred from the CT data around 1850-1900 may indicate mobilization of the sand dunes. Too few geochemical measurements were made to identify any significant trends, but both lakes generally show potential erosional signals. The biggest change is that during Zone 4 the tall tree pollen begins to slowly recover, and pine appears.

6.6 Summary

The environmental proxy records generated for lakes Ngatu and Rotoroa successfully identified when human modification of the landscape occurred and the intensity of landscape alteration in the lake catchments. These methods cannot definitively inform whether these catchments and the surrounding landscape were specifically modified to develop horticultural spaces, but theoretically, landscape alteration to practice horticulture seems likely given the archaeological evidence that cultivation was practiced widely in the region, including lake catchments. Durations of anthropogenic land use were derived for the catchments and the initial burn period identified in each lake. The multi-proxy results suggest that the lakes behaved differently to each other prior to human arrival and reacted to anthropogenic modification differently. The differences in the environmental records between the lakes are interpreted as showing that Ngatu's catchment was selected to practice horticulture, while Rotoroa's steeper catchment was not primarily used for cultivation.

7. Synthesis of Multi-Proxy Results

7.1 Introduction

The first part of this chapter briefly reviews the key results in the context of the research questions. Section 7.3 compares the timing of Polynesian arrival derived from the model to a lacustrine record from the Far North and then to a couple of important early archaeological sites in New Zealand. Section 7.4 provides a discussion of how the rates and intensity of landscape modification recorded in the environmental proxies from Lakes Ngatu and Rotoroa compare to other environmental reconstructions from both the North and South Islands.

7.2 Summary of Research Findings

The dating experiment was undertaken to determine which lacustrine organic materials provide the most robust ^{14}C dates. When compared to macrofossils, ages from post-human arrival pollen concentrates were significantly older. This demonstrated that human landscape modification can impact pollen concentrate ages, probably caused by anthropogenic mobilization of fossil pollen in catchment soils. Additionally, separate algal and cellular material concentrates showed that, while these contaminates did affect the accuracy of the pollen concentrates, they were not responsible for the post-human arrival offsets. This result supports the theory that the offsets between the post-impact pollen concentrates and matching macrofossils were anthropogenically driven. An important implication of this finding is that even closed lake systems could be affected significantly enough, either by humans, or large scale or long-term environmental events, to render pollen unsuitable for accurate measurement. Other research has suggested the possibility that human landscape alteration could affect closed lakes in this manner (Chester and Prior, 2004), but this experiment has tested and shown that human modification can directly impact closed lakes. The outcomes of this experiment guided sample selection for construction of the age-depth model.

An age-depth model was successfully constructed for the lakes to determine when Polynesian colonization began in the Far North. The model contains a high-resolution of likelihood data through the period of human arrival to present, which allowed the period of interest, Polynesian arrival, and settlement, to be precisely modelled. The modelled age range of 1165-1280 AD for human arrival is well supported by a radiocarbon measurement on a piece of charcoal just above where human arrival was identified by the pollen and charcoal records in the sediment cores. This sample returned both an unmodeled and modelled 13th century calibrated age range. The age-depth model is robust with an agreement index of >78% to the likelihood data and contained no outliers or inverted dates.

Finally, the isotopic and geochemical signals successfully indicated land use duration and intensity in the Far North. Furthermore, when compared to the regional pollen and charcoal records, catchment specific elemental, isotopic and geochemical measurements overall indicate environmental alteration at similar depths and times. This comparison suggests that both regional and local anthropogenic alteration to the landscape occurred nearly simultaneously. The elemental and isotopic data showed change through time which allowed for zoning of land use intensity and duration to be described. However, the lakes showed distinct differences to each other in the proxy data through time, illustrating the utility of catchment specific proxy data to understand the local signals of human impact as well as the regional signals.

The implications of these key research results for the overarching aim of using a lacustrine record in the Far North to identify initial Polynesian settlement and anthropogenic landscape modification are discussed below.

7.3 Comparison of the Chronology to Other Research

The modelled age range of 1165-1280 cal. AD this research produced for human arrival to the Far North is early in the human settlement history of New Zealand (Anderson, 2018; Higham and Jones, 2004; Wilmshurst et al., 2011). This result is supported by the independent geochemical and isotopic proxy data which show evidence of environmental disturbance occurring through this time period with increased erosion and alterations in lake chemistry. The accuracy of the chronology is further supported by the dating experiment so that the most robust targets were chosen to construct the age model. With the precision of the chronology established, how does the modelled age-range of human arrival compare to other well-dated early sites in New Zealand?

Ideally, the age-depth model would be compared to previous research from the Far North looking into the timing of human occupation. The Far North, however, has not been well dated and limited data exists from the region for comparison. As discussed in Chapter 5, the radiocarbon dates from the nearby archaeological site Houhora support the early modelled date for Polynesian arrival to the region. However, to compare Ngatu and Rotoroa's age-depth model to a more similar environment, a lacustrine chronology from Lake Taumatawhana in the Far North is considered. Elliot et al. (1995) produced a low-resolution model for the lake from just eight radiocarbon dates on bulk sediment through the timeframe of the late Holocene through to Polynesian arrival. Age reversals were seen at the top of the core through suspected pre-European to European depths. The poor quality of the chronology did not allow for an accurate human arrival age to be derived, but Elliot and colleagues projected a rough 1150 AD date for initial anthropogenic impact (Elliot et al., 1995). This settlement date would suggest that the modelled timing of human arrival at Lakes Ngatu and Rotoroa is a little young. However, while the pollen records and other proxy data measured from Lake Taumatawhana sediments do show evidence supporting anthropogenic landscape modification, the materials used to construct the model and the chronological issues with ¼ of the samples make the chronology unreliable and the timing of arrival uncertain. Additionally, the results of the dating experiment (see Chapter 4) also suggest that the accuracy of bulk sediments dates used for the Taumatawhana chronology were likely compromised by inclusions of algae, cellular material and possibly fossil pollen. These materials could have depleted the ^{14}C activities of the sediment and inaccurately aged the chronology. This may also account for the age reversal in the upper sediment.

To compare the modelled results instead to early archaeological complexes that have been well dated we look first at Shag River Mouth. This South Island occupation and moa butchery site has high-resolution dates on robust targets like shell, flax, charcoal and moa eggshell excavated from the site. Results from these have produced an early 14th century site occupation age (Anderson et al., 1996) which showed evidence that habitation lasted for only a short duration of ~200 years (Anderson and Smith, 1996). However, the earliest major archaeological site for comparison is Wairau Bar at the northern end of the South Island. Artefact assemblages, biological and isotopic indicators, and radiocarbon measurement all support this site being from the earliest part of New Zealand's settlement history (Anderson, 2018; Davidson et al., 2011; Montgomery, 2010; Walter et al., 2017). The most recent estimation of site occupation (1320-1350 AD) was produced from measurement on nine moa eggshells from a single use cooking event (Jacomb et al., 2014).

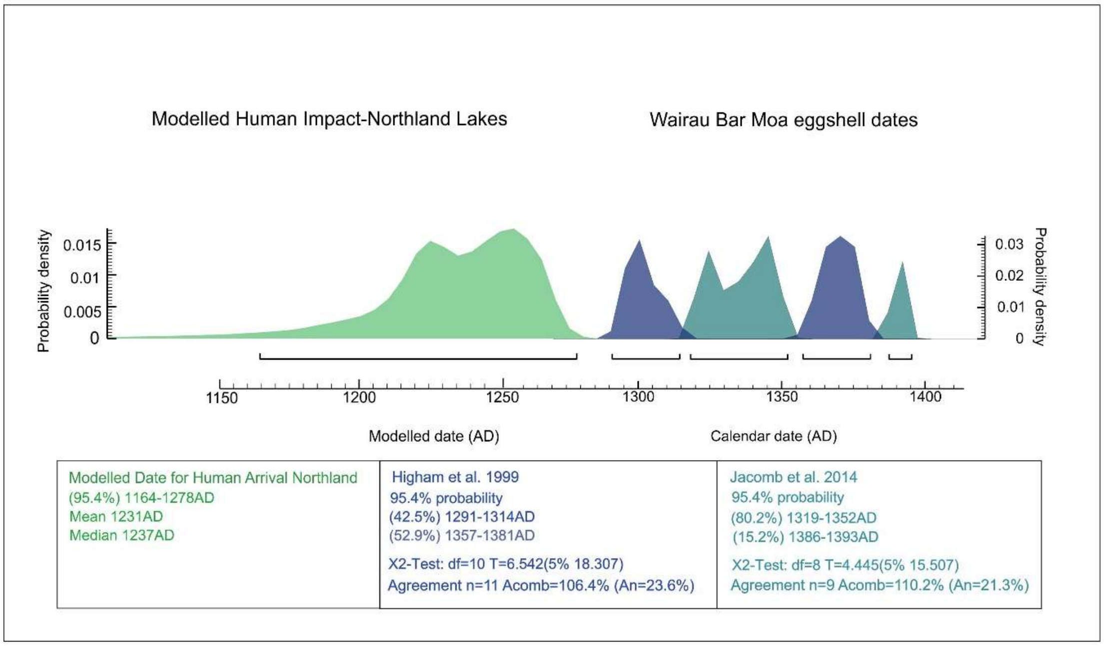

Figure 26. Modelled timing of human arrival in the Far North plotted with Wairau Bar eggshell dates using combine function in OxCal

These results are supported by a previous site chronology constructed by Higham et al. (1999) which also suggested site occupation from the late 13th to early 14th century (Higham et al., 1999; Walter et al., 2017). When the modelled age-range of human impact from Lakes Ngatu and Rotoroa is compared to the combined pdfs from this well dated site it appears that human arrival to the Far North was earlier than the occupation of Wairau Bar (Fig. 26), and that anthropogenic modification of the Far North began in the earliest period of New Zealand's settlement history.

To conclude, though the chronology and proxy data generated for this project were not obtained from a complex archaeological site, the results of these datasets provide a reliable fingerprint of human arrival early in the North. The outcomes of the age-depth model suggest that settlement of the Far North occurred as early in the settlement history of New Zealand as in the south. The high-resolution model and identification of when human arrival occurred in this research project provide one of the most robust chronologies for Polynesian settlement and landscape modification developed for the Far North thus far.

7.4 Comparison of Environmental Impact to Other Research

The intensity of anthropogenic impact and the length of the IBP has been found to vary between regions in New Zealand based on precipitation, combustibility of the forests, elevation and other environmental factors (McWethy et al., 2010; McWethy et al., 2009; McWethy et al., 2014; Newnham et al., 2018; Perry et al., 2012; Wilmshurst et al., 2004). This has been studied more thoroughly on the South Island and research has found that the IBP began shortly after human arrival, but results were diachronous and fell between c. 1280-1600 AD (McWethy et al., 2010; McWethy et al., 2009).

To determine the length of the IBP on the South Island, McWethy et al. (2014) compared two lakes from the Otago District; Lake Kirkpatrick, with a lower elevation (570m a.s.l.) and annual precipitation (1077mm/yr) to Dukes Tarn with higher elevation (830m a.s.l.) and annual precipitation (1340mm/yr). High-resolution chronologies were created by radiocarbon dating of macrofossils for these lakes which allowed the IBP to be accurately identified through time in the pollen and CHAR analysis from the charcoal records that were created. The modelled results from this research showed that the length of the IBP was only 17 (SD-7) years at the dry site (Lake Kirkpatrick), and 48 (SD-19) years at the wetter site (Dukes Tarn) (McWethy et al., 2014). Minor differences in the intensity of impact and forest recovery were also observed between several southern lakes, but in all cases, the IBP found to be of short duration (McWethy et al., 2010; McWethy et al., 2009).

On the North Island, around coastal Taranaki, Wilmshurst et al. (2004) observed that anthropogenic landscape modification first occurred significantly later (mid-17th century) compared to much of the south and that in this wet environment, with annual rainfall reported as 2000mm/yr, the intensity of human landscape modification was not as pronounced. The chronologies for these sites are poorly constrained but the IBP appears to be roughly a few decades in length. Wilmshurst et al. suggest that landscape clearance was more limited and later in the region because the occupants were clearing land primarily for swidden horticulture rather than travel which required less modification and that the landscape was also harder to burn clear than drier regions (Wilmshurst et al., 2004).

On the East Coast of the North Island, Wilmshurst (1997), like McWethy et al. (2014), compared the environmental records from two lakes proximal to each other with different climate conditions. One lake, Tutira, received a mean annual rainfall of 1400mm while the other lake, Rotonuiaha saw 2000mm/yr. The chronologies are at poor-resolution, relying on a few tephra due to difficulties with radiocarbon measurement at these sites, but Wilmshurst suggests that deforestation began in the mid-15th century and that the IBP took roughly 59 years at Tutira, the drier site, and 153 years at Rotonuiaha, the wetter site (Wilmshurst, 1997).

More recently in the Auckland region, Newham et al. (2018) have developed an environmental reconstruction at Lake Pupuke supported by a more robust tephrochronology. The site area is humid and receives ~1240mm of annual rainfall. The research found that the IBP began around 1350 AD in this area, but that this event caused only minor environmental impact until 1400-1450 AD. This was followed by a second phase of intense landscape modification that rapidly removed the native forests by fire (Newnham et al., 2018). Newham et al. (2018) have attributed this second phase of higher intensity impact possibly to horticultural intensification of warmer climates following the effects of the Little Ice Age (LIA). Anderson (2016, 2018) has suggested that the LIA shifted the growing limits of sweet potato and other crops further north and that horticultural intensification began in the north around 1500 AD in response to this.

Further north, the environmental impact patterns observed from Lake Taumatawhana in the Far North appear similar to those recorded on the South Island with a single rapid and intense landscape transformation pulse shortly after human arrival (Elliot et al., 1995). The sampling resolution (10cm intervals) may have contributed to these observations and, as mentioned previously, the chronology is low-resolution and imprecise over the time interval that these impact signals occurred. The poor quality of the chronology does not allow for a meaningful estimation of the IBP at this site, however, this area probably receives a similar amount of annual precipitation as Lakes Ngatu and Rotoroa which is estimated at 1200mm/yr.

In addition to low sampling resolution, another reason that the Lake Taumatawhana environmental reconstruction might appear similar to southern records could be related to soil types and microclimates. Elliot et al. (1995) have indicated that the late Holocene environment in Northland prior to human arrival is not as well understood as the South Island. Elliot and colleagues do, however, suggest that there is some evidence for drier, windier conditions in the Far North prior to human arrival, which has also been observed by other researchers (Dodson et al., 1988; Enright et al., 1988; Newnham, 1999; Newnham et al., 2004). Elliot interprets the oscillation in the abundance of kauri in the site's pollen record as showing signs of drought prior to settlement since these trees require between 1000 and 2500mm of rainfall annually (Ecroyd, 1982). These effects might have been exacerbated at this site since sand dunes are especially sensitive to moisture loss (Elliot et al., 1995). If this is the case, the environment of the Far North, particularly the sand dunes, may have been slightly drier and the vegetation more combustible during the modelled time of human arrival than in Auckland and Taranaki.

In comparison to the research above the results from Ngatu and Rotoroa appear to come from a drier, rather than a wetter location, which implies that the IBP should be of short duration. The possible drier conditions of the region through the period of Polynesian settlement, particularly as related to the sand dunes, as identified above by Elliot et al. (1995) could explain why tall and small tree pollen around Lakes Ngatu and Rotoroa recede quickly after human arrival. This might also be a reason why tall tree pollen abundance varied through Zone 1. The quick reduction in tree pollen in Zone 2 is supported by the carbon and nitrogen results in this zone which also suggest that a rapid transition in lake chemistry occurred shortly after initial anthropogenic impact.

However, the modelled durations of the IBP for these lakes are much longer (339-581 years in Ngatu and 272-435 years in Rotoroa) than those recorded in the other sites. Overall, the length of the IBP at Ngatu and Rotoroa most resembles the total length of the IBP as recorded in two-steps in Lake Pupuke by Newham et al. (2018), which appears to last as long as 150-200 years. Some refinement of the length of the IBP for Lakes Ngatu and Rotoroa could come out of the more thorough pollen and charcoal environmental reconstruction that will be created separately as part of the larger project, but the length should not drastically change. The simplified records used here are still indicative of the timing of tall and small tree pollen reduction and charcoal particle and bracken fern spore increase within the chronology. This leaves the question of why the IBP might be longer in duration at Lakes Ngatu and Rotoroa?

The duration of the IBP at the research lakes could partly be related to environmental factors and the reasons the landscape was altered. Early land use on the South Island included clearing to create access to valuable lithic resources (Walter et al., 2017), hunt moa and encourage bracken fern and tī kōuka growth (Anderson, 1989; McGlone et al., 1994; McWethy et al., 2010; McWethy et al., 2009).

The work presented here suggests that Polynesian settlers with tropical crops were likely modifying the landscape in the sub-tropical Far North soon after arrival. Initial and continued modification of the landscape was probably not done to improve travel to stone sources or to hunt moa as in the south, but more likely to take advantage of the warm climate to practice horticulture and possibly also for bracken fern growth. As discussed in Chapter 2, some of the Polynesian cultivars such as tī pore could only be grown in Northland, and this region was the only area in New Zealand to have the environmental conditions to support all of the Polynesian cultigen suite that was successfully transferred to New Zealand (Furey, 2006). Yams for instance, which did not generally grow well in

New Zealand, were identified by starch granules in the horticultural soils at Motutangi on the Aupouri Peninsula (Horrocks and Barber, 2005).

The differences in the environmental reconstructions between the two lakes lend support to this theory. The increased erosion signals after human arrival suggest that Ngatu's flatter catchment and wetlands were developed for horticulture, perhaps even wetland horticulture, since archaeological evidence of this practice has been suggested to have occurred in the region (Barber, 1989, 2001; Horrocks and Barber, 2005). Ngatu's environmental history might also lend support to the work of Newham et al. (2018) and show evidence of land use intensification after 1500 AD, which could also be related to increased land use in the north once the impact the LIA began in the south.

Landscape modification might have also needed to be undertaken at a different pace to maintain productive gardens. Root crops are known to deplete the soils of nutrients (Leach, 1984) which could be improved by mulching or burning nearby forests to release phosphates and other nutrients into the soil (Elliot et al., 1997; Elliot et al., 1995; McWethy et al., 2010). These requirements may have produced longer initial burn periods at both Ngatu and Rotoroa than recorded at other sites. However, Rotoroa's steeper catchment might have been less suitable for cultivation, at least for wetland practices, and the catchment appears to have not been modified directly for this purpose, but its nearness to Ngatu meant that the timing and regional environmental signals of impact were also recorded in this lake. Rotoroa's erosional stability after 1500 AD is consistent with Wilmshurst (1997), and suggests that once the native forest was removed, Rotoroa's catchment was chiefly left for bracken fern growth or other landscape uses which limited erosion.

In conclusion, the reasons for landscape alteration differed regionally and possibly even locally, and this may have had as much impact on the pace and intensity of change in the environmental records as differences in forest combustibility, and regional climate. The longer duration of the modelled IBP at Lakes Ngatu and Rotoroa compared to many other sites may indicate that, within the sandy soils and warm climate of the Aupouri Peninsula, early settlement and land use were probably tied to horticultural practices and that landscape modification for these practices required continued landscape modification. The differences between the proxy data in these two lakes, which have the same climate and experienced human arrival and landscape modification at the same time illustrate first, the utility of catchment specific environmental proxies, which allow for local changes to be identified and compared to the regional pollen and charcoal signals. Lastly, these results show the power in using multiple sites to develop land use histories since each lake may behave differently, highlighting potential variability in land use.

8. Conclusions

The aim of this research was to provide an accurate age for Polynesian settlement in the Far North of New Zealand and to increase our understanding regarding the impact that land use practices had on the region. Though the Far North may have been colonized early in New Zealand's settlement history and utilized for horticultural practices due to the warm, mild climate, it has not been as extensively researched or as well dated compared to some other areas in New Zealand.

To establish the timing of arrival and to determine the effects that anthropogenic landscape alteration had on the research area a high-resolution chronology was required. Lake sediments from two lakes near archaeological features were cored and organic materials were isolated to build radiocarbon chronologies. To verify that the most precise targets were selected to build the chronologies macrofossils and pollen concentrates were tested against each other for accuracy. Prior to human impact macrofossils and pollen concentrates provide similar ages for sediment deposition, especially once the ^{14}C activities of the contaminating material were removed from the pollen's age, while after anthropogenic landscape modification in a closed lake system pollen concentrates may produce ages significantly older than macrofossils from the same depth. The offset in ages between the two materials could not be explained by the inclusion of ^{14}C depleted materials, such as algae. The experiment provides the first outcome of the research project and demonstrates that human landscape modification can significantly increase the mobilization of fossil pollen within catchment soils and that post-anthropogenic pollen concentrates either should not be utilized or should only be used with great caution to build age-depth models. The results of these tests could have implications on the outcomes of prior research and could affect the research strategies of future projects.

The results of the dating experiment informed the construction of the age-depth model. Macrofossils were specifically isolated along with four select pre-impact pollen concentrate dates from Lake Ngatu, which appears to have had minimal pre-impact fossil carbon contamination based on the experimental work. Bayesian modelling of these radiocarbon dates and other likelihood information suggest that initial human impact to the catchments occurred between 1165 and 1280 AD. Though this age range is early in New Zealand's settlement history, prior radiocarbon dates and material culture uncovered from archaeological sites in the region also indicate that the area was occupied since the very beginning of human colonization of New Zealand. This high-resolution chronology is one of the most accurate models for human influence for the region and is the second outcome of the research project.

The robust chronology allowed the elemental, isotopic and geochemical proxies to be precisely placed in time. These catchment specific proxies were used to derive durations of land use and determine the intensity of alteration compared to regional scale pollen and charcoal records from the lakes. The results from these measurements indicate that human arrival and sustained landscape impacts were observable in the data sets. Increased erosion and loss of vegetation resulting from anthropogenic burning of the landscape around the catchments affected both lakes as seen in lower C:N ratios and higher detrital inputs into the lake basins as evidenced by elemental titanium and zirconium in lake sediments. The speed of landscape alteration observed in the proxy data is slower than southern model but the intensity of landscape change is similar (McWethy et al., 2010; McWethy et al., 2009; McWethy et al., 2014). Previous environmental research from sites on the North Island have suggested that more minor or stepped impact occurred in these wetter, less combustible regions (Newnham et al., 2018; Wilmshurst et al., 2004). The outcomes of this research support a slower IBP in the north and imply that different subsistence practices and regional environmental conditions may affect the pace of landscape transformation.

In summary, this research provides a high-resolution age-model for an area that is not well dated. The chronology is robust due to thorough testing of sample materials and age modelling with Bayesian statistics. The model has produced a settlement date that is early in the New Zealand settlement history which suggests that Polynesians began modifying the Far North shortly after arrival. The geochemical and isotopic proxy data suggest that the landscape was continuously used and never fully abandoned. Based on climate, regional archaeological features, and historical documents, local crop production and other subsistence practices are likely reasons for initial early settlement and continued land use in this region. The rates of landscape change provided by the proxy data show slow but intense initial landscape modification. Though the traditional pollen and charcoal data and catchment specific isotopic and geochemical proxies show that change occurred over the same time periods, the intensity of these changes can be quite different and be site specific. These results illustrate how regional factors and environmental conditions should be considered when developing settlement models in New Zealand.

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Appendies

Appendix A

A.1 Location Images

Figure A.1 Lake Ngatu, looking west. Photo supplied by DOC

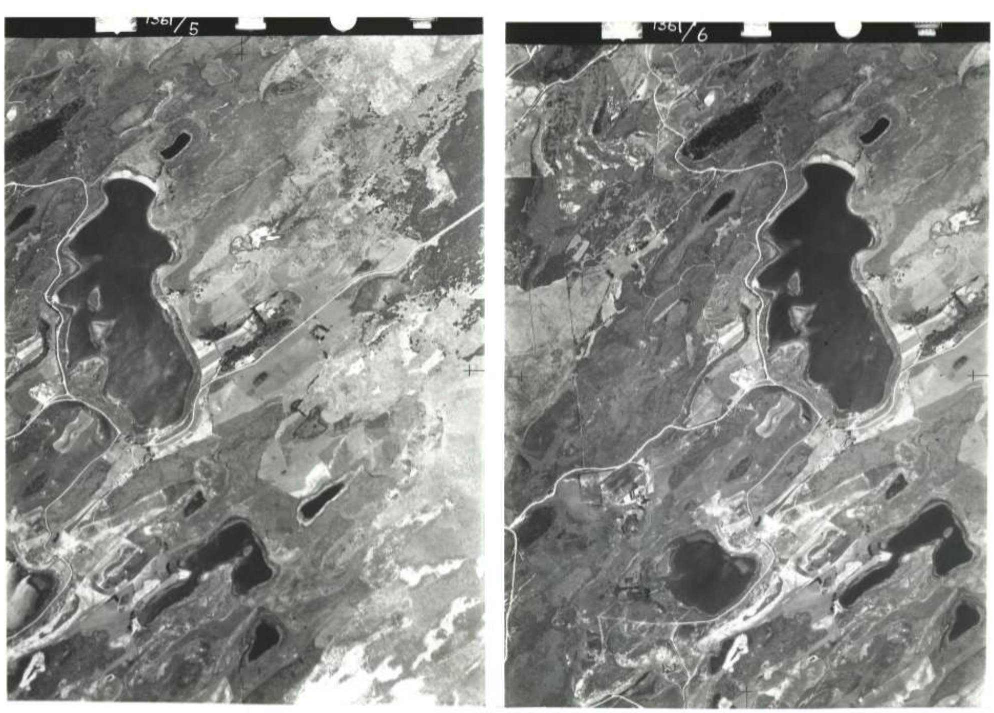


Figure A.2 1950s aerial survey photos of Lake Ngatu

Figure A.3 Lake Rotoroa, looking southwest to pā site

Figure A.4 Lake Rotoroa, eastern bank

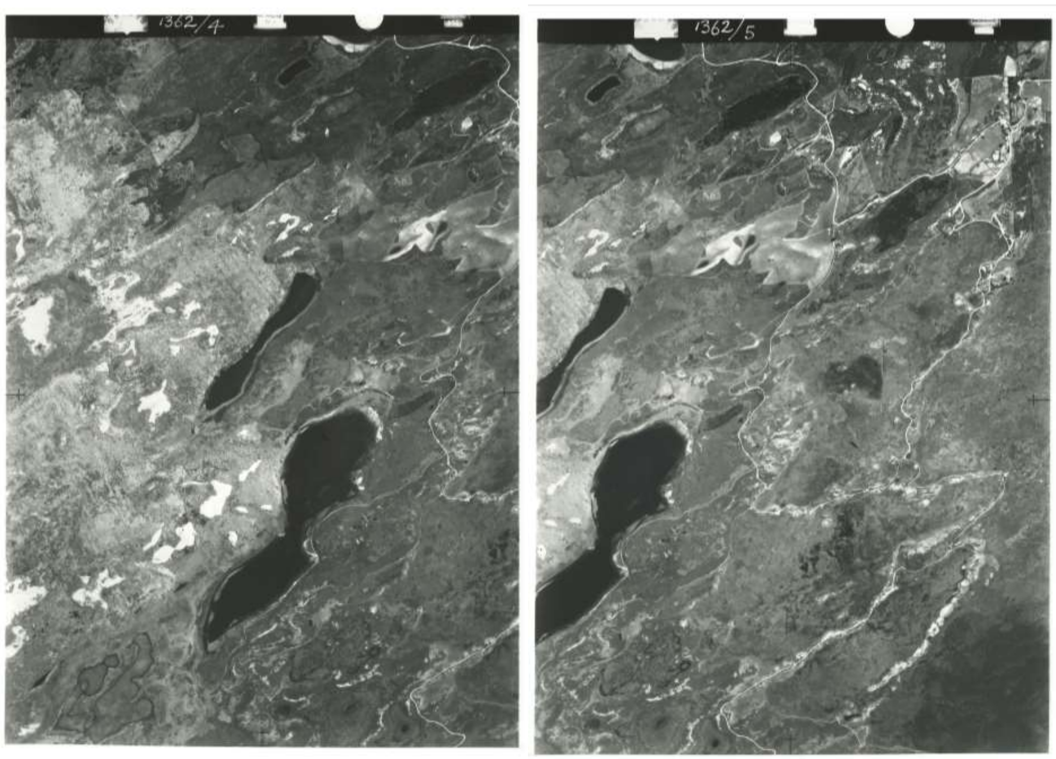


Figure A.5 1950s aerial survey photos of Lake Rotoroa

A.2 Archaeological Site Record

NEW ZEALAND ARCHAEOLOGICAL ASSOCIATION

SITE RECORD FORM (NZMS1)

NZMS 1 map number N9
NZMS 1 map name Ahipara
NZMS 1 map edition 2nd 1975

NZAA NZMS 1 SITE NUMBER N9/149
DATE VISITED 25/12/82
SITE TYPE Pa
SITE NAME: MAORI
OTHER

Grid Reference Easting 0 6 9 4 0 0 Northing 8 7 4 8 0 0

1. Aids to relocation of site *(attach a sketch map)* Situated west and above the southern end of Lake Rotoroa between Lake Rotoroa and Split Lake.

2. State of site and possible future damage Grassed consolidated dune ridge

3. Description of site *(Supply full details, history, local environment, references, sketches, etc. If extra sheets are attached, include a summary here)* Small rather isolated knoll at end of low ridge running along N.W. side of Lake rotoroa. Low profile with squarish flat tihi. No internal features, no obvious ditch but encompassing terrace with indications of irregular surface features in it which might be associated with musket warfare(?). Several outer terraces with indistinct central depressions. No mapm made of site as no pencil or paper available.

4. Owner Unknown
Address

Tenant/Manager
Address

5. Nature of information *(hearsay, brief or extended visit, etc.)* walked over site

Photographs *(reference numbers, and where they are held)*

Aerial photographs *(reference numbers, and clarity of site)* number not noted but shows very indistinctly on it.

6. Reported by A. Leahy
Address Auckland.

Filekeeper [signature]
Date 20/3/83

7. Key words Pa, Possible musket features.

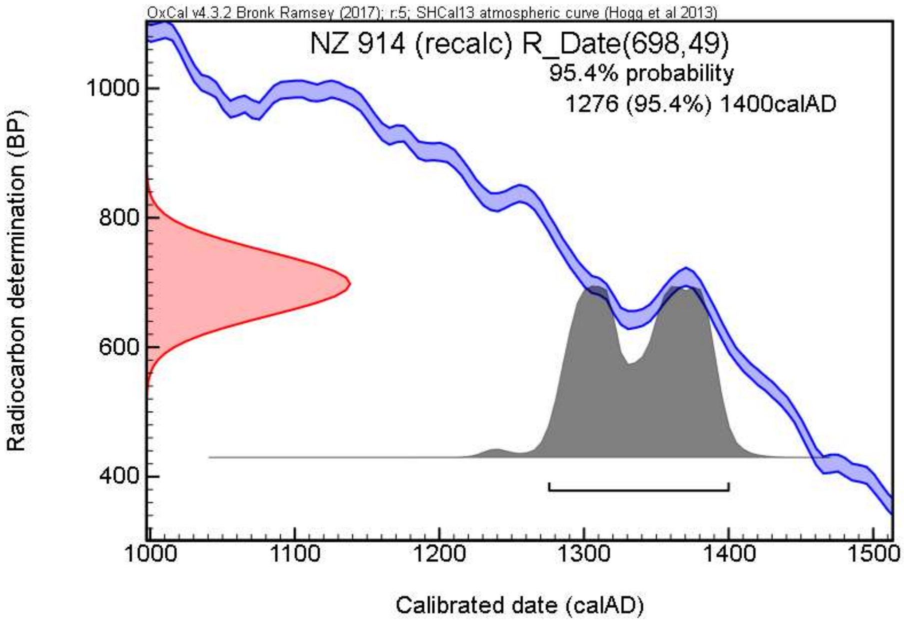
8. New Zealand Register of Archaeological Sites *(for office use)*
NZHPT Site Field Code

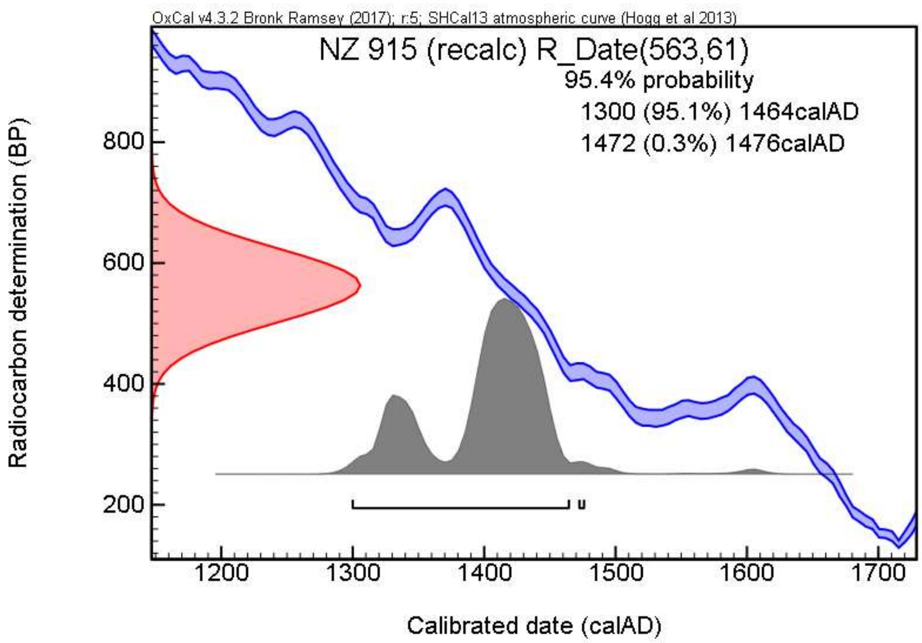
A	D	Type of site	B	A	Present condition and future danger of destruction
B	C	Local environment today	A	A	Security code
–	–	Land classification	D	R	Local body

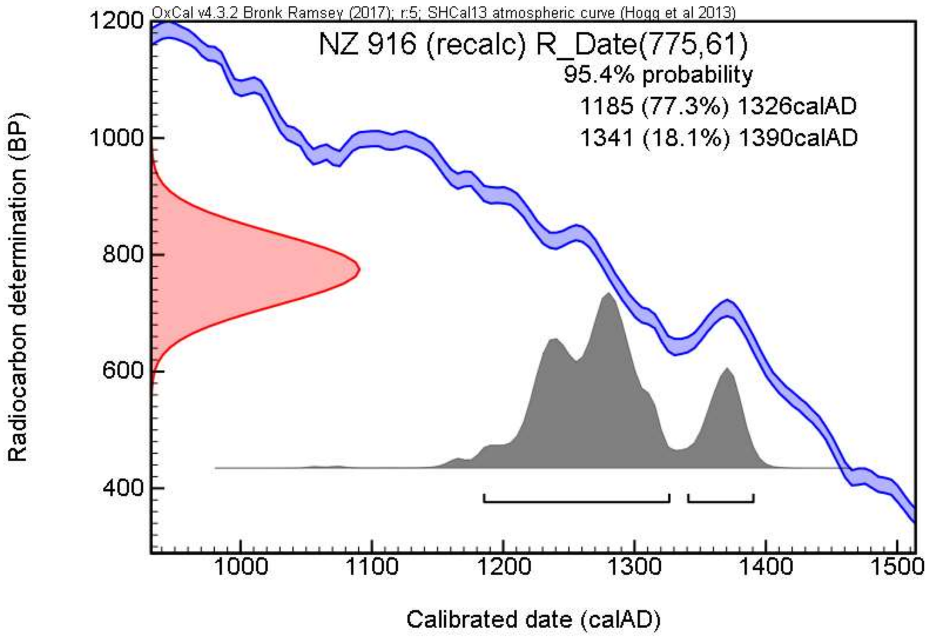
0

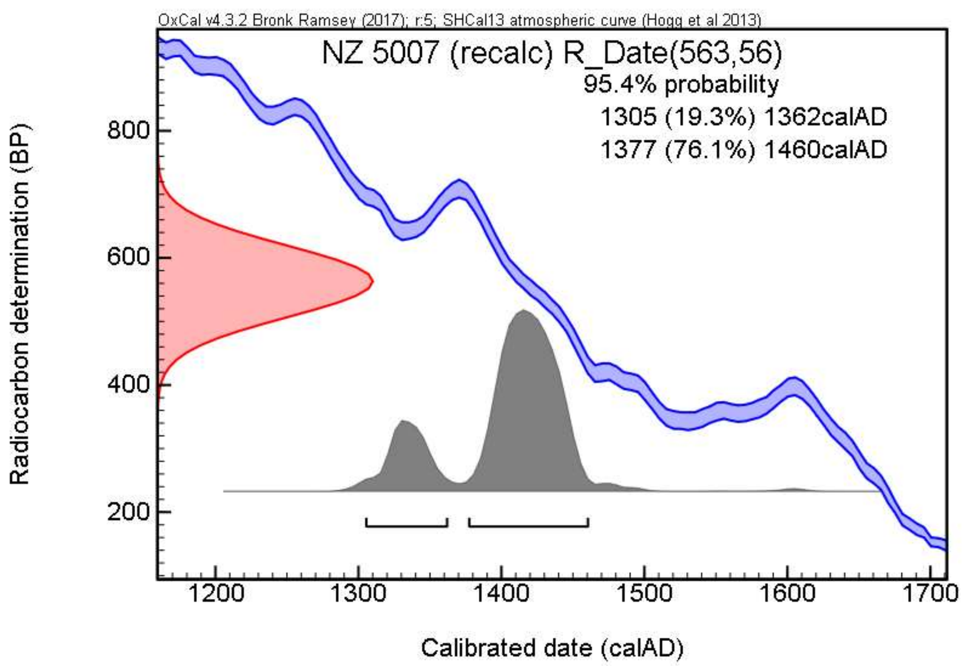
Figure A.6 NZAA Site Record for pā site N9/149

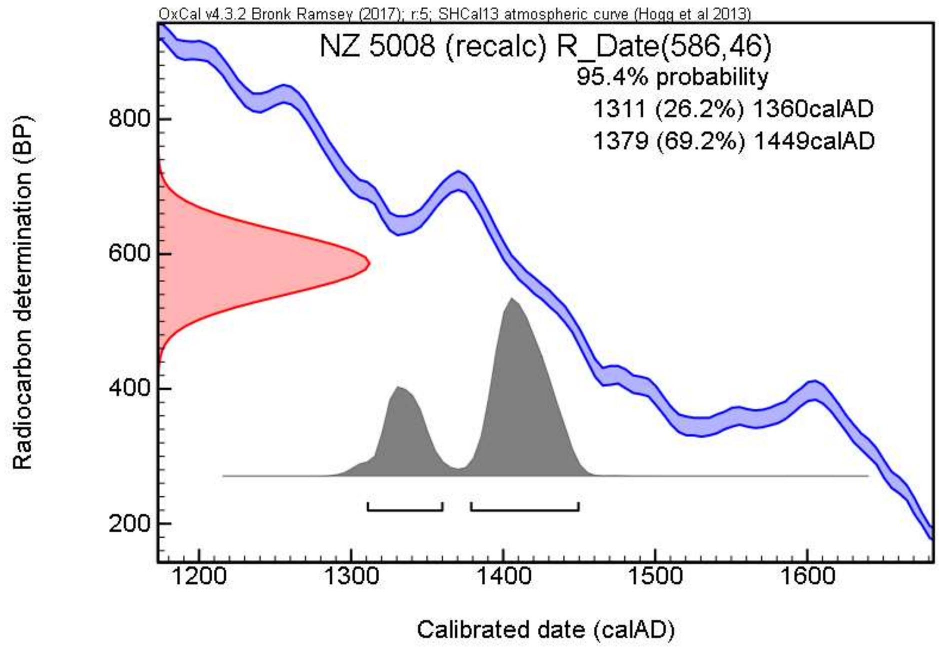
A.3 PDFs of samples from Houhora calibrated with SHCal13



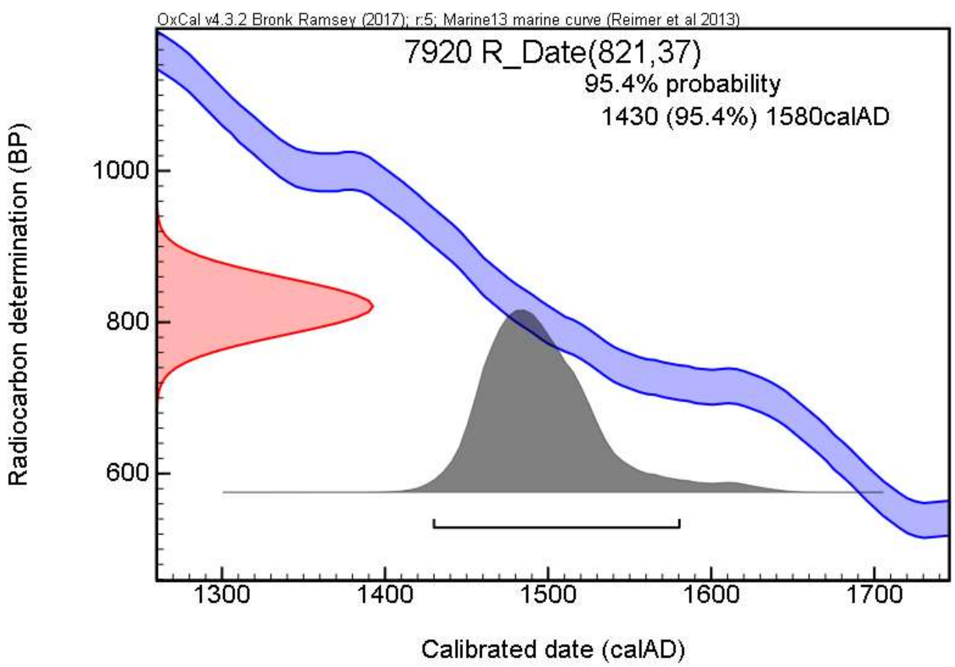



OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
NZ 916 (recalc) R_Date(775,61)
95.4% probability
1185 (77.3%) 1326calAD
1341 (18.1%) 1390calAD
Radiocarbon determination (BP)
Calibrated date (calAD)

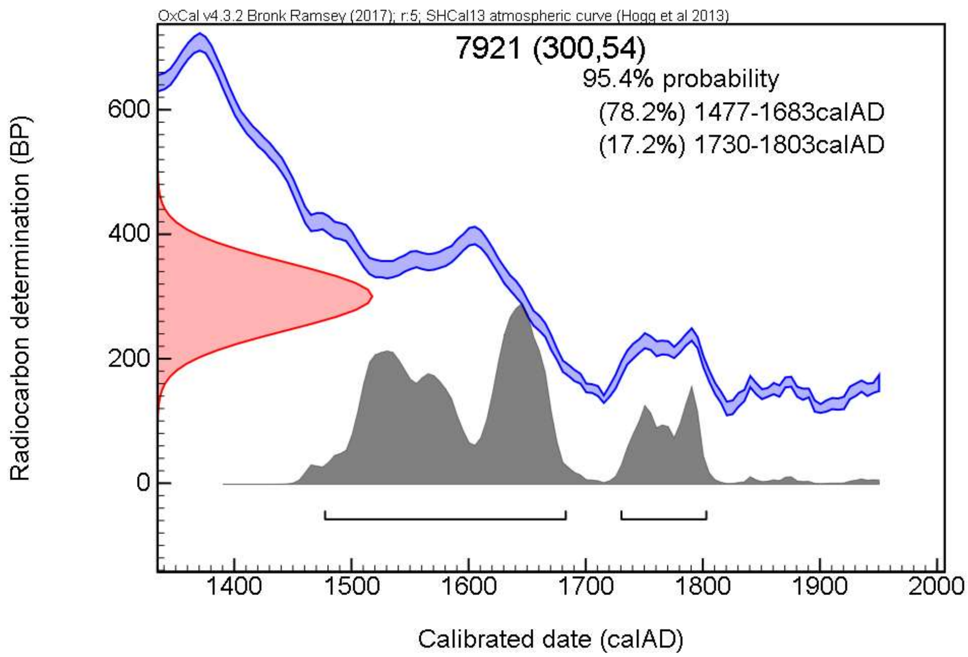

OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
NZ 5007 (recalc) R_Date(563,56)
95.4% probability
1305 (19.3%) 1362calAD
1377 (76.1%) 1460calAD
Radiocarbon determination (BP)
Calibrated date (calAD)



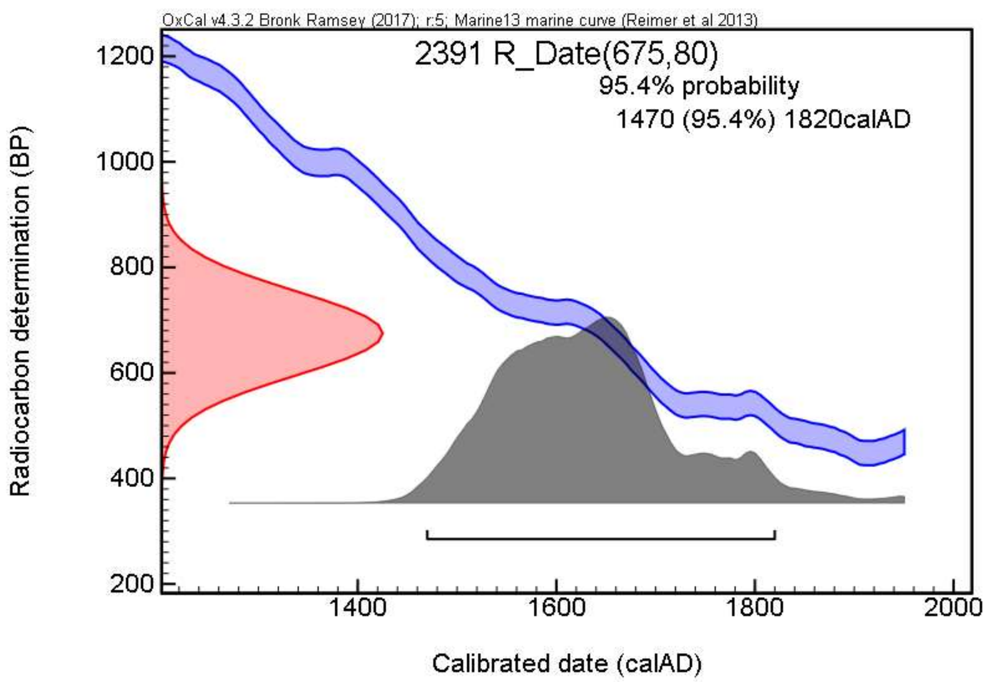
OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
NZ 5008 (recalc) R_Date(586,46)
95.4% probability
1311 (26.2%) 1360calAD
1379 (69.2%) 1449calAD
Radiocarbon determination (BP)
Calibrated date (calAD)



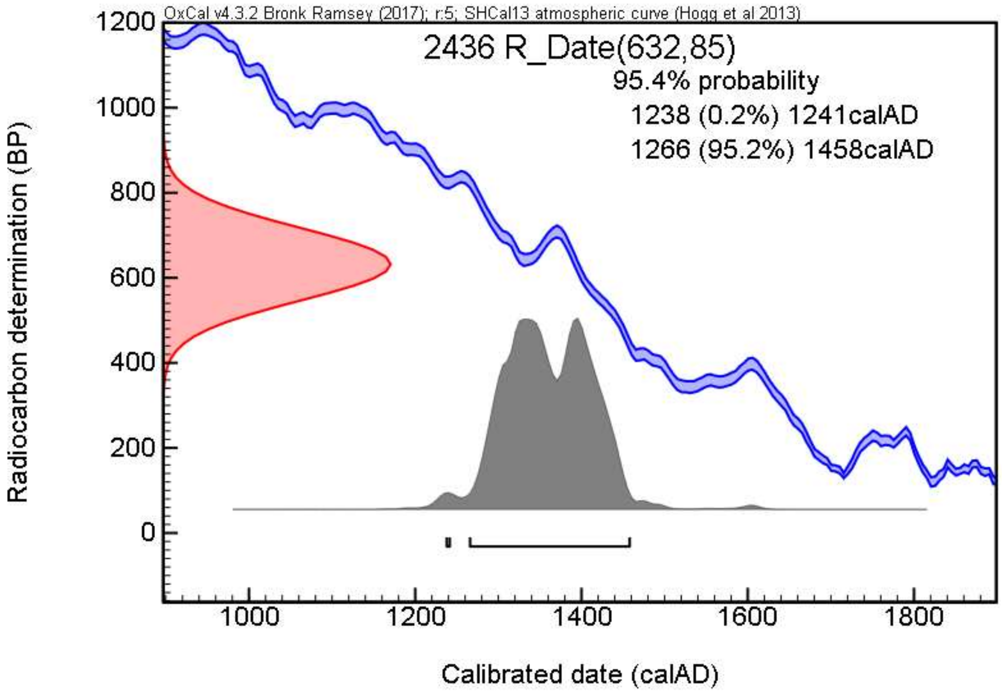
OxCal v4.3.2 Bronk Ramsey (2017); r:5; Marine13 marine curve (Reimer et al 2013)
7920 R_Date(821,37)
95.4% probability
1430 (95.4%) 1580calAD
Radiocarbon determination (BP)
Calibrated date (calAD)

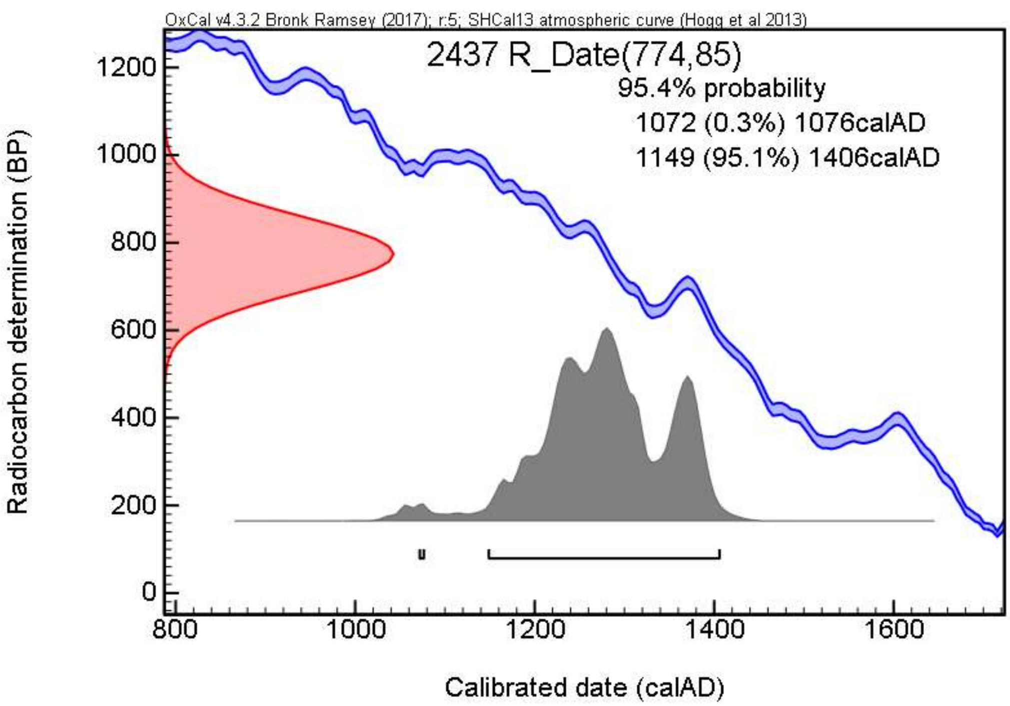


OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
7921 (300,54)
95.4% probability
(78.2%) 1477-1683calAD
(17.2%) 1730-1803calAD
Radiocarbon determination (BP)
Calibrated date (calAD)



OxCal v4.3.2 Bronk Ramsey (2017); r:5; Marine13 marine curve (Reimer et al 2013)
2391 R_Date(675,80)
95.4% probability
1470 (95.4%) 1820calAD
Radiocarbon determination (BP)
Calibrated date (calAD)


OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
2436 R_Date(632,85)
95.4% probability
1238 (0.2%) 1241calAD
1266 (95.2%) 1458calAD
Radiocarbon determination (BP)
Calibrated date (calAD)


OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
2437 R_Date(774,85)
95.4% probability
1072 (0.3%) 1076calAD
1149 (95.1%) 1406calAD
Radiocarbon determination (BP)
Calibrated date (calAD)

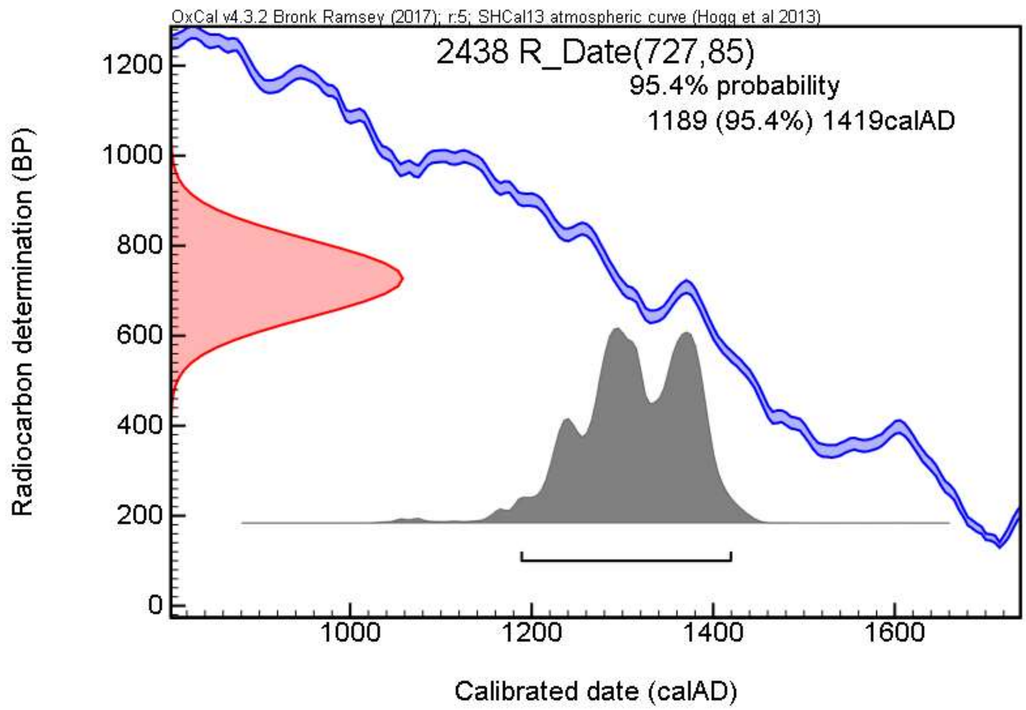
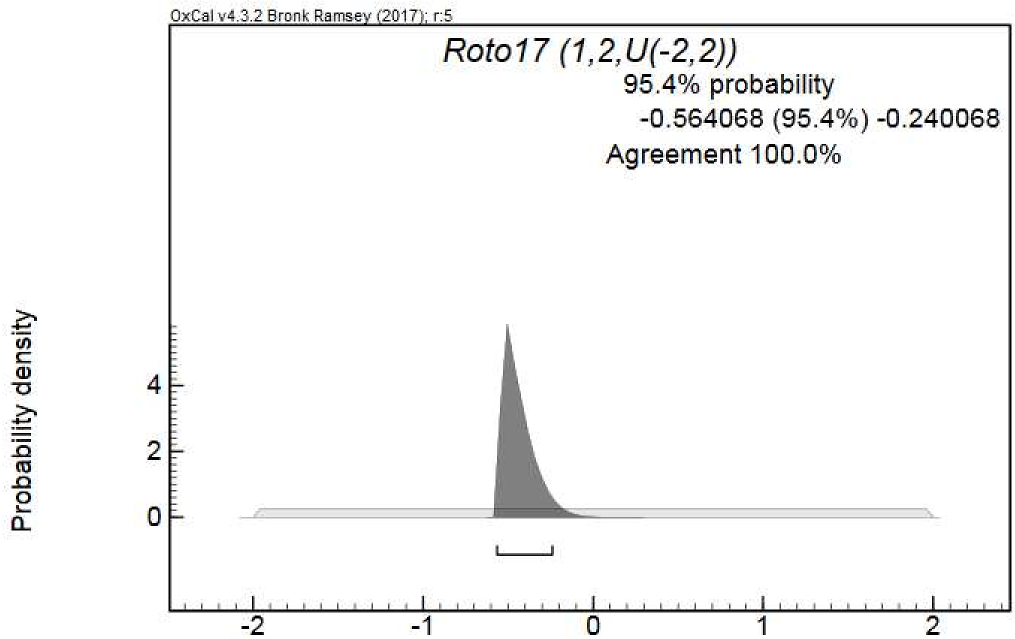
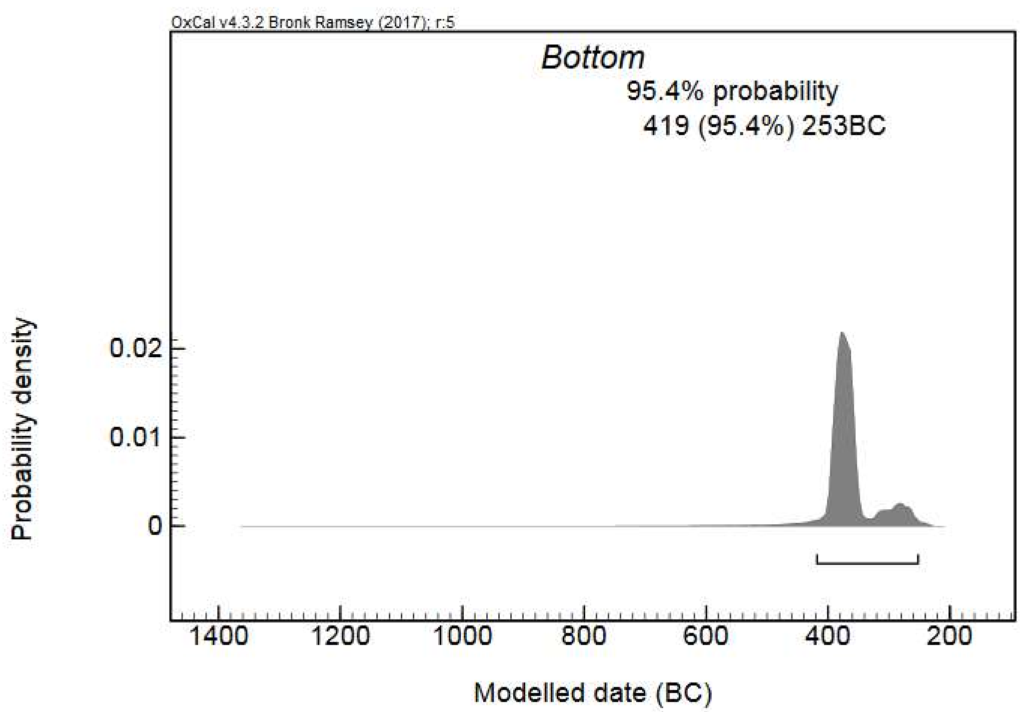


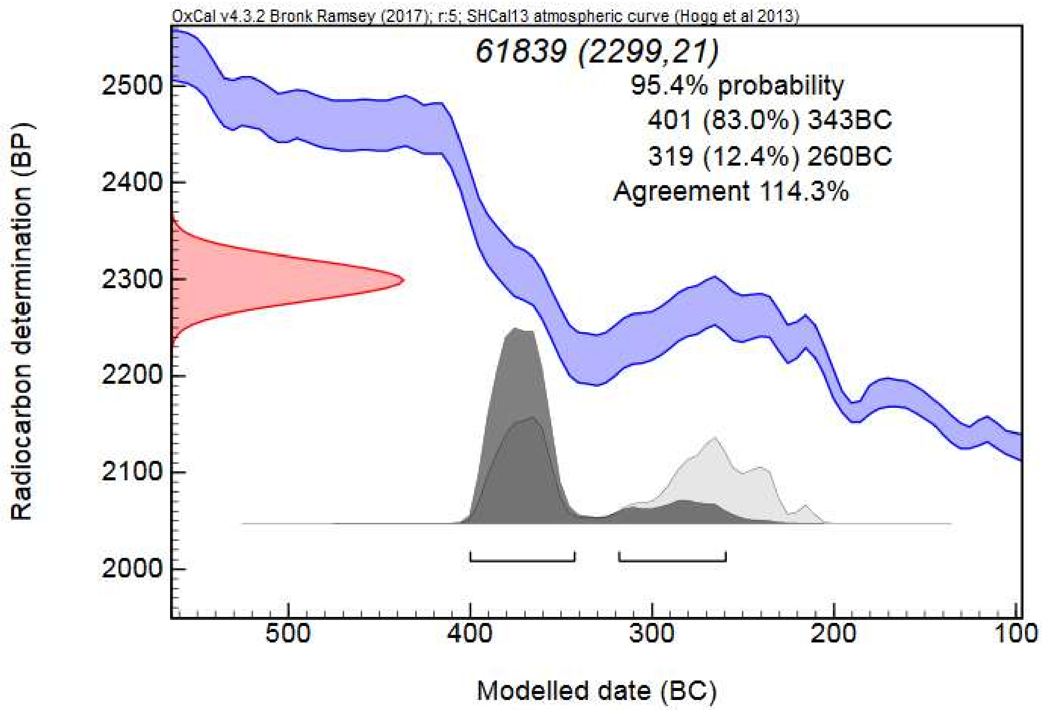
Figure A.7 Calibrations of previously measured samples from Houhora with SHCal13 (Hogg et al., 2013)

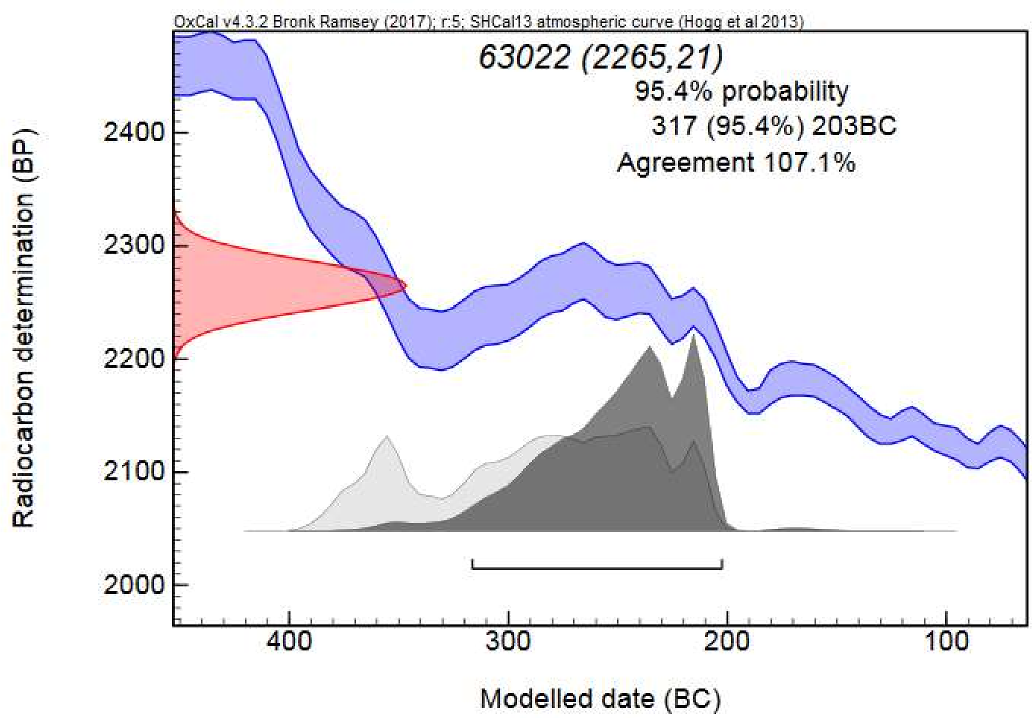
Appendix B.

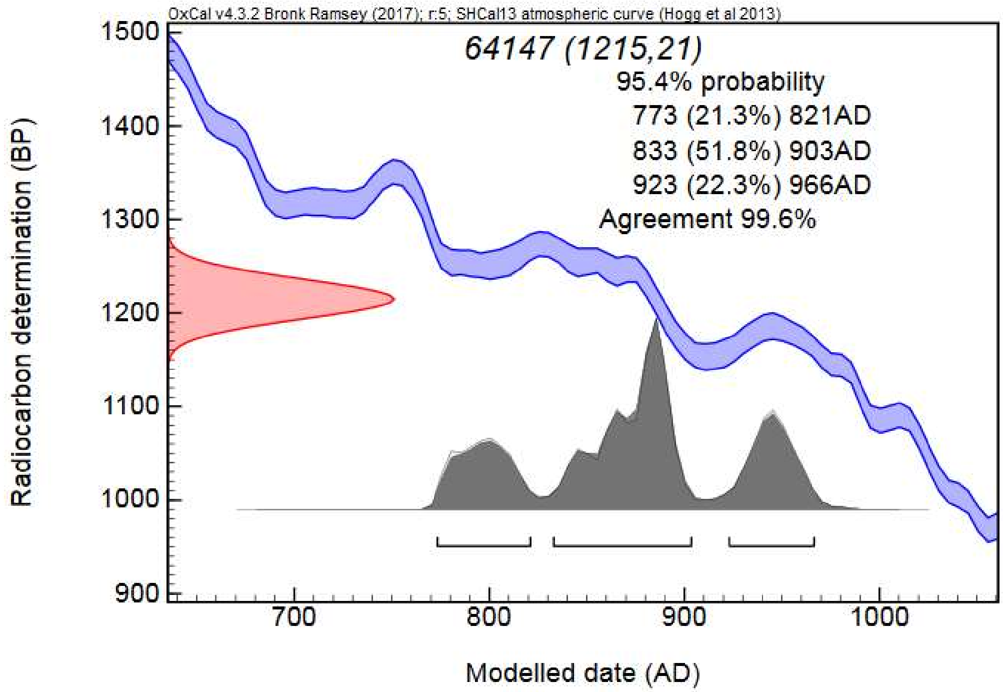
B.1 Probability Density Functions for Likelihoods

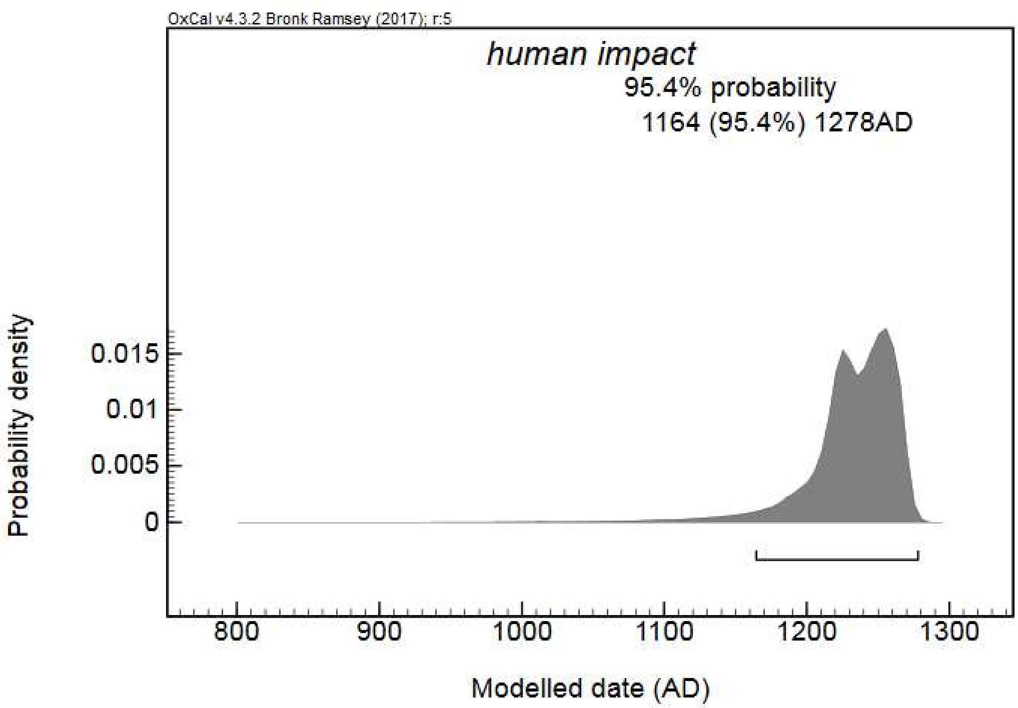


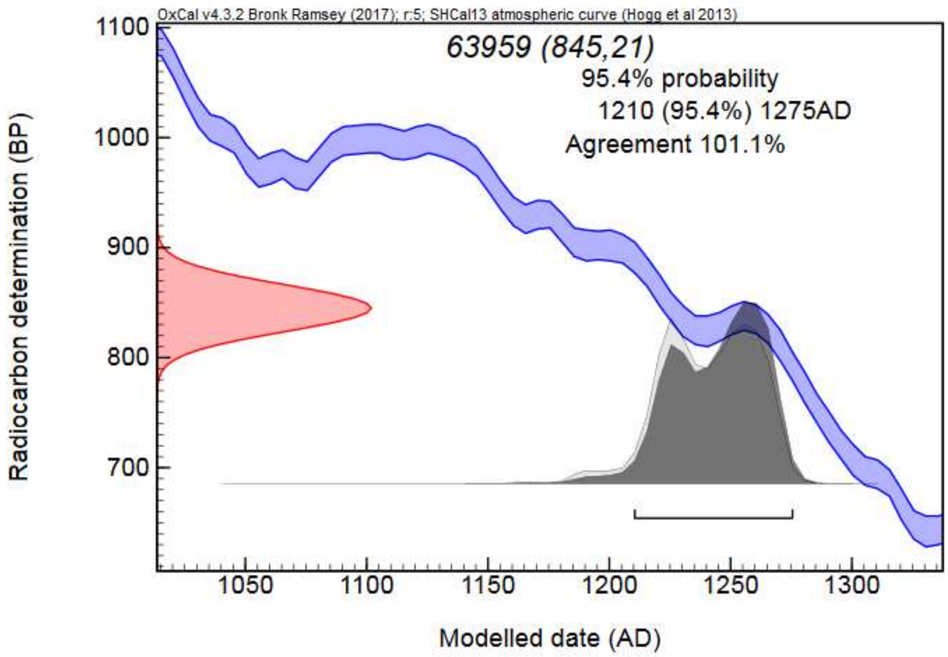


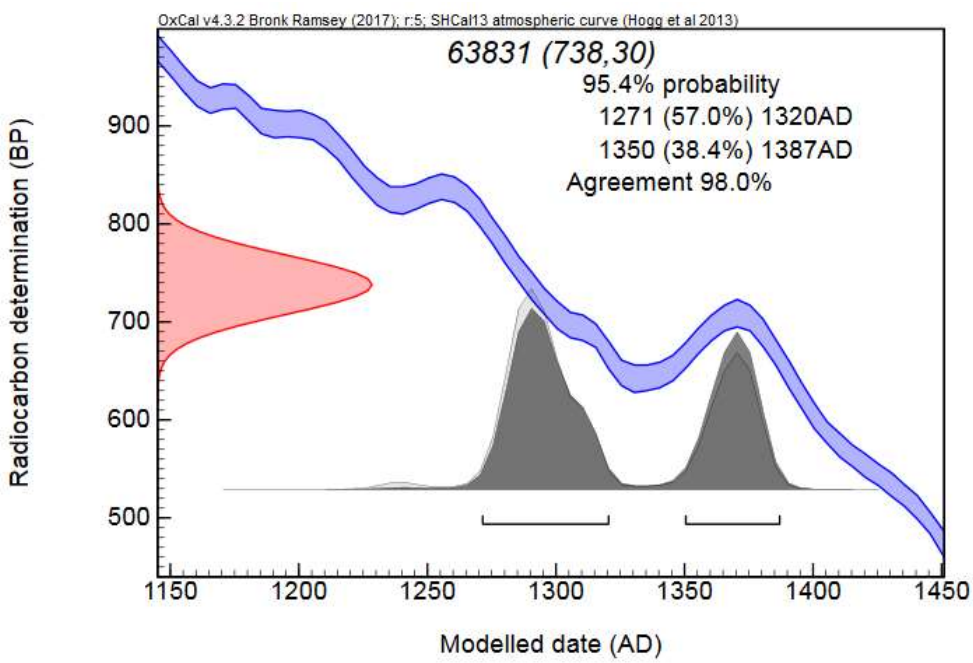

OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
61839 (2299,21)
95.4% probability
401 (83.0%) 343BC
319 (12.4%) 260BC
Agreement 114.3%
Radiocarbon determination (BP)
2500
2400
2300
2200
2100
2000
500
400
300
200
100
Modelled date (BC)

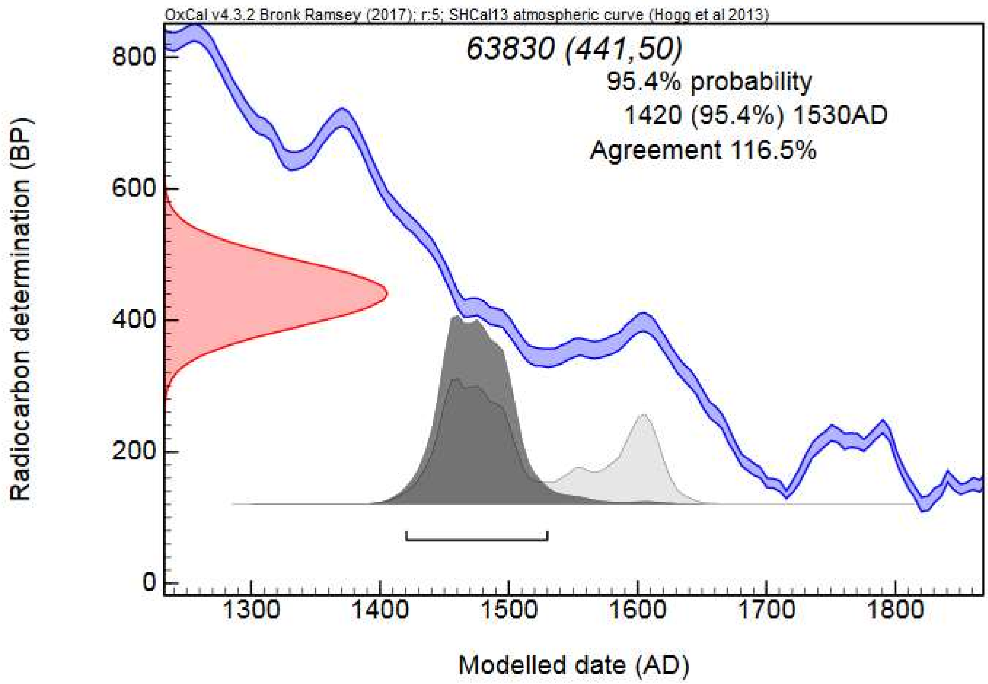

OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
63022 (2265,21)
95.4% probability
317 (95.4%) 203BC
Agreement 107.1%
Radiocarbon determination (BP)
2400
2300
2200
2100
2000
400
300
200
100
Modelled date (BC)

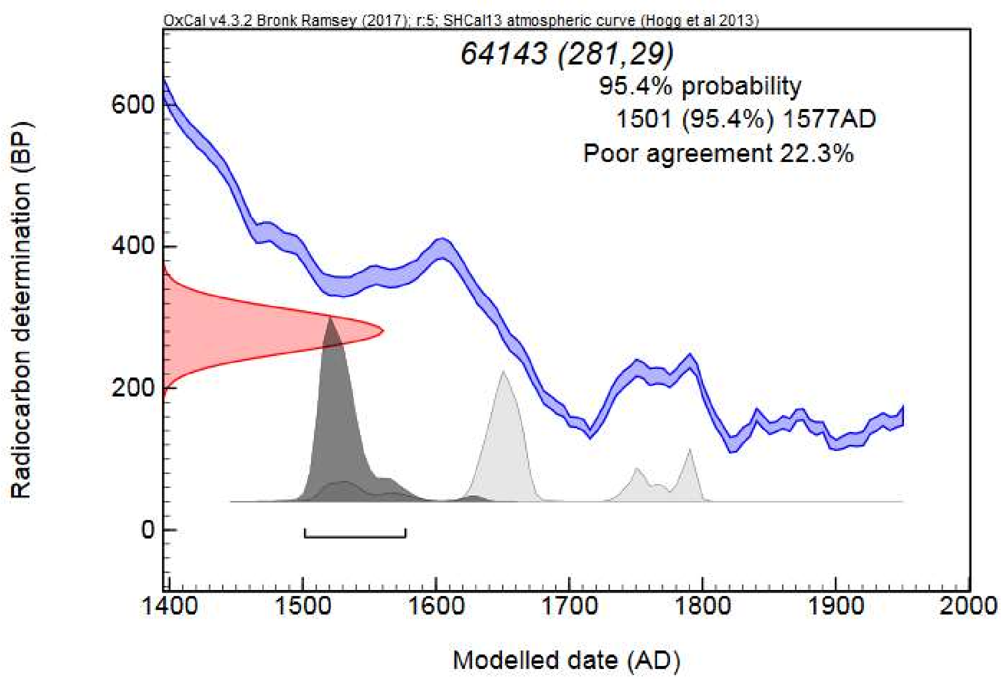

OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
64147 (1215,21)
95.4% probability
773 (21.3%) 821AD
833 (51.8%) 903AD
923 (22.3%) 966AD
Agreement 99.6%
Radiocarbon determination (BP)
Modelled date (AD)

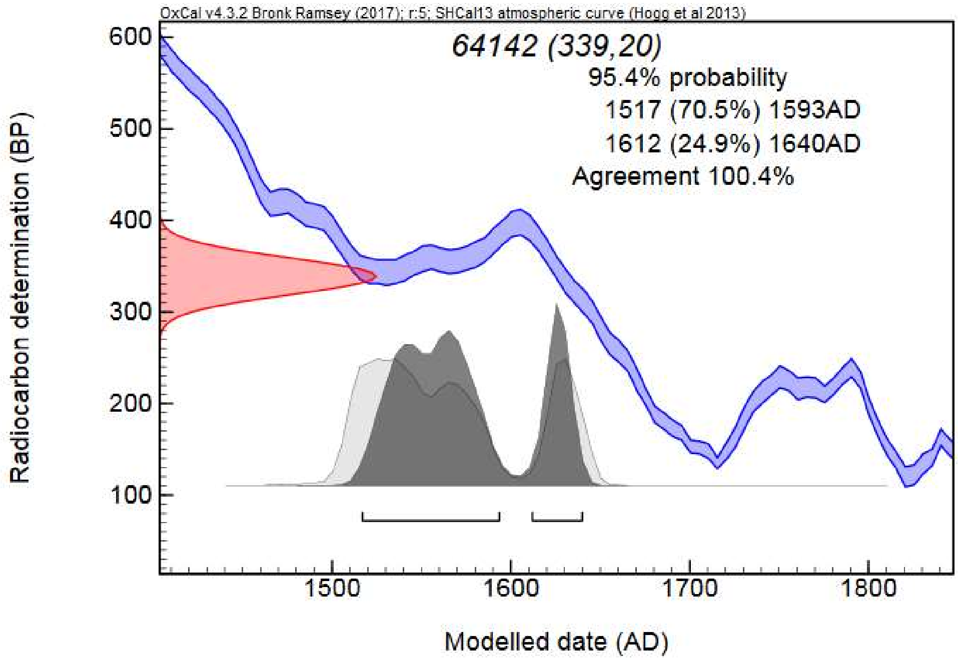

OxCal v4.3.2 Bronk Ramsey (2017); r:5
human impact
95.4% probability
1164 (95.4%) 1278AD
Probability density
Modelled date (AD)


OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
63959 (845,21)
95.4% probability
1210 (95.4%) 1275AD
Agreement 101.1%
Radiocarbon determination (BP)
1100
1000
900
800
700
1050
1100
1150
1200
1250
1300
Modelled date (AD)

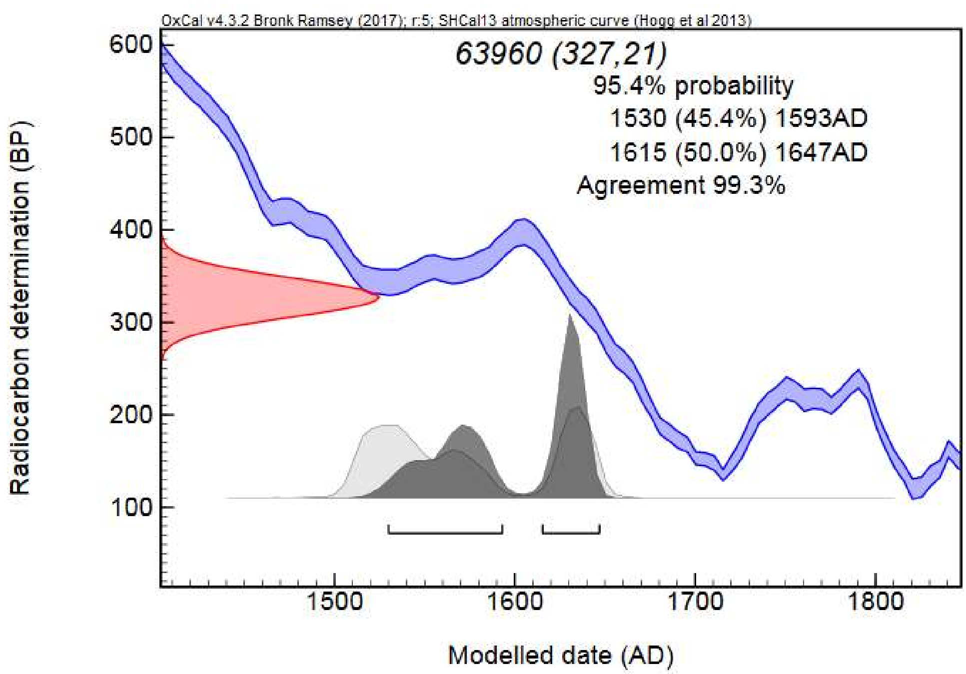

OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
63831 (738,30)
95.4% probability
1271 (57.0%) 1320AD
1350 (38.4%) 1387AD
Agreement 98.0%
Radiocarbon determination (BP)
900
800
700
600
500
1150
1200
1250
1300
1350
1400
1450
Modelled date (AD)


OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
63830 (441,50)
95.4% probability
1420 (95.4%) 1530AD
Agreement 116.5%
Radiocarbon determination (BP)
800
600
400
200
0
1300
1400
1500
1600
1700
1800
Modelled date (AD)

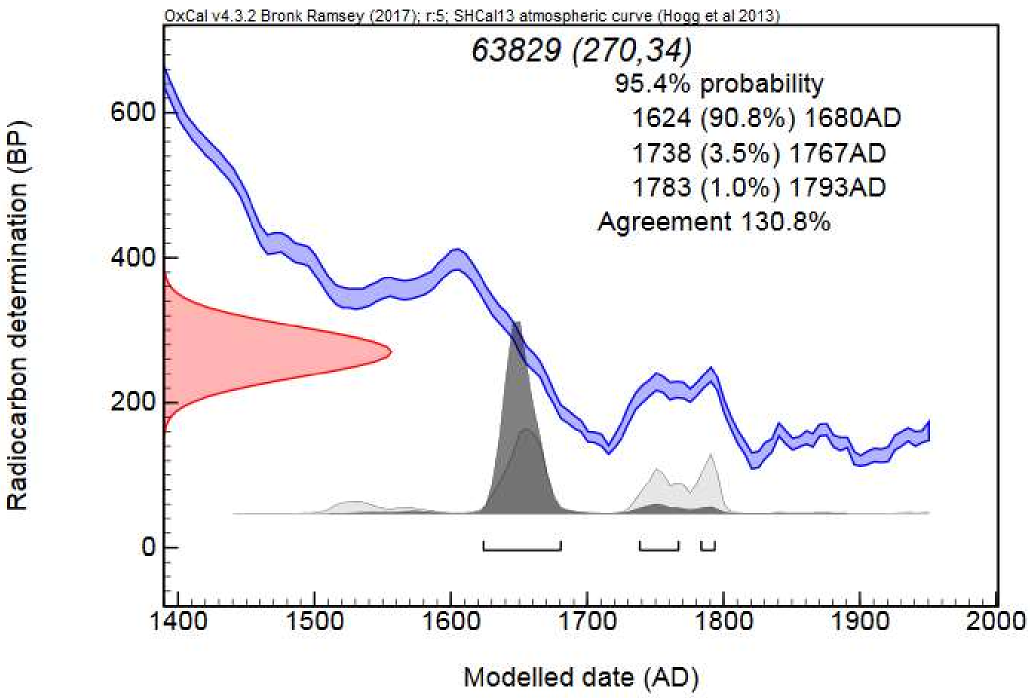

OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
64143 (281,29)
95.4% probability
1501 (95.4%) 1577AD
Poor agreement 22.3%
Radiocarbon determination (BP)
600
400
200
0
1400
1500
1600
1700
1800
1900
2000
Modelled date (AD)

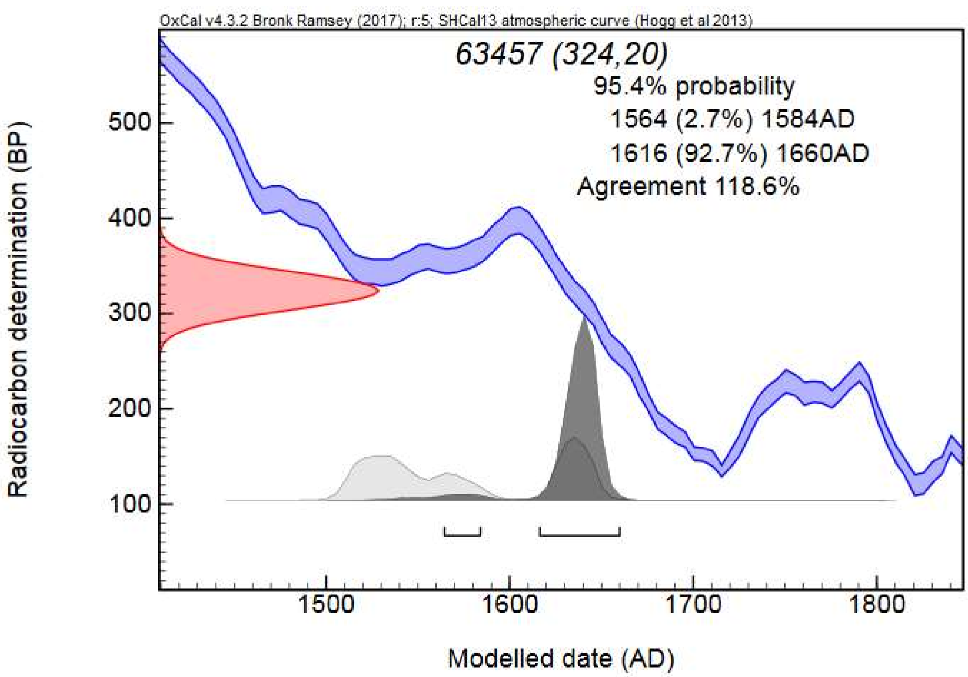


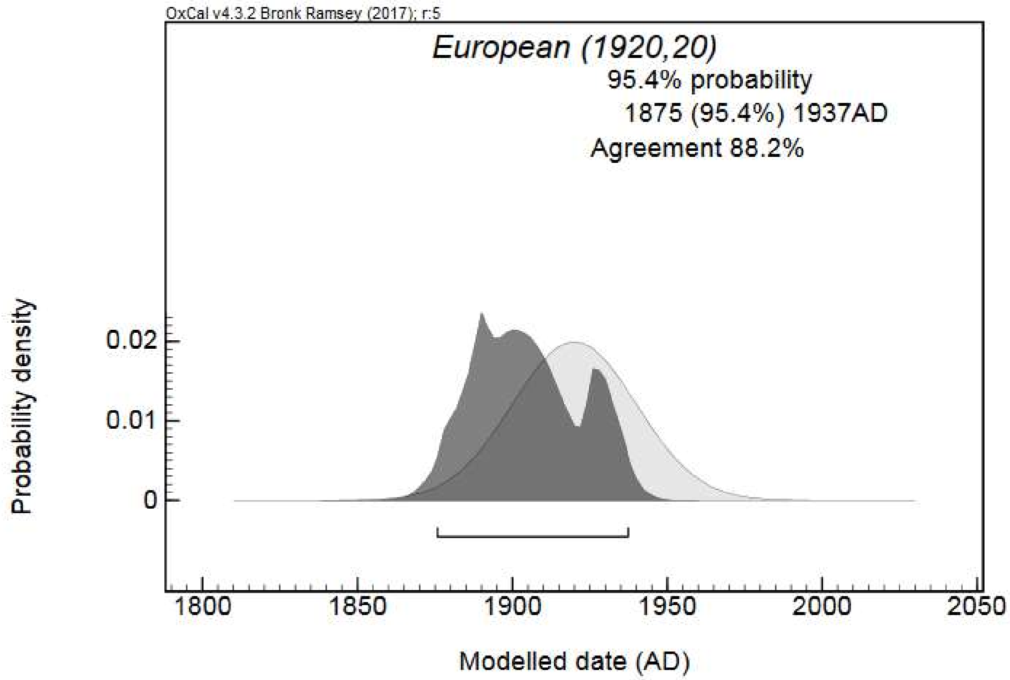
OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
64142 (339,20)
95.4% probability
1517 (70.5%) 1593AD
1612 (24.9%) 1640AD
Agreement 100.4%
Radiocarbon determination (BP)
600
500
400
300
200
100
1500
1600
1700
1800
Modelled date (AD)

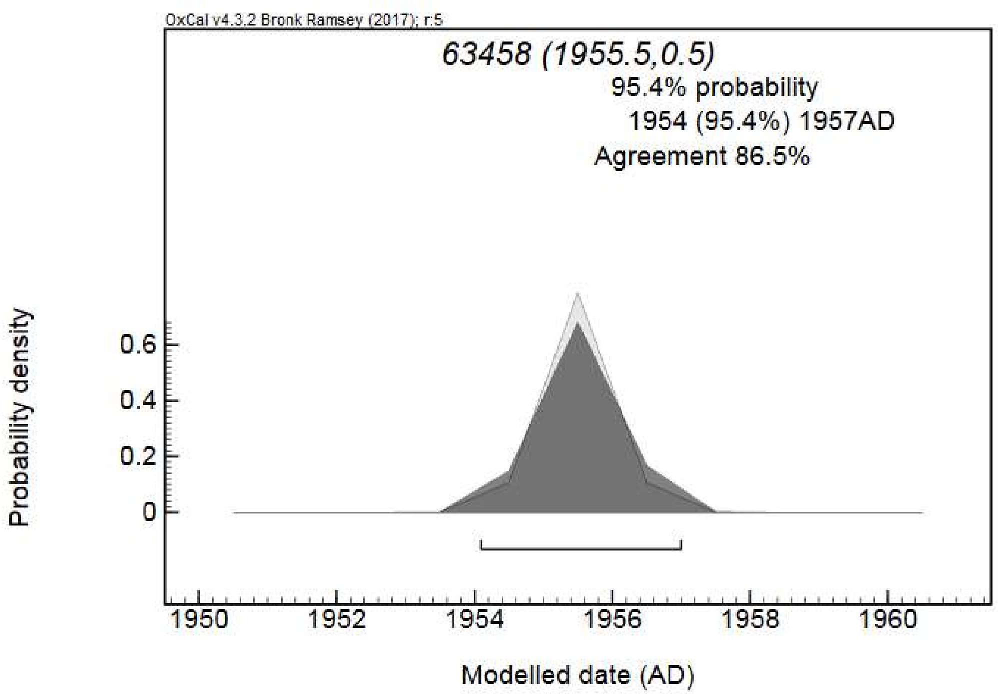


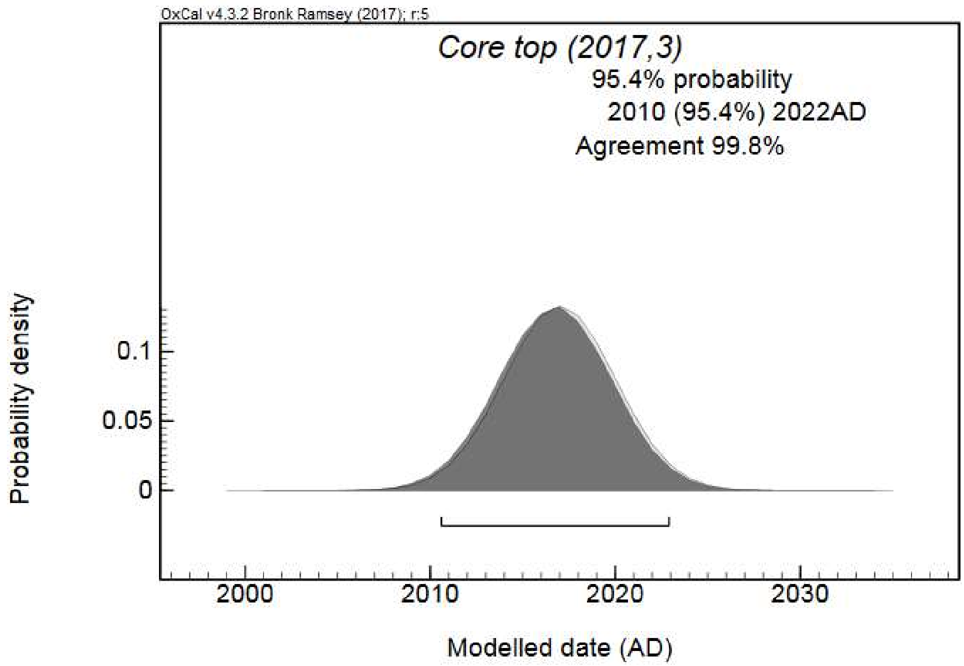
OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
63960 (327,21)
95.4% probability
1530 (45.4%) 1593AD
1615 (50.0%) 1647AD
Agreement 99.3%
Radiocarbon determination (BP)
600
500
400
300
200
100
1500
1600
1700
1800
Modelled date (AD)

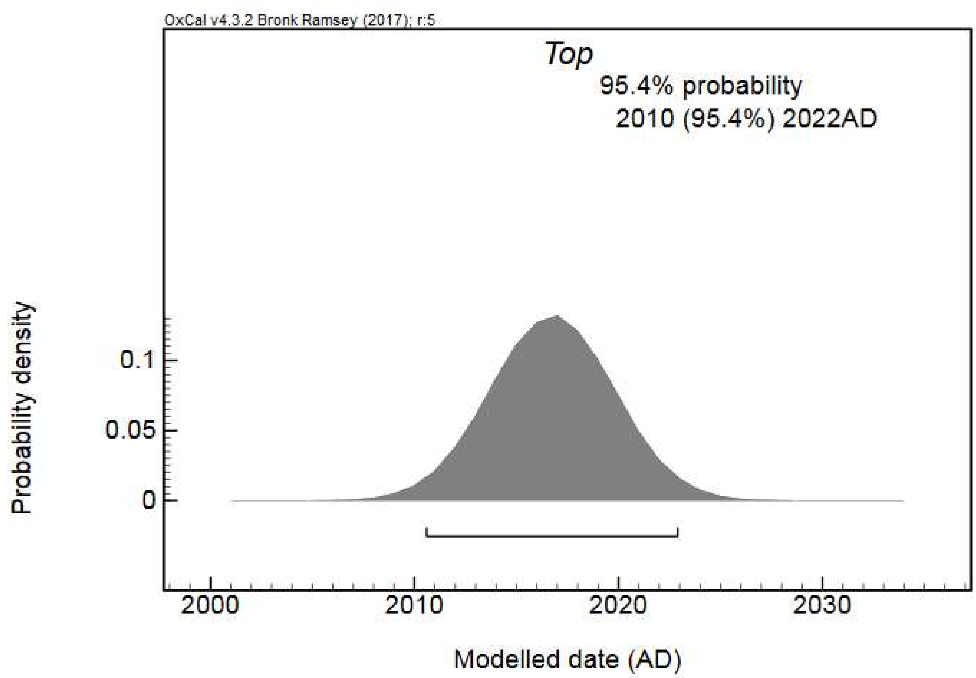

OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
63829 (270,34)
95.4% probability
1624 (90.8%) 1680AD
1738 (3.5%) 1767AD
1783 (1.0%) 1793AD
Agreement 130.8%
Radiocarbon determination (BP)
Modelled date (AD)

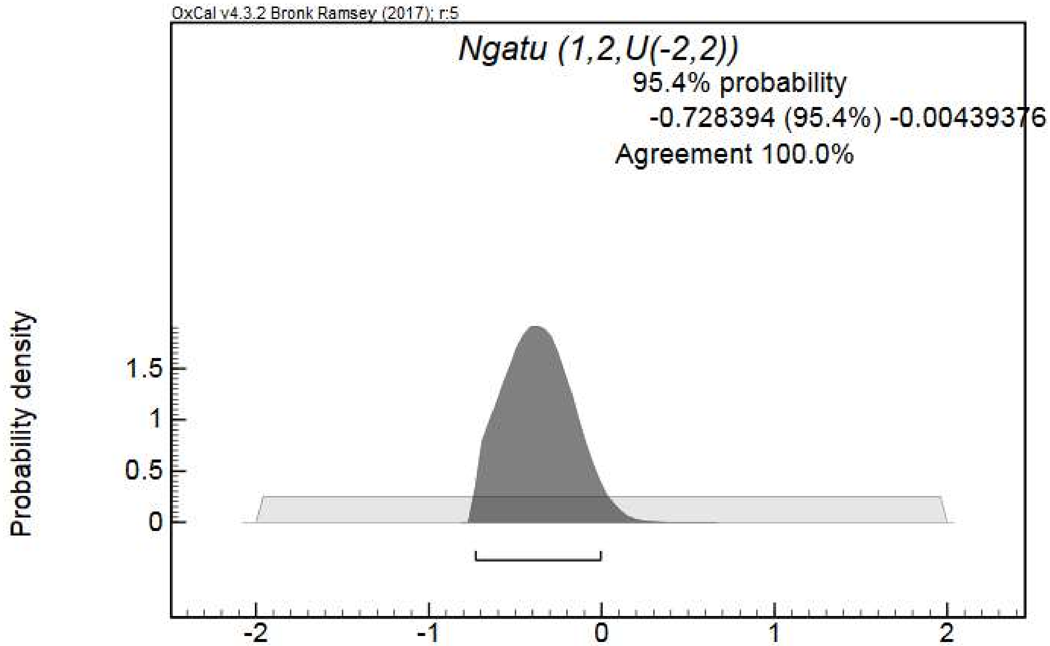

OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
63457 (324,20)
95.4% probability
1564 (2.7%) 1584AD
1616 (92.7%) 1660AD
Agreement 118.6%
Radiocarbon determination (BP)
Modelled date (AD)

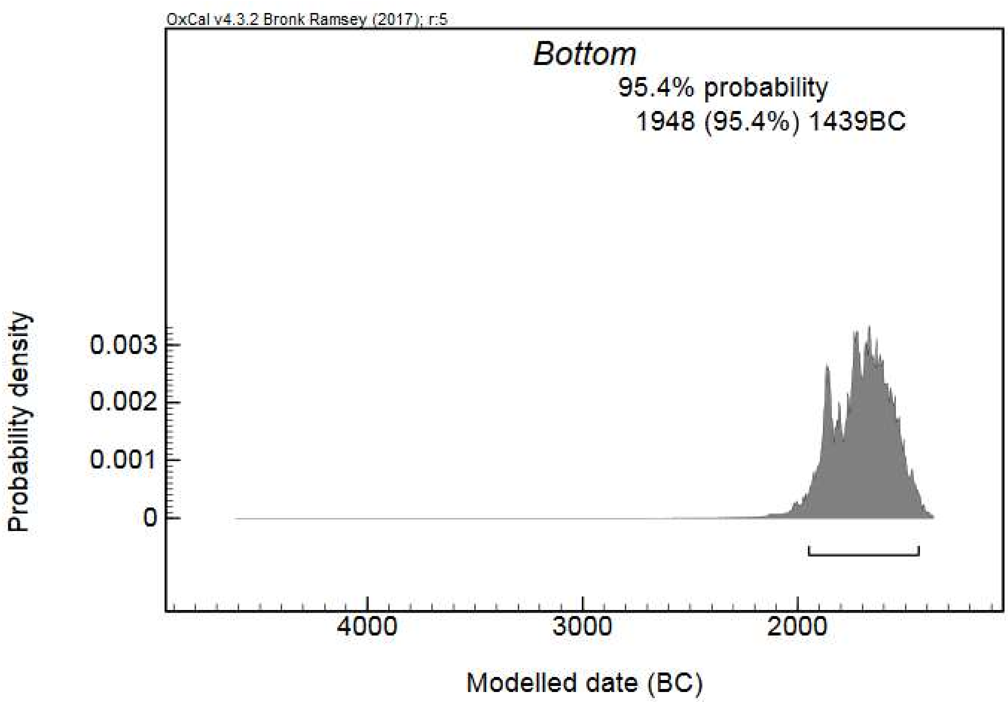

OxCal v4.3.2 Bronk Ramsey (2017); r:5
European (1920,20)
95.4% probability
1875 (95.4%) 1937AD
Agreement 88.2%
Probability density
0.02
0.01
0
1800
1850
1900
1950
2000
2050
Modelled date (AD)

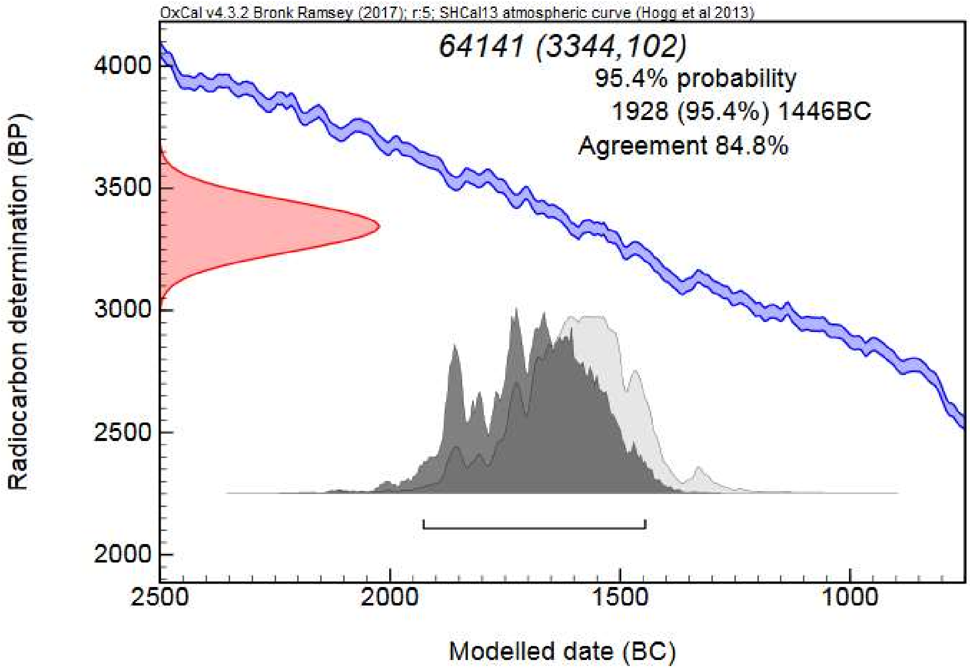

OxCal v4.3.2 Bronk Ramsey (2017); r:5
63458 (1955.5,0.5)
95.4% probability
1954 (95.4%) 1957AD
Agreement 86.5%
Probability density
0.6
0.4
0.2
0
1950
1952
1954
1956
1958
1960
Modelled date (AD)

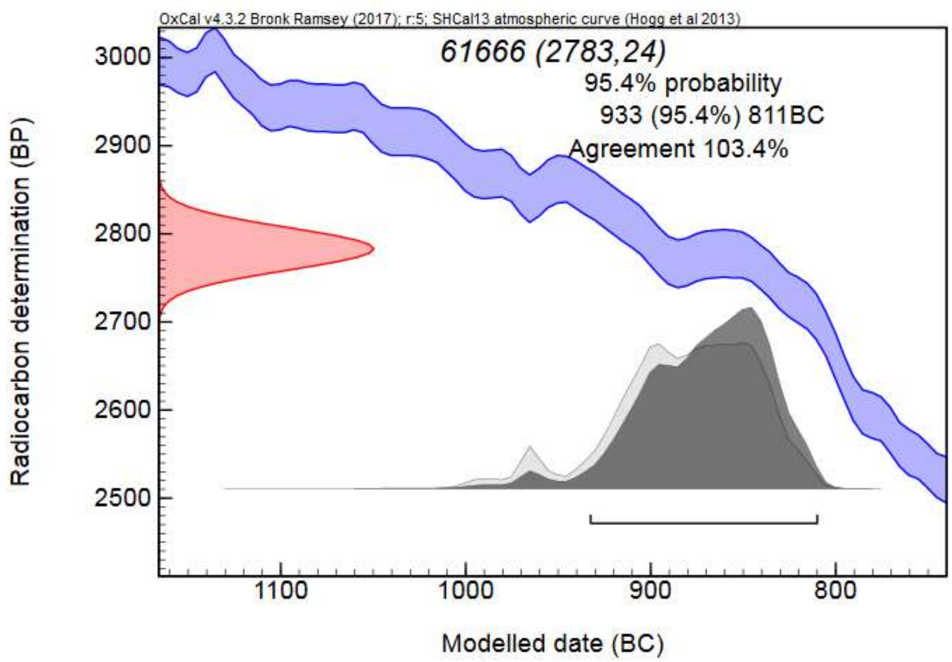

OxCal v4.3.2 Bronk Ramsey (2017); r:5
Core top (2017,3)
95.4% probability
2010 (95.4%) 2022AD
Agreement 99.8%
Probability density
0.1
0.05
0
2000
2010
2020
2030
Modelled date (AD)

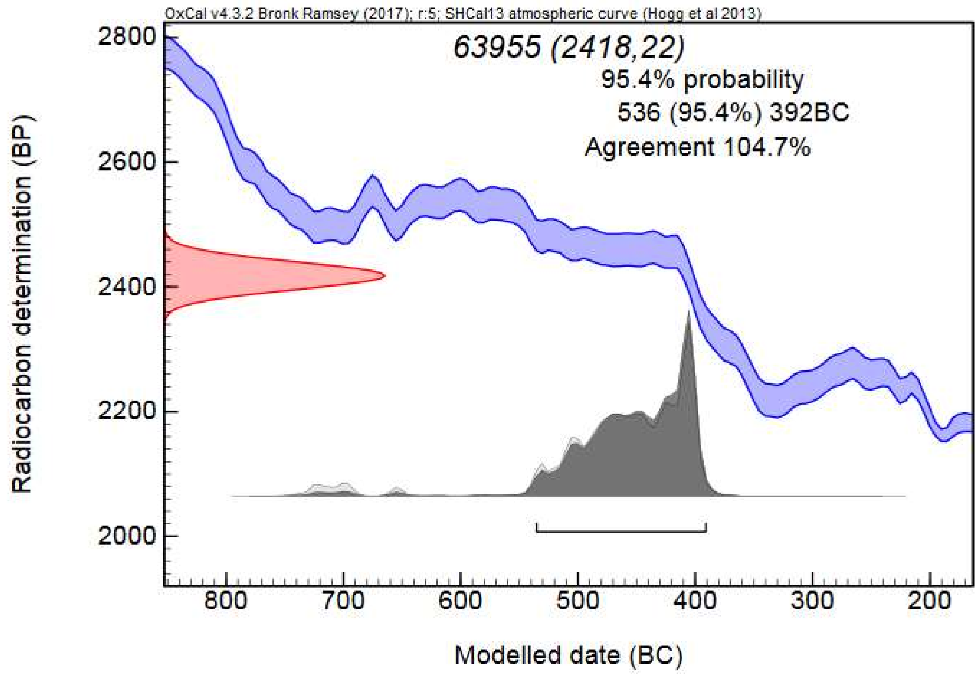

OxCal v4.3.2 Bronk Ramsey (2017); r:5
Top
95.4% probability
2010 (95.4%) 2022AD
Probability density
0.1
0.05
0
2000
2010
2020
2030
Modelled date (AD)

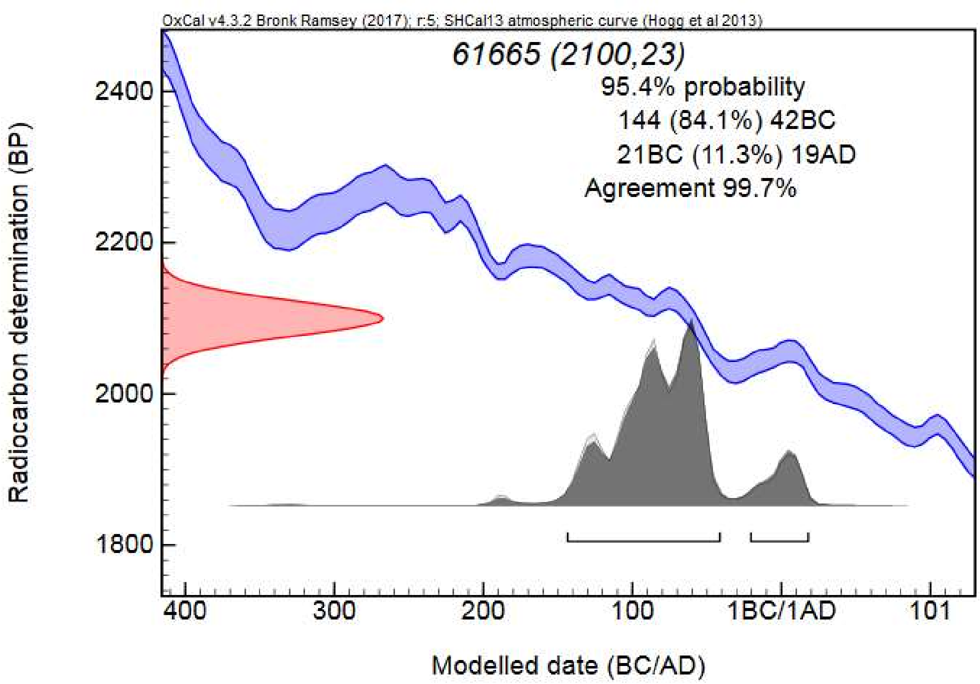

OxCal v4.3.2 Bronk Ramsey (2017); r:5
Ngatu (1,2,U(-2,2))
95.4% probability
-0.728394 (95.4%) -0.00439376
Agreement 100.0%
Probability density
1.5
1
0.5
0
-2
-1
0
1
2

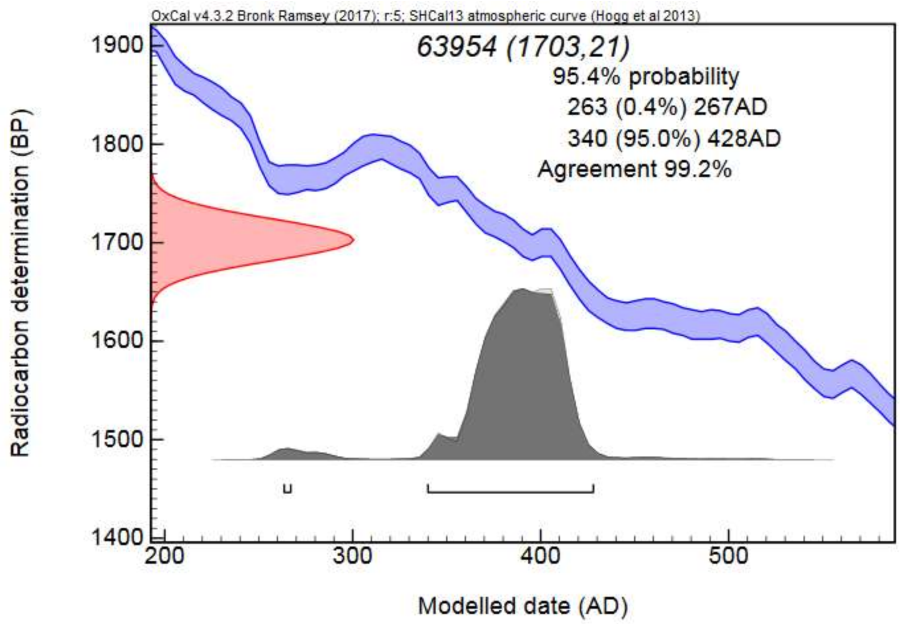

OxCal v4.3.2 Bronk Ramsey (2017); r:5
Bottom
95.4% probability
1948 (95.4%) 1439BC
Probability density
0.003
0.002
0.001
0
4000
3000
2000
Modelled date (BC)


OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
64141 (3344,102)
95.4% probability
1928 (95.4%) 1446BC
Agreement 84.8%
Radiocarbon determination (BP)
4000
3500
3000
2500
2000
2500
2000
1500
1000
Modelled date (BC)

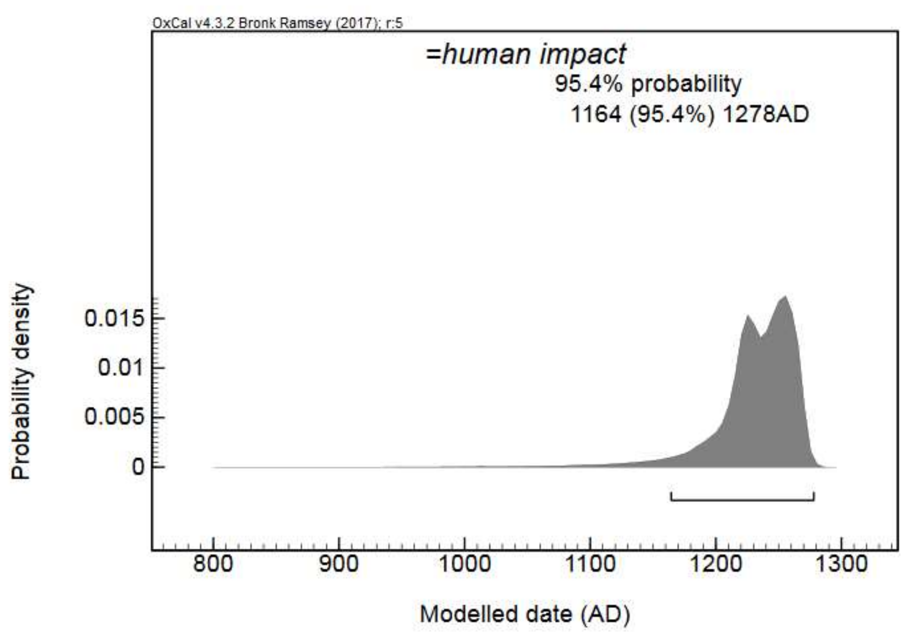

OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
61666 (2783,24)
95.4% probability
933 (95.4%) 811BC
Agreement 103.4%
Radiocarbon determination (BP)
3000
2900
2800
2700
2600
2500
1100
1000
900
800
Modelled date (BC)


OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
63955 (2418,22)
95.4% probability
536 (95.4%) 392BC
Agreement 104.7%
Radiocarbon determination (BP)
2800
2600
2400
2200
2000
800
700
600
500
400
300
200
Modelled date (BC)

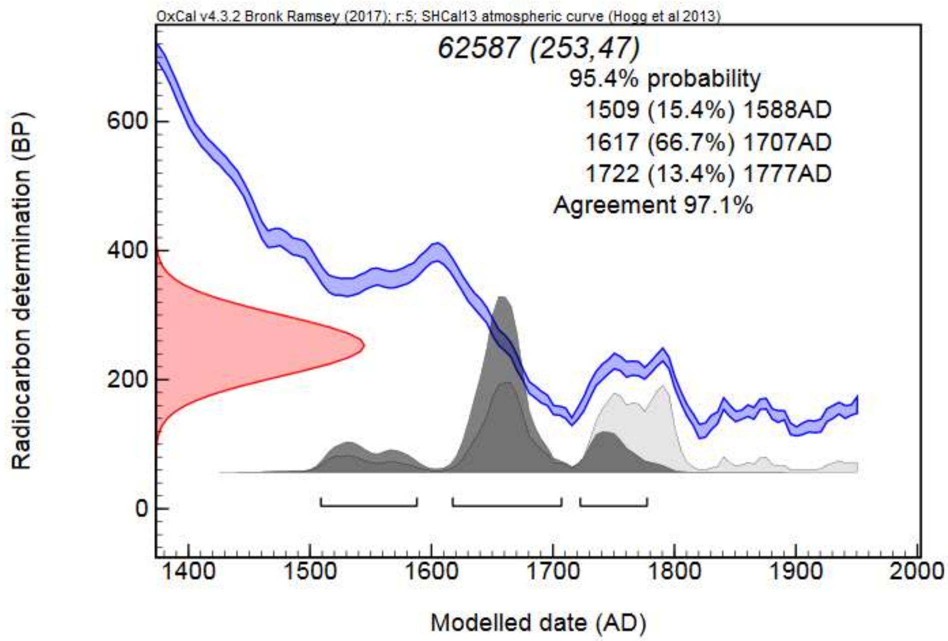

OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
61665 (2100,23)
95.4% probability
144 (84.1%) 42BC
21BC (11.3%) 19AD
Agreement 99.7%
Radiocarbon determination (BP)
2400
2200
2000
1800
400
300
200
100
1BC/1AD
101
Modelled date (BC/AD)

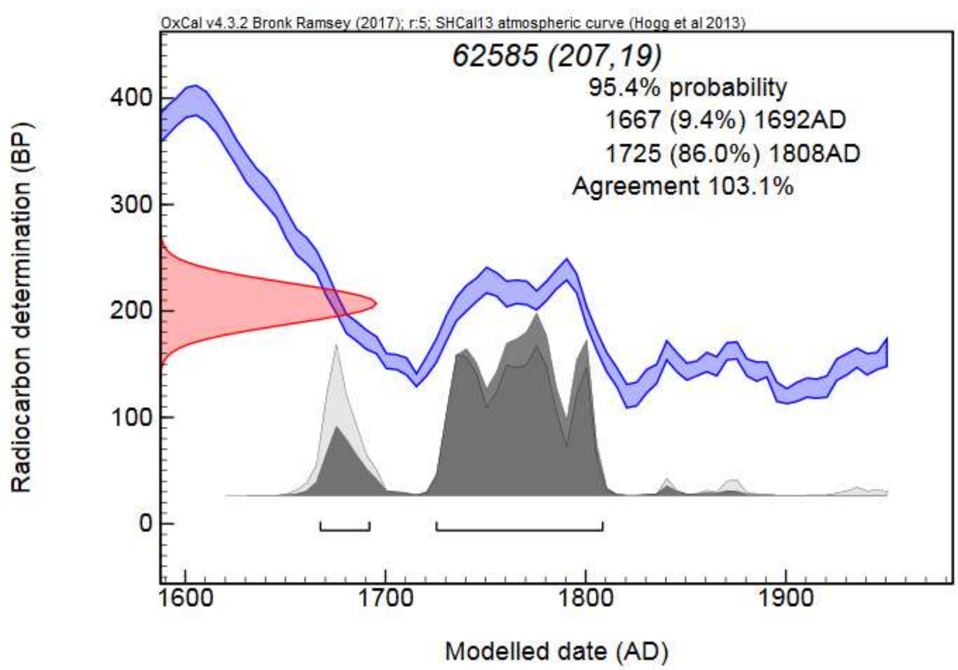


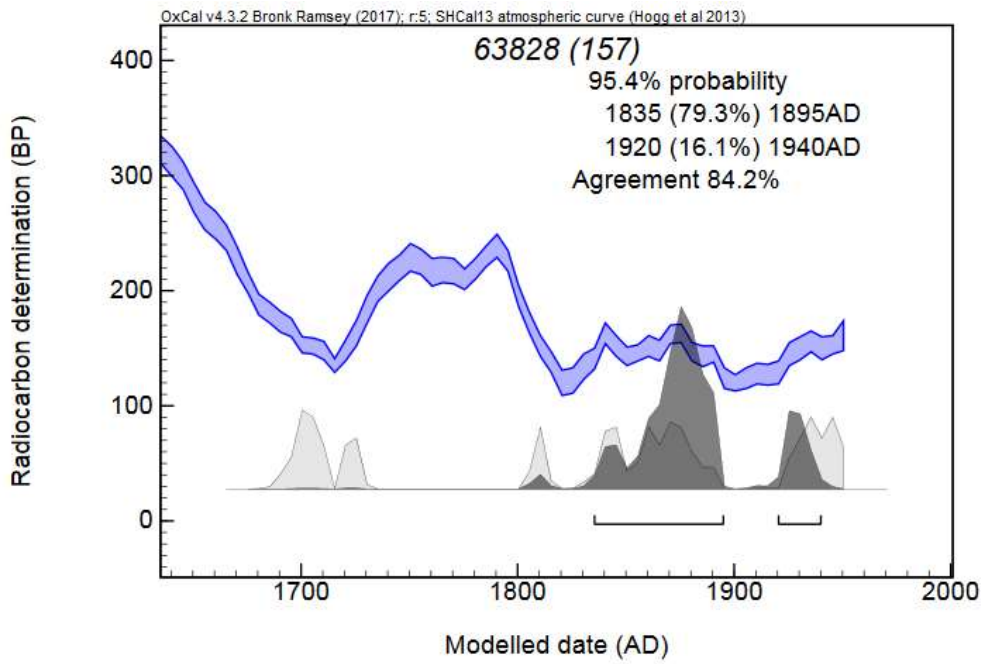
OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
63954 (1703,21)
95.4% probability
263 (0.4%) 267AD
340 (95.0%) 428AD
Agreement 99.2%
Radiocarbon determination (BP)
Modelled date (AD)

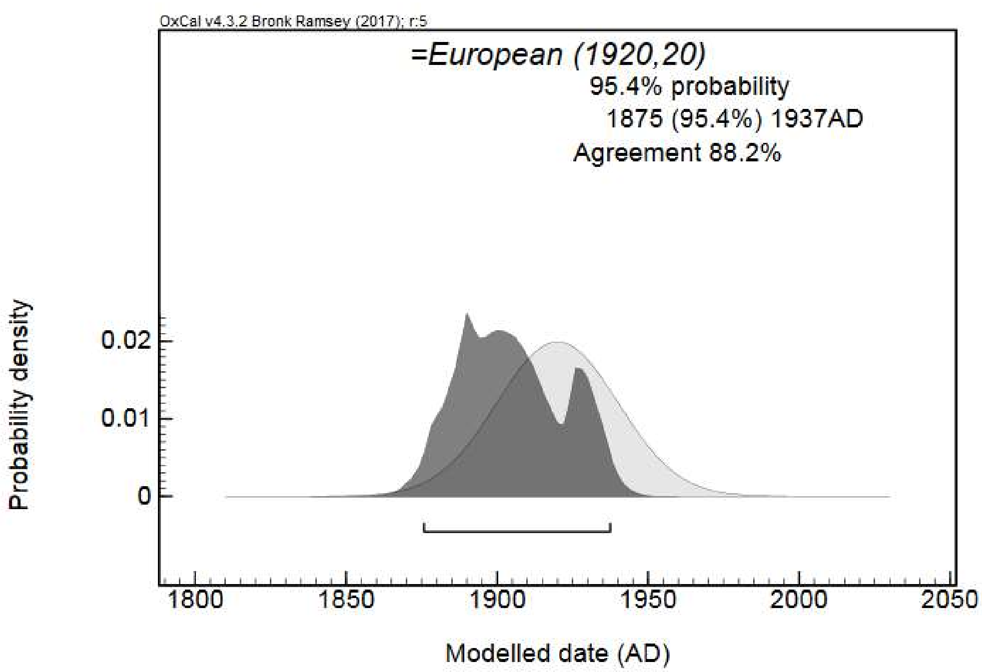


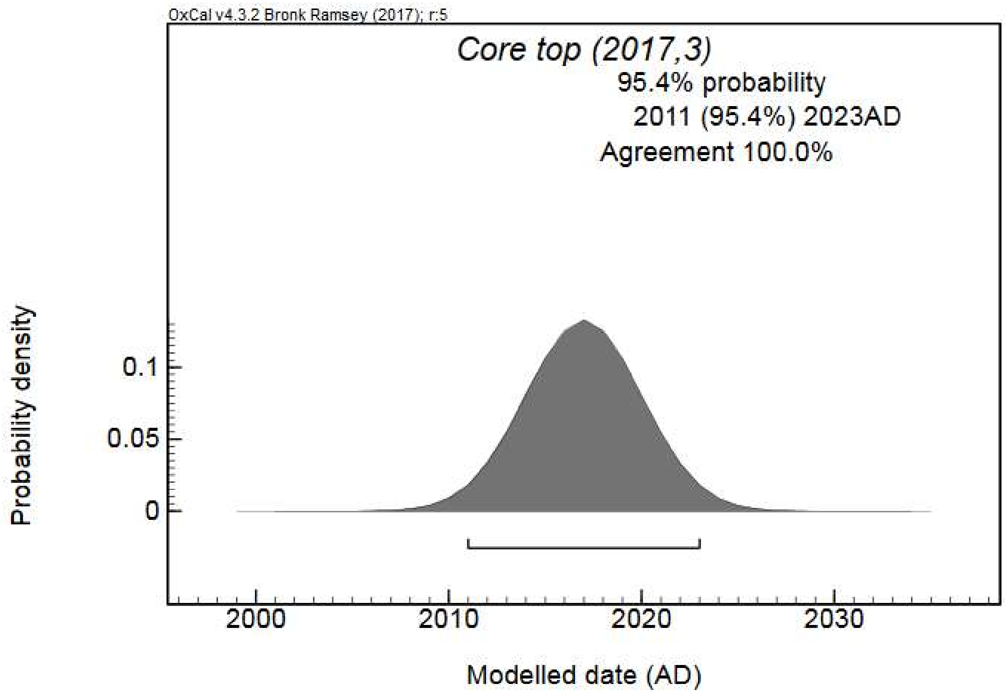
OxCal v4.3.2 Bronk Ramsey (2017); r:5
=human impact
95.4% probability
1164 (95.4%) 1278AD
Probability density
Modelled date (AD)


OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
62587 (253,47)
95.4% probability
1509 (15.4%) 1588AD
1617 (66.7%) 1707AD
1722 (13.4%) 1777AD
Agreement 97.1%
Radiocarbon determination (BP)
Modelled date (AD)


OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
62585 (207,19)
95.4% probability
1667 (9.4%) 1692AD
1725 (86.0%) 1808AD
Agreement 103.1%
Radiocarbon determination (BP)
Modelled date (AD)


OxCal v4.3.2 Bronk Ramsey (2017); r:5; SHCal13 atmospheric curve (Hogg et al 2013)
63828 (157)
95.4% probability
1835 (79.3%) 1895AD
1920 (16.1%) 1940AD
Agreement 84.2%
Radiocarbon determination (BP)
400
300
200
100
0
1700
1800
1900
2000
Modelled date (AD)


OxCal v4.3.2 Bronk Ramsey (2017); r:5
=European (1920,20)
95.4% probability
1875 (95.4%) 1937AD
Agreement 88.2%
Probability density
0.02
0.01
0
1800
1850
1900
1950
2000
2050
Modelled date (AD)



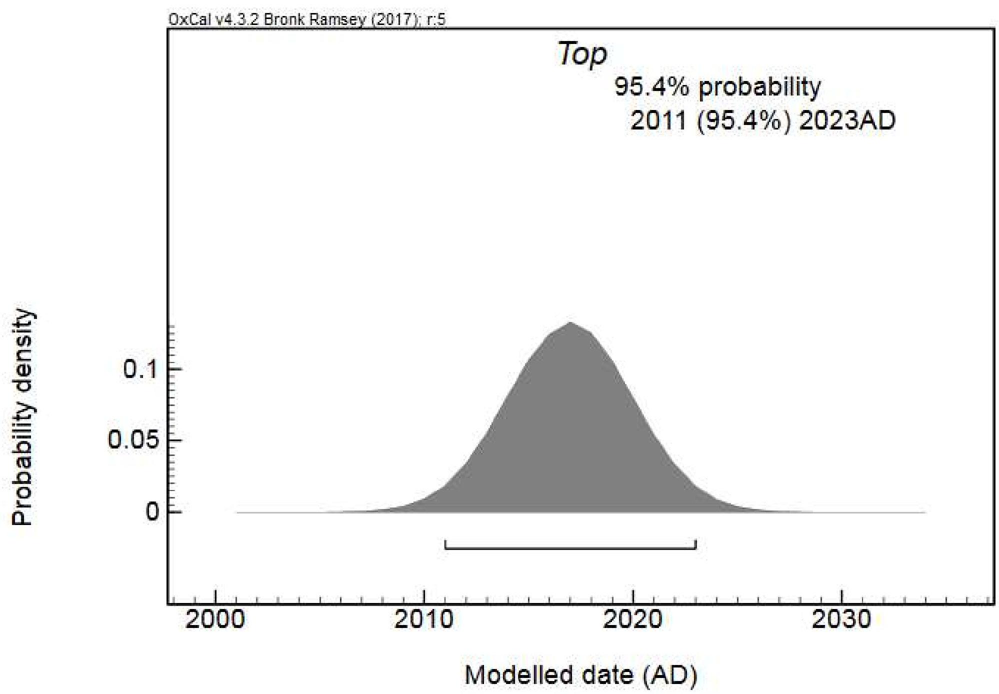


Figure B.1 PDFs of individual samples and other likelihoods from the age-depth model

B.2 OxCal Code for age-depth model

```
Options()
 {
  Curve="ShCal13.14c";
 };
 Plot()
 {
  P_Sequence("Roto17", 1, 2, U(-2,2))
  {
   Boundary("Bottom")
   {
   z=70.1;
   };
   R_Date("61839", 2299, 21)
   {
    z=70;
   };
   R_Date("63022", 2265, 21)
   {
    z=62.5;
   };
   R_Date("64147", 1215, 21)
   {
   z=45.5;
   };
   Boundary("human impact")
   {
    z=38.5;
   };
   R_Date("63959", 845, 21)
   {
    z=38;
   };
   R_Date("63831", 738, 30)
   {
    z=34.5;
   };
   R_Date("63830", 441, 50)
   {
    z=31.5;
   };
   R_Date("64143", 281, 29)
   {
    z=29;
   };
   R_Date("64142", 339, 20)
   {
    z=25;
```

```
 };
 R_Date("63960", 327, 21)
 {
  z=23;
 };
 R_Date("63457", 324, 20)
 {
  z=20;
 };
 R_Date("63829", 270, 34)
 {
  z=19;
 };
 Date("European", N(1920, 20))
 {
  z=12;
 };
 C_Date("63458", 1955.5, 0.5)
 {
  z=1.0;
 };
 C_Date("Core top", 2017, 3)
 {
  z=0;
 };
 Boundary("Top");
};
P_Sequence("Ngatu", 1, 2, U(-2,2))
{
 Boundary("Bottom")
 {
  z=70.1;
 };
 R_Date("64141", 3344, 102)
 {
  z=70;
 };
 R_Date("61666", 2783, 24)
 {
  z=46;
 };
 R_Date("63955", 2418, 22)
 {
  z=40;
 };
 R_Date("61665", 2100, 23)
 {
  z=36;
 };
 R_Date("63954", 1703, 21)
 {
```

```
   z=33;
  };
  Boundary("=human impact")
  {
   z=27;
  };
  R_Date("62587", 253, 47)
  {
   z=16;
  };
  R_Date("62585", 207, 19)
  {
   z=11;
  };
  R_Date("63828", 157   28)
  {
   z=5.5;
  };
  Date("=European", N(1920, 20))
  {
   z=5;
  };
  C_Date("Core top", 2017, 3)
  {
   z=0;
  };
  Boundary("Top");
 };
};
```

Appendix C

Elemental and Isotopic Data

Table C.1 Elemental and isotopic carbon and nitrogen results for all samples measured

Sample ID	%C	Delta 13C (‰)	%N	Delta 15N (‰)	C-N Ratio	Sample ID	%C	Delta 13C (‰)	%N	Delta 15N (‰)	C-N Ratio
NGAT16-4.5cm-U	7.052442	-21.038	0.61668	-0.83	11.43614953	ROTO17-0cm-U	23.18801	-24.64	1.959195	1.46	11.8354807
NGAT16 5.5cm U	14.4752	-21.44	1.132607	-2.12	12.78042592	ROTO17-4.0cm-U	16.78187	-22.69	1.365981	-0.35	12.2855815
NGAT16 7.0cm U	17.21609	-21.23	1.29028	-0.86	13.34291487	ROTO17-7.0cm-U	14.90292	-20.32	1.358692	0.11	10.9685774
NGAT16 10.0cm U	8.907841	-18.7	0.810989	-0.48	10.98391761	ROTO17-12.0cm-U	15.16591	-19.41	1.46617	0.02	10.3438969
NGAT16 14.0cm U	19.77067	-20.13	1.573643	-1.12	12.56362829	ROTO17-16.0cm-U	16.74784	-18.89	1.604936	-0.41	10.4352109
NGAT16 16.0cm U	17.53019	-20.32	1.437762	-1.02	12.19269439	ROTO17-18.0cm-U	14.46774	-18.71	1.376772	-0.45	10.5084481
NGAT16 18.0cm U	18.38927	-20.21	1.550576	-0.43	11.85964107	ROTO17-22.0cm-U	15.86931	-18.9	1.482748	-0.25	10.7026375
NGAT16 19.0cm U	16.46799	-20.15	1.490662	0.88	11.04743447	ROTO17-25.0cm-U	6.827591	-20.01	0.613665	1.44	11.1259299
NGAT16 21.0cm U	11.16975	-22.59	0.941946	1.39	11.85815548	ROTO17-29.0cm-U	6.522063	-23.08	0.498257	1.35	13.0897529
NGAT16 22.0cm U	12.92253	-23.17	0.977903	-0.06	13.21452516	ROTO17-33.0cm-U	19.75979	-26.24	1.118576	2.17	17.6651312
NGAT16 23.5cm U	8.561159	-26.13	0.601768	2.59	14.22668561	ROTO17-38.0cm-U	23.24043	-28.07	1.060994	2.17	21.904403
NGAT16 25.0cm U	17.96029	-26.69	1.110122	3.7	16.17866084	ROTO17-43.0cm-U	25.36243	-28.36	1.084363	2.74	23.3892464
NGAT16 27.5cm U	26.65555	-27.7	1.428301	3.88	18.66241348	ROTO17-47.0cm-U	31.35625	-28.31	1.311406	2.06	23.9104101
NGAT16 30.0cm U	24.10571	-28.01	1.318817	3.98	18.27828299	ROTO17-56.0cm-U	20.0125	-28.12	0.82276	1.71	24.3236199
NGAT16 32.0cm U	20.87713	-27.9	1.170174	3.28	17.84104575	ROTO16 60.0cm U	28.37716	-28.45	1.266328	2.14	22.4090017
NGAT16 34.0cm U	18.83124	-28.3	1.031423	3.3	18.2575334	ROTO16-68.0cm-U	27.53013	-28.43	1.105362	1.9	24.9059956
NGAT16 40.0cm U	19.4406	-28.07	1.073769	4.35	18.10501251	ROTO16-79.0cm-U	31.01198	-28.2	1.224779	2.12	25.3204688
Sample ID	%C	Delta 13C (‰)	%N	Delta 15N (‰)	C-N Ratio	Sample ID	%C	Delta 13C (‰)	%N	Delta 15N (‰)	C-N Ratio
NGAT16 4.5cm T	8.726333	-20.97	0.759309	-1.58	14.15050867	ROTO17 0 cm T	23.38836	-24.56	1.938078	1.62	11.9377398
NGAT16 5.5cm T	13.44289	-21.33	1.06884	-0.3	11.8689782	ROTO17 4.0cm T	19.88982	-22.55	1.613145	-0.22	14.5608294
NGAT16 7.0cm T	17.14004	-21.29	1.338301	-1.11	13.28397015	ROTO17 7.0cm T	13.19097	-20.22	1.225073	0.1	9.70857838
NGAT16 10.0cm T	10.6679	-18.94	0.944719	-0.29	13.15417972	ROTO17 12.0cm T	15.48239	-19.35	1.501988	0.15	10.5597551
NGAT16 14.0cm T	17.76779	-20.19	1.469219	-0.85	11.290863	ROTO17 16.0cm T	20.4812	-18.68	1.954603	-0.47	12.7613868
NGAT16 16.0cm T	16.58135	-20.22	1.398822	-0.76	11.53275276	ROTO17 18.0cm T	16.55751	-18.63	1.550317	-0.56	12.0263235
NGAT16 18.0cm T	20.29111	-20.36	1.709288	-0.14	13.0861771	ROTO17 22.0cm T	13.18903	-19.04	1.244063	-0.31	8.89499232
NGAT16 19.0cm T	16.07323	-20.22	1.468736	0.88	10.78261138	ROTO17 25.0cm T	5.891611	-19.94	0.534943	1.53	9.60069856
NGAT16 21.0cm T	12.36413	-22.77	0.979918	1.14	13.12615005	ROTO17 29.0cm T	3.922179	-23.15	0.309254	0.99	7.87179691
NGAT16 22.0cm T	14.97212	-23.02	1.096621	1.41	15.3104271	ROTO17 33.0cm T	22.04033	-26.29	1.22369	1.84	19.7039208
NGAT16 23.5cm T	7.976526	-25.97	0.534817	1.92	13.2551587	ROTO17 38.0cm T	22.70703	-28.03	1.053868	1.66	21.4016656
NGAT16 25.0cm T	18.53823	-26.76	1.095898	3.82	16.69926848	ROTO17 43.0cm T	23.90924	-28.32	1.038944	2.3	22.049114
NGAT16 27.5cm T	25.77084	-27.72	1.394924	3.18	18.04299896	ROTO17 47.0cm T	30.49172	-28.31	1.268835	1.78	23.2511687
NGAT16 30.0cm T	24.94183	-27.98	1.342403	4.18	18.91228013	ROTO16 56.0cm T	27.35174	-28.45	1.19141	2.02	21.5992461
NGAT16 32.0cm T	19.92774	-27.81	1.076871	2.69	17.02972046	ROTO17 60.0cm T	20.67541	-28.16	0.839907	1.73	25.1293351
NGAT16 34.0cm T	20.02136	-28.13	1.049107	3.59	19.41140213	ROTO16 68.0cm T	29.45382	-28.33	1.183867	1.55	26.6463247
NGAT16 40.0cm T	19.65379	-28.04	1.038628	4.09	18.30355903	ROTO16 79.0cm T	27.51237	-28.28	1.127222	1.72	22.4631256
Sample ID	%C	Delta 13C (‰)	%N	Delta 15N (‰)	C-N Ratio	Sample ID	%C	Delta 13C (‰)	%N	Delta 15N (‰)	C-N Ratio
NGAT16 4.5cm T-2	7.779279	-20.9	0.685764	-1.59	12.61477854	ROTO17 7.0cm T-2	12.9863	-20.3	1.201491	-0.09	9.55793943
NGAT16 7.0cm T-2	16.48082	-21.41	1.214593	-0.12	12.77305757	ROTO17 18.0cm T-2	14.04047	-18.67	1.341554	-0.55	10.1981096
NGAT16 16.0cm T-2	15.48611	-20.34	1.280384	-0.56	10.77098809	ROTO17 29.0cm T-2	5.577769	-23.06	0.430192	1.44	11.1945594
NGAT16 22.0cm T-2	13.47366	-23.03	0.946041	1.5	13.77811729	ROTO17 47.0cm T-2	32.26228	-28.34	1.338069	2.45	24.601289
NGAT16 27.5cm T-2	25.55383	-27.48	1.341246	3.03	17.89106884						
NGAT16 32.0cm T-2	19.36485	-27.64	1.035027	4.2	16.54868559						

Description of Elemental and Isotopic Results by Depth

The $\delta^{13}C$ values of the treated and untreated sediment from corresponding depths were statistically the same, indicating that overall there was very limited to no carbonate material in the sediments. The inclusion of carbonate would be evidenced by heavier $\delta^{13}C$ values associated with carbonate matter in the untreated sediments compared to the treated. The uniformity of the values suggests that acidification to remove calcium carbonate from the sediments was not required, therefore, the untreated C:N ratios and percent carbon are used for the archaeological and environmental interpretations of the lake basins.

Elemental and isotopic data through the cores in each lake was similar with both carbon and nitrogen values shifting from higher elemental percentages deep in the core to much lower values at mid-core depths. This transition is also marked by the $\delta^{13}C$ values becoming ~10‰ (-28‰ to -18‰) heavier through roughly 5cm of depth while the $\delta^{15}N$ values lighten by 2-3‰ in both lakes. After the mid-core decline in elemental carbon and nitrogen, the values fluctuate but remain lower than pre-impact through several centimetres of depth while in the top centimetres of the cores the carbon percentages begin to return to basal values (>20%). In both lakes the nitrogen values from the tops of the cores are even higher than those measured in pre-impact sediments, 2 to 2.5% compared to 1.3 to 1.5%. Largely the elemental carbon and nitrogen values show a positive correlation, and the isotopic data a negative correlation.

Both lakes experienced a step change of a ~10‰ decline in their C:N ratios through just 5-10cm of depth the lowest C:N ratios corresponding to the heaviest $\delta^{13}C$ values recorded in both lakes. C:N ratios in Lake Ngatu range between 20 and 10 while values from Lake Rotoroa drift from 24 at the base of the core to 10 near the top. Neither lake has yet returned to the C:N values measured from sediments prior to impact.

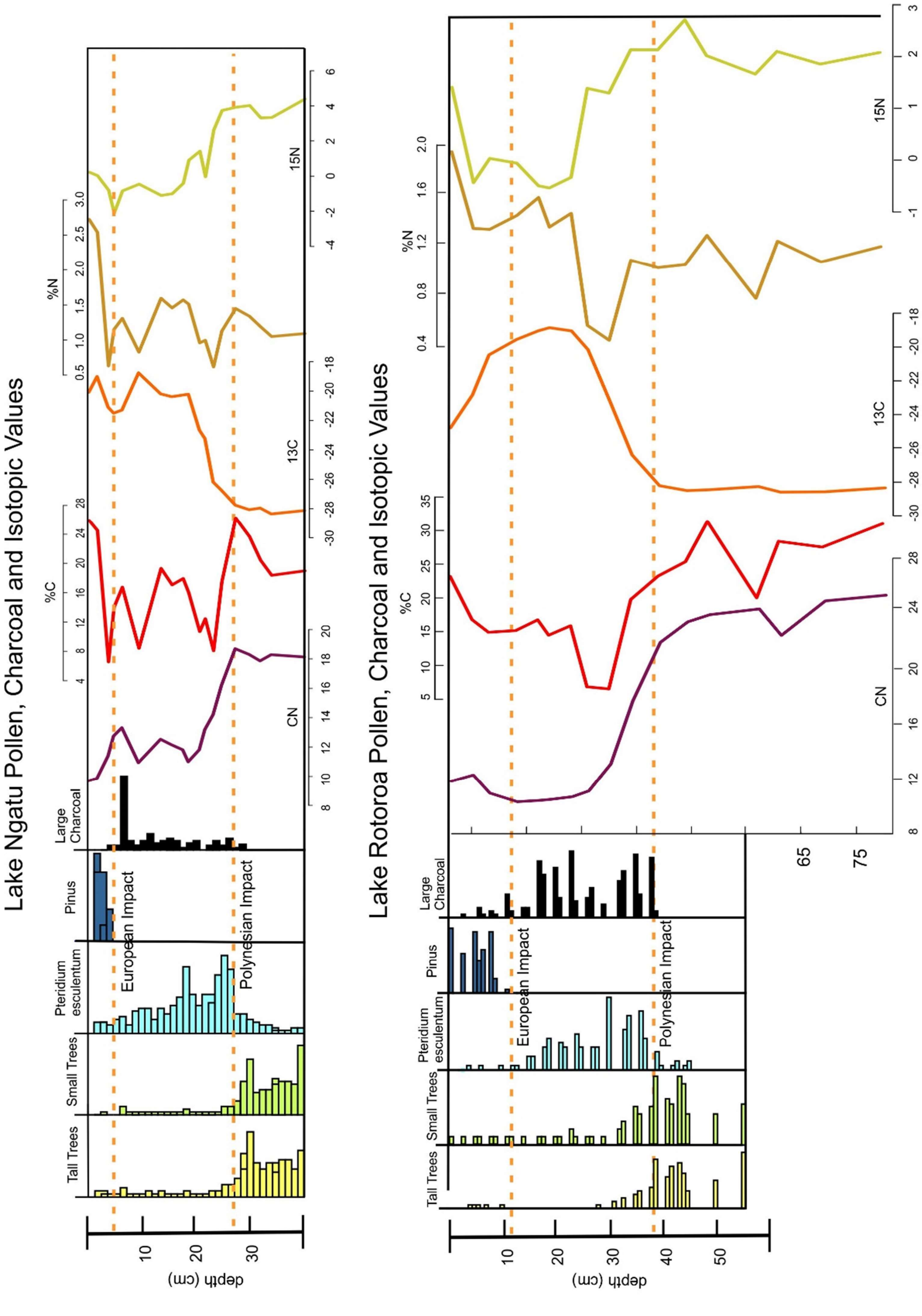


Figure C.1. Elemental and isotopic data next to pollen and charcoal identifications for Lakes Ngatu and Rotoroa by depth

Appendix D.

XRF Data

Table D.1 Ngatu XRF results

Sample ID	Al corrected	Si corrected	Si:Al	P corrected	P:Al	S corrected	S:Al	K corrected	K:Al	Ca corrected	Ca:Al
Ngatu 4.0cm	62133.4	186098.7	2.995	676.0	0.011	16550.0	0.266	9479.3	0.153	10603.2	0.171
Ngatu 5.0cm	61615.3	166380.1	2.700	715.3	0.012	18845.0	0.306	8827.9	0.143	9079.5	0.147
Ngatu 6.0cm	62596.9	164004.0	2.620	606.2	0.010	19893.0	0.318	8583.0	0.137	8919.2	0.142
Ngatu 7.0cm	60701.3	162579.8	2.678	744.4	0.012	22546.0	0.371	8475.9	0.140	9001.9	0.148
Ngatu 8.0cm	61004.8	162673.6	2.667	680.4	0.011	23161.0	0.380	8830.8	0.145	8259.7	0.135
Ngatu 9.0cm	59777.2	190544.7	3.188	545.1	0.009	18276.0	0.306	9869.6	0.165	9807.6	0.164
Ngatu 10.0cm	60136.1	187405.2	3.116	847.7	0.014	20245.0	0.337	9947.1	0.165	9832.8	0.164
Ngatu 11.0cm	61116.7	173172.9	2.833	1157.6	0.019	22223.0	0.364	9495.6	0.155	9369.9	0.153
Ngatu 12.0cm	58024.1	180224.1	3.106	1007.7	0.017	18993.0	0.327	9401.9	0.162	9707.8	0.167
Ngatu 13.0cm	57710.5	148029.9	2.565	1368.5	0.024	24680.0	0.428	8130.5	0.141	8202.2	0.142
Ngatu 14.0cm	55801.1	157117.4	2.816	1032.5	0.019	21238.0	0.381	8467.3	0.152	8970.6	0.161
Ngatu 15.0cm	55304.3	146872.0	2.656	1161.9	0.021	21182.0	0.383	8320.9	0.150	8273.8	0.150
Ngatu 16.0cm	52306.1	131635.6	2.517	1294.3	0.025	20221.0	0.387	7971.7	0.152	7973.3	0.152
Ngatu 17.0cm	56641.1	164386.2	2.902	1356.9	0.024	21209.0	0.374	9363.6	0.165	9763.2	0.172
Ngatu 18.0cm	55731.7	150658.1	2.703	1541.6	0.028	22527.0	0.404	8614.6	0.155	9588.8	0.172
Ngatu 19.0cm	63041.9	192411.2	3.052	1710.4	0.027	21144.0	0.335	10464.6	0.166	14014.6	0.222
Ngatu 21.0cm	59693.0	164384.4	2.754	1163.4	0.019	22542.0	0.378	9107.2	0.153	7697.0	0.129
Ngatu 22.0cm	57466.3	199126.2	3.465	630.9	0.011	17960.0	0.313	10340.3	0.180	7969.3	0.139
Ngatu 23.0cm	58040.8	218843.9	3.771	335.6	0.006	15623.0	0.269	11901.5	0.205	9473.8	0.163
Ngatu 24.0cm	55180.4	184503.8	3.344	513.1	0.009	17417.0	0.316	9769.2	0.177	6299.4	0.114
Ngatu 25.0cm	55617.0	167654.8	3.014	591.7	0.011	17747.0	0.319	9503.3	0.171	7016.3	0.126
Ngatu 26.0cm	55080.4	158301.0	2.874	587.3	0.011	19078.0	0.346	9147.4	0.166	6970.0	0.127
Ngatu 27.0cm	55446.8	150908.4	2.722	475.3	0.009	19219.0	0.347	9236.4	0.167	6904.4	0.125
Ngatu 28.0cm	56975.0	158750.4	2.786	465.1	0.008	19393.0	0.340	9542.5	0.167	7184.7	0.126
Ngatu 29.0cm	56022.2	154965.2	2.766	462.2	0.008	16168.0	0.289	9309.1	0.166	5576.3	0.100
Ngatu 30.0cm	57904.8	162888.6	2.813	524.7	0.009	16396.0	0.283	9704.1	0.168	6322.6	0.109
Ngatu 31.0cm	56968.6	160295.8	2.814	585.8	0.010	11499.0	0.202	9434.4	0.166	5736.7	0.101
Ngatu 32.0cm	67142.8	205827.0	3.066	948.1	0.014	14739.0	0.220	11877.5	0.177	9083.6	0.135
Ngatu 33.0cm	61087.1	177662.3	2.908	581.5	0.010	11425.0	0.187	10429.3	0.171	7497.3	0.123
Ngatu 34.0cm	60711.5	170323.6	2.805	817.2	0.013	12173.0	0.201	10249.4	0.169	6807.6	0.112
Ngatu 35.0cm	62095.5	173019.0	2.786	655.7	0.011	11693.0	0.188	10056.2	0.162	6721.9	0.108
Ngatu 36.0cm	61023.3	165330.0	2.709	665.9	0.011	12740.0	0.209	9706.1	0.159	6691.6	0.110
Ngatu 37.0cm	60713.4	158937.0	2.618	683.3	0.011	12818.0	0.211	9387.5	0.155	6865.1	0.113
Ngatu 38.0cm	60801.3	160590.4	2.641	840.4	0.014	13276.0	0.218	9329.2	0.153	6987.1	0.115
Ngatu 39.0cm	60480.2	165386.7	2.735	818.6	0.014	13330.0	0.220	9192.4	0.152	6837.8	0.113
Ngatu 40.0cm	59563.5	166597.7	2.797	775.0	0.013	14085.0	0.236	9262.2	0.156	7708.1	0.129
Ngatu 41.0cm	59332.2	148708.4	2.506	648.4	0.011	16453.0	0.277	8512.2	0.143	6406.3	0.108
Ngatu 42.0cm	58897.4	145653.9	2.473	769.1	0.013	18470.0	0.314	8580.1	0.146	7054.7	0.120
Ngatu 43.0cm	58521.8	144213.8	2.464	734.2	0.013	17380.0	0.297	8533.3	0.146	6925.6	0.118
Ngatu 44.0cm	56173.0	133281.9	2.373	460.7	0.008	15562.0	0.277	7721.1	0.137	6405.2	0.114
Ngatu 45.0cm	57111.0	143702.5	2.516	604.8	0.011	16119.0	0.282	8130.5	0.142	6909.4	0.121
Ngatu 46.0cm	57015.7	149390.4	2.620	649.9	0.011	15728.0	0.276	8194.6	0.144	6802.6	0.119
Ngatu 47.0cm	55758.5	147572.6	2.647	657.1	0.012	16478.0	0.296	8432.8	0.151	5515.8	0.099
Ngatu 48.0cm	58906.7	154384.9	2.621	712.4	0.012	15745.0	0.267	8695.9	0.148	6408.3	0.109
Ngatu 49.0cm	51251.5	134721.1	2.629	537.8	0.010	13881.0	0.271	7856.0	0.153	5361.6	0.105

Table D.1 Ngatu XRF results continued

Sample ID	Ti Corrected	Ti:Al	Fe corrected	Fe:Al	Mn corrected	Mn:Al	Zr corrected	Zr: Al	Ca/Ti	Fe/Mn	Si/Ti	Ti/Zr
Ngatu 4.0cm	4169.2	0.067	23645.5	0.381	373.48	0.0060	236.93	0.00381	2.543	63.311	44.637	17.597
Ngatu 5.0cm	3949.7	0.064	24724.1	0.401	267.13	0.0043	257.70	0.00418	2.299	92.556	42.124	15.327
Ngatu 6.0cm	3712.8	0.059	25422.6	0.406	304.86	0.0049	242.35	0.00387	2.402	83.390	44.173	15.320
Ngatu 7.0cm	3848.8	0.063	26011.4	0.429	327.74	0.0054	248.67	0.00410	2.339	79.367	42.242	15.477
Ngatu 8.0cm	3219.3	0.053	25501.0	0.418	177.92	0.0029	159.25	0.00261	2.566	143.325	50.531	20.215
Ngatu 9.0cm	3770.5	0.063	25131.7	0.420	284.28	0.0048	159.25	0.00266	2.601	88.405	50.536	23.676
Ngatu 10.0cm	3325.4	0.055	23279.1	0.387	272.84	0.0045	175.51	0.00292	2.957	85.320	56.355	18.947
Ngatu 11.0cm	3034.9	0.050	23586.7	0.386	256.83	0.0042	162.87	0.00266	3.087	91.837	57.060	18.634
Ngatu 12.0cm	3731.3	0.064	22907.8	0.395	260.26	0.0045	158.35	0.00273	2.602	88.017	48.300	23.564
Ngatu 13.0cm	2776.3	0.048	22118.1	0.383	131.04	0.0023	133.06	0.00231	2.954	168.793	53.319	20.865
Ngatu 14.0cm	2644.5	0.047	21353.0	0.383	136.76	0.0025	159.25	0.00285	3.392	156.140	59.414	16.605
Ngatu 15.0cm	3052.4	0.055	21191.3	0.383	144.76	0.0026	121.32	0.00219	2.711	146.389	48.117	25.160
Ngatu 16.0cm	3041.1	0.058	20491.8	0.392	131.04	0.0025	114.09	0.00218	2.622	156.382	43.286	26.654
Ngatu 17.0cm	3041.1	0.054	20062.7	0.354	197.37	0.0035	162.87	0.00288	3.210	101.652	54.055	18.672
Ngatu 18.0cm	3200.8	0.057	20174.4	0.362	206.51	0.0037	132.16	0.00237	2.996	97.690	47.069	24.219
Ngatu 19.0cm	4907.8	0.078	25170.9	0.399	437.52	0.0069	218.86	0.00347	2.856	57.531	39.205	22.424
Ngatu 21.0cm	3491.3	0.058	21191.3	0.355	193.94	0.0032	224.28	0.00376	2.205	109.270	47.084	15.566
Ngatu 22.0cm	4038.3	0.070	21984.9	0.383	306.01	0.0053	220.67	0.00384	1.973	71.844	49.309	18.300
Ngatu 23.0cm	4175.3	0.072	22445.3	0.387	347.18	0.0060	247.77	0.00427	2.269	64.651	52.413	16.852
Ngatu 24.0cm	3770.5	0.068	20198.9	0.366	164.20	0.0030	175.51	0.00318	1.671	123.013	48.934	21.483
Ngatu 25.0cm	2974.1	0.053	17620.3	0.317	95.59	0.0017	141.19	0.00254	2.359	184.341	56.371	21.065
Ngatu 26.0cm	2845.3	0.052	16042.0	0.291	40.69	0.0007	108.67	0.00197	2.450	394.222	55.635	26.182
Ngatu 27.0cm	2806.2	0.051	14421.6	0.260	0.67	0.0000	103.25	0.00186	2.460	21628.062	53.777	27.177
Ngatu 28.0cm	2910.3	0.051	13731.9	0.241	2.95	0.0001	89.71	0.00157	2.469	4648.573	54.549	32.442
Ngatu 29.0cm	2800.0	0.050	12433.8	0.222	0.00	0.0000	91.51	0.00163	1.992	0.000	55.344	30.597
Ngatu 30.0cm	2923.6	0.050	14043.4	0.243	0.00	0.0000	91.51	0.00158	2.163	0.000	55.714	31.948
Ngatu 31.0cm	2971.0	0.052	12646.4	0.222	1.81	0.0000	96.93	0.00170	1.931	6985.404	53.953	30.651
Ngatu 32.0cm	4307.2	0.064	17185.3	0.256	135.61	0.0020	124.03	0.00185	2.109	126.725	47.787	34.728
Ngatu 33.0cm	3257.4	0.053	13996.4	0.229	68.14	0.0011	123.13	0.00202	2.302	205.409	54.541	26.456
Ngatu 34.0cm	3285.2	0.054	15329.8	0.253	169.92	0.0028	134.87	0.00222	2.072	90.218	51.845	24.359
Ngatu 35.0cm	3084.4	0.050	13975.8	0.225	38.41	0.0006	117.71	0.00190	2.179	363.901	56.096	26.204
Ngatu 36.0cm	2876.3	0.047	13586.9	0.223	0.00	0.0000	96.93	0.00159	2.327	0.000	57.481	29.673
Ngatu 37.0cm	2817.5	0.046	13271.4	0.219	0.00	0.0000	96.93	0.00160	2.437	0.000	56.410	29.067
Ngatu 38.0cm	3019.5	0.050	13933.7	0.229	23.54	0.0004	95.13	0.00156	2.314	591.946	53.185	31.742
Ngatu 39.0cm	2600.2	0.043	13926.8	0.230	32.69	0.0005	107.77	0.00178	2.630	426.059	63.606	24.127
Ngatu 40.0cm	2839.2	0.048	14627.3	0.246	54.42	0.0009	109.58	0.00184	2.715	268.806	58.678	25.910
Ngatu 41.0cm	2641.4	0.045	16189.0	0.273	12.10	0.0002	93.32	0.00157	2.425	1337.622	56.300	28.305
Ngatu 42.0cm	2638.3	0.045	17268.6	0.293	16.68	0.0003	87.90	0.00149	2.674	1035.462	55.208	30.014
Ngatu 43.0cm	2774.3	0.047	16540.7	0.283	13.25	0.0002	84.29	0.00144	2.496	1248.693	51.983	32.914
Ngatu 44.0cm	2359.1	0.042	13944.5	0.248	0.00	0.0000	75.26	0.00134	2.715	0.000	56.497	31.348
Ngatu 45.0cm	2358.1	0.041	13659.4	0.239	0.00	0.0000	81.58	0.00143	2.930	0.000	60.941	28.906
Ngatu 46.0cm	2301.4	0.040	13568.3	0.238	0.00	0.0000	80.67	0.00141	2.956	0.000	64.913	28.527
Ngatu 47.0cm	2635.2	0.047	14662.6	0.263	0.00	0.0000	77.06	0.00138	2.093	0.000	56.001	34.196
Ngatu 48.0cm	2768.1	0.047	14727.3	0.250	4.10	0.0001	88.80	0.00151	2.315	3594.118	55.773	31.171
Ngatu 49.0cm	2470.4	0.048	12977.5	0.253	0.00	0.0000	72.55	0.00142	2.170	0.000	54.535	34.052

Table D.2 Rotoroa XRF Results

Sample ID	Al corrected	Si corrected	Si:Al	P corrected	P:Al	S corrected	S:Al	K corrected	K:Al	Ca Corrected	Ca:Al
ROTO17-2cm	47806.18	94448.02	1.97564	3648.738	0.07632	15521	0.32467	7709.63	0.1613	16008.734	0.3349
ROTO17-3cm	53954.96	109041.8	2.02098	3044.785	0.05643	15594	0.28902	8261.796	0.1531	15644.102	0.2899
ROTO17-4cm	53603.57	121761.6	2.27152	2468.078	0.04604	14065	0.26239	8763.765	0.1635	15217.065	0.2839
ROTO17-5cm	54651.26	121427.1	2.22185	2374.987	0.04346	15236	0.27879	8496.048	0.1555	15279.469	0.2796
ROTO17-6cm	55316.19	182388.7	3.29720	1319.205	0.02385	13519	0.24439	9990.371	0.1806	14872.01	0.2689
ROTO17-7cm	53178.66	157085.2	2.95391	1732.436	0.03258	14922	0.28060	8958.117	0.1685	15381.028	0.2892
ROTO17-8cm	47662.38	147549.4	3.09572	2016.248	0.04230	14957	0.31381	8564.264	0.1797	15310.059	0.3212
ROTO17-9cm	45533.5	132323.7	2.90607	2774.595	0.06094	15310	0.33624	8998.017	0.1976	16368.473	0.3595
ROTO17-10cm	45954.08	149813.2	3.26006	1836.879	0.03997	14875	0.32369	9741.961	0.2120	15520.518	0.3377
ROTO17-11cm	37347.73	112164.6	3.00325	1419.107	0.03800	14902	0.39901	7928.437	0.2123	14189.241	0.3799
ROTO17-12cm	36567.11	101481.4	2.77521	1478.14	0.04042	18265	0.49949	7681.314	0.2101	14371.558	0.3930
ROTO17-13cm	34652.3	110348.3	3.18445	1353.262	0.03905	16531	0.47705	7878.24	0.2274	14214.937	0.4102
ROTO17-14cm	36899.03	115656.5	3.13441	2059.388	0.05581	17048	0.46202	8057.147	0.2184	14841.42	0.4022
ROTO17-15cm	42096.36	154236.8	3.66390	1110.319	0.02638	14847	0.35269	10027.7	0.2382	15204.829	0.3612
ROTO17-16cm	33578.67	103417.6	3.07986	1230.655	0.03665	18074	0.53826	7671.017	0.2284	13423.268	0.3998
ROTO17-17cm	33748.42	102063.8	3.02425	1142.106	0.03384	17135	0.50773	7376.271	0.2186	13398.796	0.3970
ROTO17-18cm	34001.42	101712	2.99141	1412.295	0.04154	16988	0.49963	7022.319	0.2065	13551.746	0.3986
ROTO17-19cm	27879.66	89453.51	3.20856	381.488	0.01368	16317	0.58527	6506.192	0.2334	13658.199	0.4899
ROTO17-20cm	40052.89	132567	3.30980	2104.798	0.05255	21023	0.52488	9390.583	0.2345	14816.948	0.3699
ROTO17-21cm	35445.9	116586	3.28913	1861.854	0.05253	20119	0.56760	7163.9	0.2021	15363.897	0.4334
ROTO17-22cm	30599.96	100513.9	3.28477	1110.319	0.03628	20108	0.65712	6669.653	0.2180	13210.361	0.4317
ROTO17-23cm	41596.85	158186.5	3.80285	1346.451	0.03237	19673	0.47294	8725.152	0.2098	13830.726	0.3325
ROTO17-24cm	38533.81	120730.6	3.13311	1882.289	0.04885	20942	0.54347	7444.487	0.1932	14257.763	0.3700
ROTO17-25cm	41253.03	174913.7	4.24002	667.571	0.01618	12874	0.31207	9515.431	0.2307	12616.915	0.3058
ROTO17-26cm	46342.23	157683.7	3.40259	1830.067	0.03949	17432	0.37616	10541.25	0.2275	15028.631	0.3243
ROTO17-27cm	46835.26	202148.8	4.31617	1171.622	0.02502	11365	0.24266	11126.88	0.2376	12862.859	0.2746
ROTO17-28cm	41764.43	165419.4	3.96077	910.5145	0.02180	12194	0.29197	8977.424	0.2150	12160.512	0.2912
ROTO17-29cm	40997.86	138265	3.37249	1671.132	0.04076	17625	0.42990	8853.862	0.2160	13480.777	0.3288
ROTO17-30cm	44494.46	171187.7	3.84739	1098.966	0.02470	15780	0.35465	9485.828	0.2132	13516.261	0.3038
ROTO17-31cm	40082.09	153243.9	3.82325	1525.82	0.03807	15570	0.38845	7579.633	0.1891	12624.257	0.3150
ROTO17-32cm	36886.06	154608.2	4.19151	1696.108	0.04598	11991	0.32508	7465.081	0.2024	12802.902	0.3471
ROTO17-33cm	39903.69	170006.8	4.26043	1811.903	0.04541	10371	0.25990	7660.72	0.1920	12817.586	0.3212
ROTO17-34cm	41661.72	182543.3	4.38156	2499.865	0.06000	10567	0.25364	7797.153	0.1872	14409.489	0.3459
ROTO17-35cm	38025.64	162350.7	4.26951	2663.341	0.07004	9818	0.25819	7067.367	0.1859	13737.733	0.3613
ROTO17-36cm	34978.82	151415	4.32876	1832.338	0.05238	9154	0.26170	6977.27	0.1995	13625.162	0.3895
ROTO17-37cm	41201.13	180268	4.37532	1805.092	0.04381	7573	0.18381	8040.415	0.1952	14890.364	0.3614
ROTO17-38cm	38953.31	186983.1	4.80018	449.603	0.01154	6449	0.16556	7855.072	0.2017	13880.894	0.3563
ROTO17-39cm	37173.66	192799.8	5.18646	1010.417	0.02718	7712	0.20746	7266.868	0.1955	15691.822	0.4221
ROTO17-40cm	38698.15	177357.3	4.58310	976.359	0.02523	7592	0.19619	7541.02	0.1949	16695.174	0.4314
ROTO17-41cm	36159.49	162552.6	4.49543	1112.589	0.03077	6724	0.18595	7662.007	0.2119	17253.136	0.4771
ROTO17-42cm	34101.97	158946.5	4.66092	565.3985	0.01658	6756	0.19811	6909.054	0.2026	17340.011	0.5085
ROTO17-43cm	37483.96	176302.2	4.70340	1612.099	0.04301	7542	0.20121	7202.513	0.1921	15677.139	0.4182
ROTO17-44cm	30571.85	138517.6	4.53089	1133.024	0.03706	6725	0.21997	5212.656	0.1705	14553.874	0.4761
ROTO17-45cm	36573.59	157554.6	4.30788	1668.862	0.04563	8508	0.23263	5548.589	0.1517	15669.797	0.4284
ROTO17-46cm	33730.04	148224	4.39442	1198.868	0.03554	7352	0.21797	5740.367	0.1702	15126.519	0.4485
ROTO17-47cm	36509.8	143633.2	3.93410	2002.625	0.05485	7978	0.21852	5966.897	0.1634	15730.977	0.4309
ROTO17-48cm	33974.39	147102	4.32979	2272.815	0.06690	7008	0.20627	5647.696	0.1662	15639.207	0.4603
ROTO17-49cm	33506.23	126470.1	3.77452	1916.346	0.05719	6036	0.18015	5213.943	0.1556	16534.882	0.4935
ROTO17-50cm	31419.51	115059.2	3.66203	1882.289	0.05991	5595	0.17807	5013.156	0.1596	15823.971	0.5036
ROTO17-51cm	35645.92	123356.4	3.46060	1909.535	0.05357	6089	0.17082	5803.435	0.1628	16675.596	0.4678
ROTO17-52cm	33840.32	130051.9	3.84311	2443.102	0.07220	6307	0.18638	5179.191	0.1530	17117.316	0.5058
ROTO17-53cm	34148.46	117048.4	3.42763	2250.11	0.06589	6999	0.20496	5229.388	0.1531	17869.83	0.5233
ROTO17-54cm	34499.85	109951.6	3.18702	2297.79	0.06660	6462	0.18731	5156.024	0.1495	17440.346	0.5055
ROTO17-55cm	36258.96	103881.2	2.86498	2020.789	0.05573	5545	0.15293	6001.648	0.1655	17658.147	0.4870
ROTO17-56cm	40033.43	150700	3.76435	2200.159	0.05496	6570	0.16411	6660.644	0.1664	16972.931	0.4240

Table D.2 Rotoroa XRF Results continued

Sample ID	Ti corrected	Ti:Al	Fe corrected	Fe:Al	Mn corrected	Mn/Al	Zr corrected	Zr:Al	Ca/Ti	Fe/Mn	Si/Ti	Ti/Zr
ROTO17-2cm	1512.95	0.0316	19984.54	0.4180	95.5856	0.00200	70.4093	0.0015	10.5811	209.0748	62.4264	21.4879
ROTO17-3cm	2048.052	0.0380	20169.09	0.3738	142.4732	0.00264	99.1128	0.0018	7.6385	141.5641	53.2417	20.6638
ROTO17-4cm	2283.584	0.0426	20145.4	0.3758	169.9196	0.00317	109.7741	0.0020	6.6637	118.5584	53.3204	20.8026
ROTO17-5cm	2297.694	0.0420	24018	0.4395	196.2224	0.00359	95.8324	0.0018	6.6499	122.4019	52.8474	23.9762
ROTO17-6cm	2434.454	0.0440	24771	0.4478	205.3712	0.00371	104.0334	0.0019	6.1090	120.6158	74.9198	23.4007
ROTO17-7cm	3834.62	0.0721	27351.75	0.5143	263.6948	0.00496	130.2766	0.0024	4.0111	103.7250	40.9650	29.4345
ROTO17-8cm	2770.928	0.0581	26596.77	0.5580	193.9352	0.00407	117.9751	0.0025	5.5252	137.1425	53.2491	23.4874
ROTO17-9cm	2623.314	0.0576	23669.62	0.5198	295.7156	0.00649	166.361	0.0037	6.2396	80.0418	50.4414	15.7688
ROTO17-10cm	3183.38	0.0693	23181.11	0.5044	184.7864	0.00402	125.356	0.0027	4.8755	125.4481	47.0610	25.3947
ROTO17-11cm	2381.27	0.0638	25320.71	0.6780	245.3972	0.00657	82.7108	0.0022	5.9587	103.1825	47.1029	28.7903
ROTO17-12cm	1836.399	0.0502	27060.61	0.7400	179.0684	0.00490	95.8324	0.0026	7.8259	151.1188	55.2611	19.1626
ROTO17-13cm	2066.504	0.0596	22369.87	0.6456	182.4992	0.00527	144.2183	0.0042	6.8787	122.5752	53.3986	14.3290
ROTO17-14cm	2511.518	0.0681	21873.46	0.5928	89.8676	0.00244	114.6947	0.0031	5.9093	243.3966	46.0505	21.8974
ROTO17-15cm	2243.424	0.0533	21267.51	0.5052	182.4992	0.00434	90.9118	0.0022	6.7775	116.5348	68.7506	24.6769
ROTO17-16cm	1929.743	0.0575	24678.23	0.7349	201.9404	0.00601	95.0123	0.0028	6.9560	122.2055	53.5914	20.3105
ROTO17-17cm	1542.255	0.0457	26643.15	0.7895	37.262	0.00110	72.8696	0.0022	8.6878	715.0220	66.1782	21.1646
ROTO17-18cm	1734.371	0.0510	25534.86	0.7510	182.4992	0.00537	85.9912	0.0025	7.8136	139.9177	58.6449	20.1692
ROTO17-19cm	1830.972	0.0657	24005.17	0.8610	141.3296	0.00507	103.2133	0.0037	7.4595	169.8524	48.8558	17.7397
ROTO17-20cm	2404.063	0.0600	28140.28	0.7026	285.4232	0.00713	159.8002	0.0040	6.1633	98.5914	55.1429	15.0442
ROTO17-21cm	2267.303	0.0640	28574.51	0.8061	105.878	0.00299	114.6947	0.0032	6.7763	269.8815	51.4206	19.7682
ROTO17-22cm	1829.886	0.0598	29711.42	0.9710	164.2016	0.00537	181.9429	0.0059	7.2192	180.9448	54.9290	10.0575
ROTO17-23cm	2566.873	0.0617	26078.64	0.6269	318.5876	0.00766	140.9379	0.0034	5.3882	81.8571	61.6262	18.2128
ROTO17-24cm	2541.909	0.0660	32357.3	0.8397	251.1152	0.00652	117.155	0.0030	5.6091	128.8544	47.4960	21.6970
ROTO17-25cm	2544.08	0.0617	25578.29	0.6200	298.0028	0.00722	221.3077	0.0054	4.9593	85.8324	68.7532	11.4957
ROTO17-26cm	2368.245	0.0511	27116.86	0.5851	378.0548	0.00816	151.5992	0.0033	6.3459	71.7273	66.5825	15.6217
ROTO17-27cm	2510.432	0.0536	21424.42	0.4574	197.366	0.00421	125.356	0.0027	5.1238	108.5517	80.5235	20.0264
ROTO17-28cm	2781.782	0.0666	23469.28	0.5619	143.6168	0.00344	131.9168	0.0032	4.3715	163.4160	59.4653	21.0874
ROTO17-29cm	3681.579	0.0898	28067.25	0.6846	159.6272	0.00389	140.1178	0.0034	3.6617	175.8300	37.5559	26.2749
ROTO17-30cm	3302.774	0.0742	23553.17	0.5294	164.2016	0.00369	143.3982	0.0032	4.0924	143.4405	51.8315	23.0322
ROTO17-31cm	2383.44	0.0595	23485.07	0.5859	193.9352	0.00484	160.6203	0.0040	5.2967	121.0975	64.2953	14.8390
ROTO17-32cm	2104.493	0.0571	20402	0.5531	143.6168	0.00389	101.5731	0.0028	6.0836	142.0586	73.4658	20.7190
ROTO17-33cm	2361.732	0.0592	18535.77	0.4645	165.3452	0.00414	96.6525	0.0024	5.4272	112.1035	71.9840	24.4353
ROTO17-34cm	2249.936	0.0540	20677.34	0.4963	262.5512	0.00630	83.5309	0.0020	6.4044	78.7555	81.1326	26.9354
ROTO17-35cm	2020.917	0.0531	18740.06	0.4928	99.0164	0.00260	66.3088	0.0017	6.7978	189.2621	80.3352	30.4774
ROTO17-36cm	1645.368	0.0470	17210.36	0.4920	93.2984	0.00267	75.3299	0.0022	8.2809	184.4658	92.0250	21.8422
ROTO17-37cm	1947.11	0.0473	18860.46	0.4578	276.2744	0.00671	85.1711	0.0021	7.6474	68.2671	92.5824	22.8612
ROTO17-38cm	2109.92	0.0542	15904.69	0.4083	134.468	0.00345	58.9279	0.0015	6.5789	118.2786	88.6210	35.8051
ROTO17-39cm	2178.3	0.0586	16955.74	0.4561	148.1912	0.00399	62.2083	0.0017	7.2037	114.4180	88.5093	35.0162
ROTO17-40cm	2129.457	0.0550	15941.21	0.4119	120.7448	0.00312	54.0073	0.0014	7.8401	132.0240	83.2876	39.4291
ROTO17-41cm	2176.129	0.0602	14234.86	0.3937	182.4992	0.00505	60.5681	0.0017	7.9284	77.9996	74.6980	35.9286
ROTO17-42cm	2724.256	0.0799	16787.97	0.4923	221.3816	0.00649	94.1922	0.0028	6.3650	75.8327	58.3449	28.9223
ROTO17-43cm	2849.077	0.0760	16489.92	0.4399	225.956	0.00603	55.6475	0.0015	5.5025	72.9785	61.8804	51.1987
ROTO17-44cm	1974.245	0.0646	17564.66	0.5745	140.186	0.00459	58.9279	0.0019	7.3719	125.2954	70.1623	33.5027
ROTO17-45cm	1792.983	0.0490	18516.03	0.5063	165.3452	0.00452	50.7269	0.0014	8.7395	111.9841	87.8729	35.3458
ROTO17-46cm	1453.253	0.0431	17275.5	0.5122	107.0216	0.00317	47.4465	0.0014	10.4087	161.4207	101.9947	30.6293
ROTO17-47cm	1713.749	0.0469	15122.08	0.4142	141.3296	0.00387	48.2666	0.0013	9.1793	106.9987	83.8123	35.5059
ROTO17-48cm	2159.848	0.0636	18547.61	0.5459	180.212	0.00530	51.547	0.0015	7.2409	102.9211	68.1076	41.9006
ROTO17-49cm	2542.994	0.0759	17768.95	0.5303	228.2432	0.00681	44.9862	0.0013	6.5021	77.8509	49.7327	56.5283
ROTO17-50cm	1988.355	0.0633	16915.28	0.5384	166.4888	0.00530	43.346	0.0014	7.9583	101.6001	57.8665	45.8717
ROTO17-51cm	1744.14	0.0489	15780.34	0.4427	148.1912	0.00416	47.4465	0.0013	9.5609	106.4864	70.7262	36.7601
ROTO17-52cm	2095.809	0.0619	15024.38	0.4440	104.7344	0.00309	40.0656	0.0012	8.1674	143.4522	62.0533	52.3094
ROTO17-53cm	2163.104	0.0633	15008.59	0.4395	92.1548	0.00270	70.4093	0.0021	8.2612	162.8628	54.1113	30.7219
ROTO17-54cm	2113.176	0.0613	16757.37	0.4857	182.4992	0.00529	72.0495	0.0021	8.2531	91.8216	52.0315	29.3295
ROTO17-55cm	3658.785	0.1009	17972.25	0.4957	323.162	0.00891	77.7902	0.0021	4.8262	55.6137	28.3923	47.0340
ROTO17-56cm	2524.542	0.0631	16579.73	0.4141	180.212	0.00450	97.4726	0.0024	6.7232	92.0013	59.6940	25.9000

Description of Geochemical Results by Depth

Elemental Si, Ti and Zr in Lake Ngatu all notably increase in concentration just above 27cm, with Si and Zr peaking at their highest values (3.8 and 0.045) at about 21cm. There is also a rise in Al after settlement, but this occurs at about 20 to 15cm and is not as pronounced or enriched as the other elements. Elemental P and S also have delayed responses but also increase, particularly P which reaches its maximum value (0.025) at ~15cm. Ca and Fe increase above 27cm also, with Fe continuing in a positive pattern until the very top of the core where it slightly reduces. The abundance of K increases quickly to its maximum (0.2) at around 22cm but then decreases and returns to pre-impact values afterward. All elements show continued fluctuation after 27cm through to the top of the core.

Comparatively, the Lake Rotoroa data are noisier, making it harder to identify patterns. Some of the elemental signals are also opposite to those from Lake Ngatu. There is a general increase in Zr from 38-12cm, with a maximum value of 0.006 at about 22cm. Zr begins to reduce to pre-impact values above 12cm. Ti concentration wavers through the whole of the core, with a peak of 0.009 at 28cm, but there are peaks as large as that below 38cm. Si was increasing in concentration up to 38cm and then, unlike Lake Ngatu, it decreases up the core. Al increases from 38 to 12cm, peaking a 5500ppm at 5cm depth. S and Fe produced nearly identical signals to each other over depth with the elements increasing above 38cm remaining high from 25 to 12 cm and decreasing above 12cm. Elemental K and P fluctuate markedly above 38cm. Above 12cm, K decreases while P continues to oscillate then sharply increase at the top of the core. Ca sharply decreases above 38cm, dropping to its lowest value of 0.25 at 26cm. Ca increases again to about 17cm before falling again above 12cm.

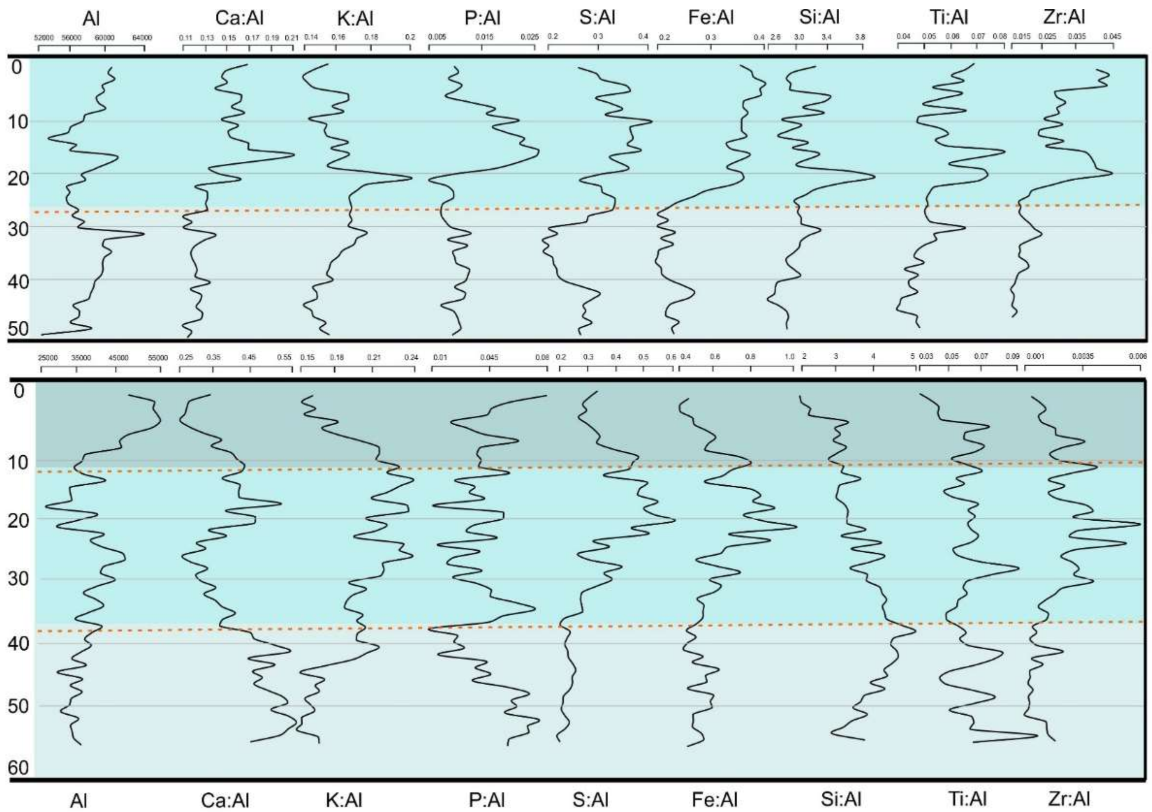


Figure D.1 XRF data to depth for Lake Ngatu at the top and Lake Rotoroa below. Demarcation of anthropogenic change (orange hashed lies) based on pollen and charcoal records. Samples corrected for inclusion of organic material with aluminium values by depth.

Elemental regressions by Zone

Calcium to titanium ratios in Lake Ngatu show an overall separation in values between the Zone 1 samples to those from Zones 2-4, which are enriched in both calcium and titanium (Fig.D.2). None of the zones shows a strong statistical correlation. Zone 1 in Rotoroa is also distinct, however, the Ca results are the reverse of Ngatu with samples from Zones 2-4 containing less elemental calcium than the Zone 1 sediments. The amount of Ti measured is similar through all zones in Rotoroa. There is evidence of a strong correlation between Ca and Ti in the Zone 2 samples in Rotoroa with an R^2 of 0.77.

Si/Ti ratios from Lake Ngatu in Zone 1 have a good fit statistically to the line of regression (R^2= 0.65), with Zone 2 samples coming close with an R^2 of 0.44. The Si/Ti values in Lake Rotoroa overlap through all four zones, but Zone 4 sediments produced good correlation (R^2=0.58).

The Fe/Mn ratio for Ngatu develops into separate groups, with increased Fe and Mn after Zone 1. Rotoroa behaves differently to Ngatu with overlapping Fe/Ti ratios between all zones. The detection limits on Mn in Ngatu are likely skewing the Zone 1 results. The Lake Rotoroa Fe/Mn Zone 4 sediments show correlation with an R^2 of 0.50. The detection limits on Mn in Lake Ngatu are likely impacting the quality of this dataset.

The results of the Ti/Zr ratios from both Lakes Ngatu and Rotoroa show increases of Zr (larger grains) after Zone 1, however in Ngatu there is evidence that in each zone Zr continues to increase, while in Rotoroa the highest abundance of Zr to Ti is seen during Zone 3.

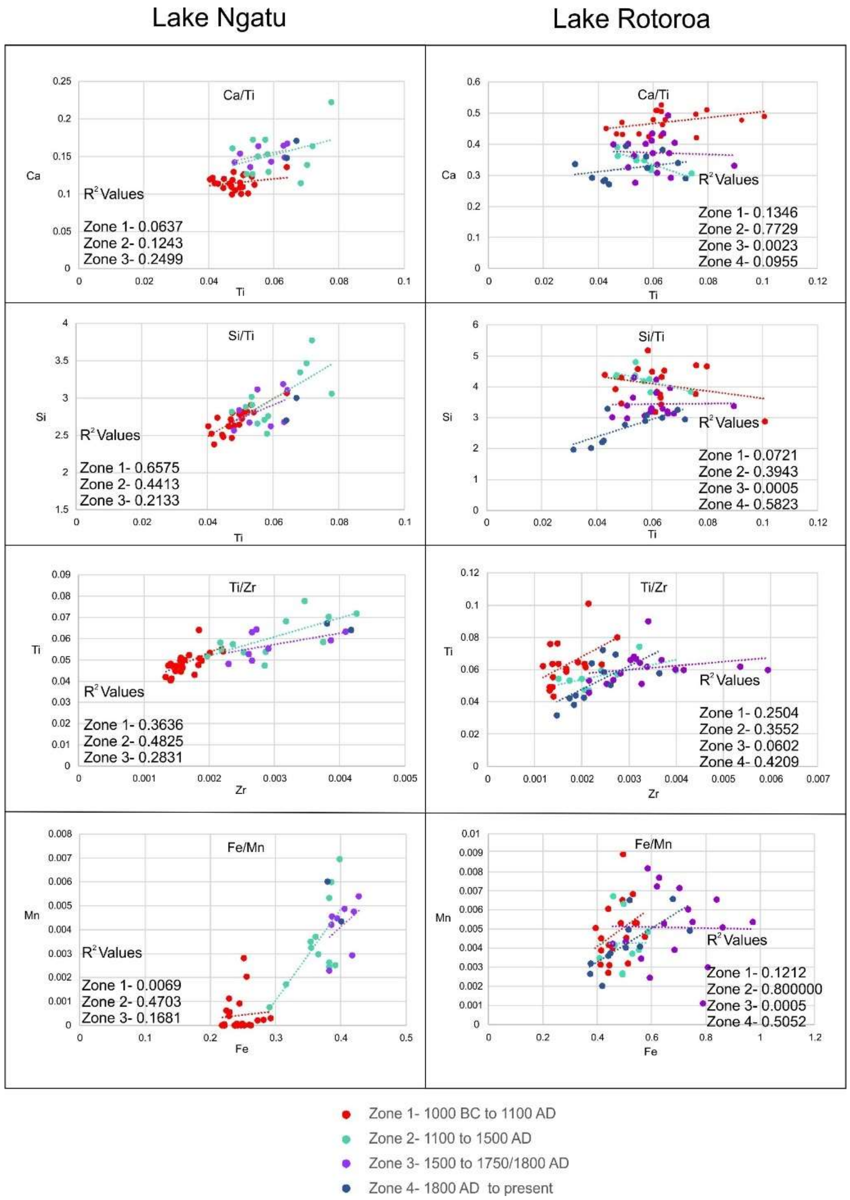


Figure D.2. Regression plots and R^2 values of selected geochemical data from XRF measurement