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Improving chronology for Aotearoa New Zealand: New research in tree-ring derived radiocarbon and stable isotope time series

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ABSTRACT

Preserved Māori wooden artefacts (taonga (treasures)) in Aotearoa New Zealand (NZ), including house components, palisade posts, carvings and canoes, provide valuable insights into the past. Understanding of the age of such objects can add value to their interpretation, determine their association with periods of social, environmental or cultural transition, and help inform future conservation and heritage protection. Empirical scientific methods such as radiocarbon dating are used to establish the calendar age of such objects. However, in NZ limitations on the accuracy of dates are imposed by radiocarbon calibration uncertainties during the last ~750 years, coincident with the entirety of human occupation in NZ. Additionally, while elsewhere dendrochronology is commonly applied to archaeological wood, in NZ this approach is hampered by species and growth ring characteristics. As a result, dendroarchaeology has been limited to dating kauri (*Agathis australis* (D.Don) Lindl.) wood from 19th and early 20th century contexts. Here we describe a long-term project employing tree-ring based ^{14}C calibration and stable isotope research that seeks to address these challenges and improve opportunities for the calendar-dating of archaeological sites and taonga in NZ.

1. Introduction

Preserved Māori wooden artefacts in Aotearoa New Zealand (NZ), including waka (canoes) (Fig. 1), house components, palisade posts, and carvings provide valuable insights into the past (Brassey, 2010; Hogg et al., 2017; Irwin, 2004; Johns, 2010, 2015; Johns et al., 2014; Neich, 2001; Wallace, 1990). These tāonga (treasures) are highly significant to iwi (tribes) and hapū (subtribes) because they provide tangible links to Māori ancestors and places. Traditional Māori knowledge or Mātauranga Māori explains the connections between people, objects and place, and frequently indicates an approximate age or temporal position within NZ's short settlement history (~750 years) (McIvor, 2024; McIvor et al., 2025). In conjunction with or alongside this knowledge, the application of empirical scientific methods such as radiocarbon dating and/or dendrochronology provides an opportunity to accurately determine the age of a wooden object and/or a site, placing it securely on a calendrical (numerical) timescale. Ultimately, establishing age can add value to the interpretation of an object or site, determine its association with periods of social, environmental or cultural transition and help inform future sustainable heritage management.

In NZ, however, there is a problem of temporal resolution in archaeological dating because the two scientific methods used to date wooden objects – radiocarbon (^{14}C) and dendrochronology – struggle to yield calendar ages constrained to a decade or single year. This is largely due to (1) radiocarbon calibration uncertainties during in the entire ~750 years of human occupation (Higham et al. 2004; Hogg et al., 2017) and (2) species and growth ring characteristics limiting application of classic tree-ring dating using climatically derived growth responses in trees (Boswijk and Johns, 2018; Boswijk et al., 2019). As a result, a significant proportion of NZ's cultural heritage remains poorly located in time. Such lack of dating precision impacts our ability to contextualise objects, hindering understanding of connections to other taonga, people and past societal and environmental change. To a certain extent, our view of the past remains somewhat obscured.

This paper introduces 'Shining a light' an interdisciplinary research project (Fig. 2), which aims to address these challenges and improve the

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calendar-dating of archaeological sites and tāonga in NZ. The project has three objectives: (1) improving the ^{14}C calibration record for New Zealand for the last millennium, using known-age kauri wood; (2) developing stable oxygen isotope chronologies for dating using kauri (*Agathis australis* (D.Don) Lindl.) and matai (*Prumnopitys taxifolia* (D. Don) Laub.) from central and upper North Island; and (3) improving understanding of the oxygen isotope composition from source water to tree ring in kauri. By focusing on radiocarbon and stable isotope-based dating methods, we aim to improve opportunities for precision dating of wooden artefacts. For example, stable isotope-based dating has enormous potential for enabling precise ^{14}C age calibration by reducing possible age ranges across the 'wiggles' in the radiocarbon curve that result in multi-intercept time intervals (Bridge et al., 2019, Davies et al., 2024). Using this combined approach, our specific goal is to improve chronology for NZ since the mid-thirteenth century, thereby increasing the accuracy and precision of radiocarbon dates, and improving opportunities for tree-ring based dating for organic archaeological materials.

The paper is organized into four parts. Part 1 outlines radiocarbon dating calibration problems for NZ and discusses how we are addressing these through high resolution analyses of calendar dated kauri wood. In Part 2, issues associated with dating wooden artifacts in NZ using classic dendrochronology are outlined. Current research to develop kauri and matai stable oxygen isotope chronologies is explained, as is the approach used for the testing and verification of their suitability for dating purposes. Part 3 briefly explains associated investigation into stable isotopes in living kauri trees, as the oxygen isotope signal in tree rings reflects a combination of the source water oxygen signal, leaf-water enrichment, and isotope fractionation during metabolic processes (Barbour et al., 2004). This tree-ring derived signal will vary from year to year, and our aim is to understand better what drives this variation in kauri trees. At present, work is ongoing across these three research strands, and results will be presented elsewhere as the project develops. Part 4 summarises the anticipated outcomes from this research and its contribution to advancing understanding of NZ's human past.

2. Radiocarbon calibration

In NZ, radiocarbon dating is the most common and reliable method for establishing the age of archaeological material and sites. However, since radiocarbon years do not directly equate to calendar years a calibration curve, such as SHCal20 (Southern Hemisphere, SH) (Hogg et al., 2020) is needed to convert conventional radiocarbon ages (CRA – reported as ^{14}C years Before Present – BP) to calendar years. This curve and the Northern Hemisphere (NH) equivalent, IntCal20 (Reimer et al., 2020), are records of atmospheric radiocarbon through time derived from incremental archives of known-age such as tree-rings and speleothems. The resulting calibration curves exhibit short term variability in ^{14}C production, termed 'wiggles' and invariant (flatter) sections of the calibration curve termed "plateau". These wiggles and plateaux impact upon the precision and accuracy of calibrated ages, limiting the fine-scale interpretation of artefacts.

In a NZ setting, with a relatively short human history, the impact of these features of the calibration curve on understanding temporal placement can be significant. For example, in 2009, the remains of a kauri waka (canoe) were found buried in sands at Muriwai Beach, on the west coast of Auckland (Fig. 1b). A single conventional radiocarbon age for the waka of 123 ± 20 BP returns a calibrated date range of 1690–1930 AD at 95 % confidence because of the plateau effect (Fig. 3). This is a 240-year time window. While it is not an early craft, it is unclear, based on the calibrated date alone, if the waka is pre- or post-European contact in age (Boswijk and Johns, 2018). (The Anglo contact and colonisation period begins in 1769, with the first visit by Captain James Cook and crew (Smith, 2019)).

One way to address such imprecision is through the application of radiocarbon wiggle-match dating to constrain the ages of objects and sites. This method matches a sequential set of ^{14}C dates from wood blocks of known relative age against the ^{14}C calibration curve to achieve a best-fit. In New Zealand, the efficacy of this method was demonstrated by Hogg et al. (2017) who were able to constrain the age of a preserved palisade alignment at Otāhau Pā (fortified settlement site) site to 1768 ± 4 AD (95 % probability). The Otāhau Pā study included construction of a kauri derived ^{14}C-dataset spanning 1650–1829 AD (Hogg et al., 2017, 2020). This curve was built using sequential 5-year blocks from a single calendar-dated timber, SPC002, from the Tree Ring Laboratory archive at the University of Auckland. It has since been extended back in time by 200 years, to 1450 AD, using wood from three different timber samples (Fig. 3). This was carried out as part of the Rua Mātītī Rua Mātātā Swamp pā project, which applied Mātauranga Māori (McIvor, 2024, McIvor et al., 2025) and radiocarbon chronology (McBride, 2024) to examine the origin and development of wetland pā in the Waikato region.

The resulting creation of a new ~380-year kauri ^{14}C data set highlighted some potential issues with Southern Hemisphere radiocarbon calibration. For the last 1000 years, SHCal20 is based on a combination of tree-ring derived atmospheric ^{14}C data from NZ Manaoa/Silver pine (*Manoao colensoi* (Hook.) Molloy) and kaikawaka /NZ cedar (*Libocedrus bidwillii* Hook.f.), data from Chile, Australia and South Africa, and additional NZ kauri data to AD 1650 (Hogg et al., 2020). The recent extension of the kauri ^{14}C record back to AD 1450 has revealed systematic differences of up to 40 ^{14}C-years with SHCal20 (Fig. 3). Additionally, there should be an offset between IntCal20 and SHCal20, that results from the larger expanse, higher mean wind speeds and circulation of the Southern Hemisphere oceans, which make contemporary atmospheric ^{14}C dates 36 ± 27 ^{14}C years older in the Southern Hemisphere than equivalent age samples from the Northern Hemisphere

Fig. 1. Two examples of canoe remains (waka). A) Anaweka waka – internal view of the hull section (6.08 m long) showing lashing holes for attachment for other fixtures around the perimeter, four carved ribs and a longitudinal stringer. The hull was made of matai. Caulking in the lashing holes was dated to ca. 674 ± 25 BP. Image reproduced from Johns et al. (2014). B) Muriwai waka – side view of the kauri dug-out hull fragment (~6.95 m long and 0.62 m wide). The hull was radiocarbon dated to 123 ± 20 BP. Image: D. Johns, 2025.

(Hogg et al., 2020). Yet, there are periods where the offset between IntCal20 and SHCal20 is either absent or significantly reduced. Around AD 1520, the SH curve is ~50 years younger than the new kauri-derived ^{14}C record – further investigations are needed to ascertain if this difference represents analytic errors or geographic location differences. With New Zealand's short prehistory, this represents uncertainties of up to 5 %. It is also apparent that there are some pre- AD 1500 time intervals (e.g., AD 1170) where the IntCal20 and SHCal20 curves almost converge, suggesting that the inter-hemispheric offset might be too small (Fig. 3). As the IntCal20 curve is extremely robust for the second millennium AD (Reimer et al., 2020), it is possible that SHCal20 might also be too young for these intervals.

In our current research program, we are addressing these two issues by extending the kauri based atmospheric ^{14}C curve to AD 950, creating an independent ~700-year regional curve for comparison with SHCal20. Two different calendar-dated timber samples (DSPL, from a display cross-section and MOR001, from a building) that collectively cover the interval AD 950–1450 were selected for ^{14}C analysis. Sequential five-ring blocks were carefully dissected from the parent timbers and chipped using a scalpel under a low-power binocular microscope. Each block was sub-sampled to produce fine slivers of wood that captured all five rings. This level of resolution was chosen to maintain continuity with the original dataset produced by Hogg et al. (2017). Cost is also a factor; with a limited budget a longer timespan can be covered using five-ring sampling compared to single-ring resolution, an advance which we hope to make in the future.

The five-ring chipped samples, along with kauri wood standards derived from a single ring (AD 1666) and kauri wood from MIS Stage 7 (background level radiocarbon), were intensively pretreated to obtain alpha-cellulose; the fraction least susceptible to modern contamination (McCormac et al., 1995). This pretreatment includes solvent extraction, acid-base-acid treatment, isolation of holo-cellulose using acidified sodium chlorite ($NaClO_2$), and a final base-acid extraction (Hogg et al., 2017). The prepared alpha-cellulose (~5 mg weight) was sent to two Accelerator Mass Spectrometer (AMS) radiocarbon dating laboratories for analysis: the CHRONOS AMS Radiocarbon Facility, University of New South Wales, Australia, and the W. M. Keck Carbon Cycle Accelerator Mass Spectrometer Facility, University of California, Irvine, USA. Additionally, a subset of 40 alpha-cellulose samples has been analysed at the AMS Terra Laboratory, also at the University of California, Irvine.

At each laboratory, the pretreated alpha-cellulose was converted to graphite before $^{14}C/^{12}C$ analysis. At CHRONOS, graphitisation utilised an AGE3 automated system and $^{14}C/^{12}C$ measurements are conducted on an Ionplus Mini Carbon Dating System (MICADAS). The Terra Laboratory also uses the AGE3 and MICADAS systems. At the Keck AMS facility, the alpha-cellulose was manually prepared to graphite using on vacuum lines. Cellulose samples were converted to CO_2 by oxidation using CuO at 800°C. The CO_2 was purified by exposure to silver wire and then reduced to graphite with H_2 at 550°C using an Fe catalyst. The $^{14}C/^{12}C$ ratio was determined on an NEC compact 0.5 MV (1.5SDH) AMS system.

The AMS $^{14}C/^{12}C$ measurements from CHRONOS and Keck provide replicate datasets of atmospheric ^{14}C for the period 950–1450 AD, with the subset of additional analyses from the Terra Laboratory across selected time periods in the 12th to 14th centuries. Combined with prior AMS measurements of kauri undertaken at the Waikato Radiocarbon Dating Laboratory (Hogg et al., 2020), this will provide a complete kauri derived atmospheric ^{14}C record for NZ for AD 950–1845. This record is independent of SHCal20 for AD 950–1650. As this is work in progress, no interpretation of the new kauri-based ^{14}C curve is offered here. The quality and consistency of the CHRONOS and Keck derived datasets are being determined currently, with the intention that the new measurements can be included in future iterations of SHCal. The previously identified systematic offset to SHCal and the periods where the offset between IntCal20 and SHCal20 reduces will be explored using these new data. We will also use this record to identify time periods in the last millennium where single ring ^{14}C analyses could be beneficial in the future.

3. Classic dendrochronology and stable isotope-based dating

The second method used to obtain accurate calendar ages for archaeological wood is dendrochronology. It relies on crossmatching the unique pattern of wide and narrow tree-rings in an object against a calendar-dated master tree-ring chronology to determine the exact years the tree-rings were laid down. From this, inferences about the timing of tree felling, manufacture and use can be made. In NZ tree-ring dating has been largely confined to the upper North Island, where kauri timbers from 19th and early 20th century buildings and *in situ* wooden features from an 1830s timber and spar station, in several cases providing accurate felling dates for the wood (Boswijk, 2010; Boswijk and Jones, 2012; Boswijk et al., 2016).

The application of dendrochronology to Māori artefacts was first raised in the 1950s (Golson, 1955; Bell and Bell, 1958; Scott, 1964) but despite several decades of research, tree-ring dating of wooden taonga has not yet been realised. Several conifer species are found as culturally modified wood, including kauri and the podocarps matai, miro (*Pectinopitys ferruginea* (G.Benn. ex D.Don in Lamb.) C.N.Page), and totara

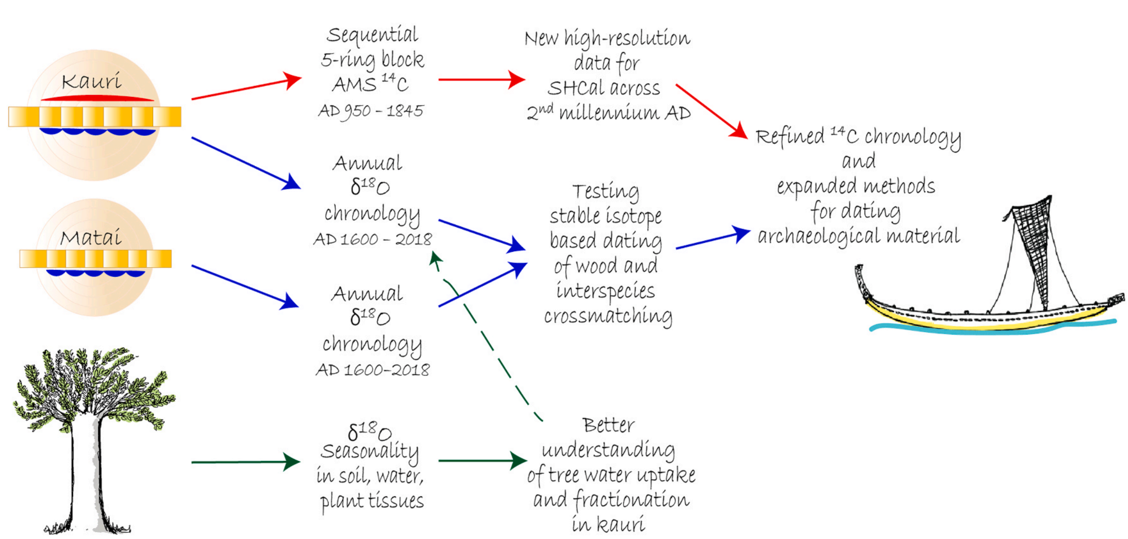

Fig. 2. Outline of "Shining a Light" an interdisciplinary research project (2023–2026).

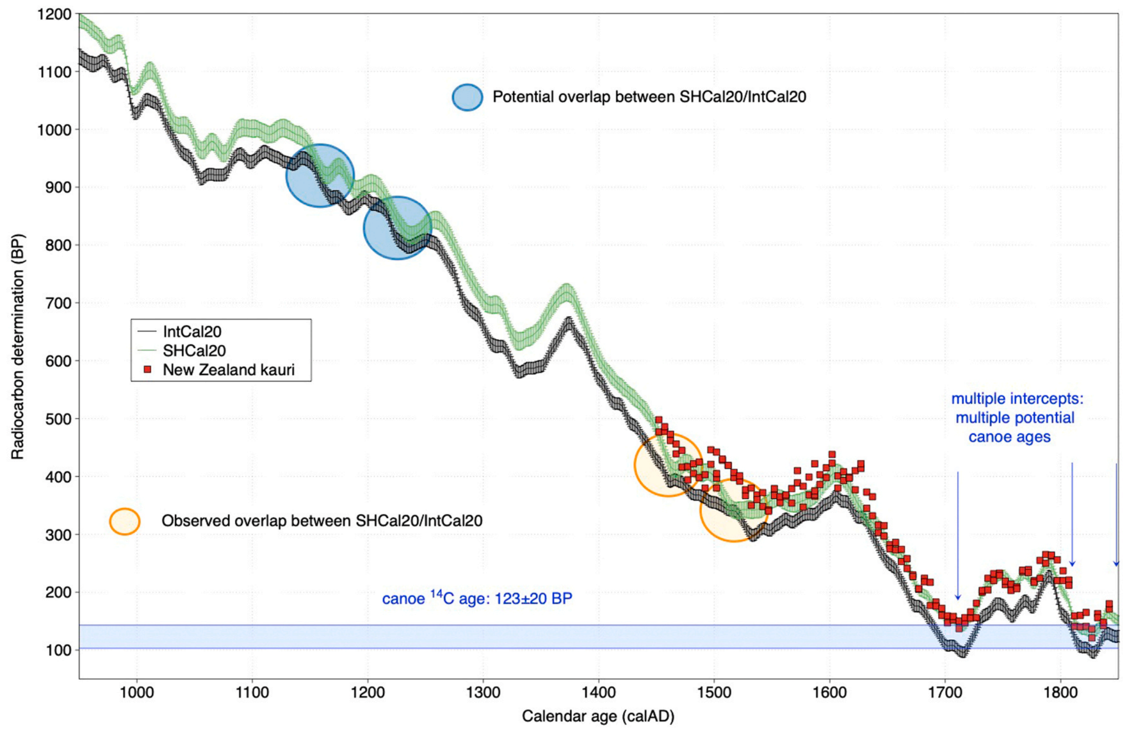

Fig. 3. Comparison between IntCal 20 (black) and SHCal20 (green) with highlighted periods (blue circles) when there are potential overlaps between the curves. The blue bar demonstrates the radiocarbon date of the Muriwai waka (canoe ^{14}C age) shown in Fig. 1 and the intercept points on SHCal, highlighting the challenges of radiocarbon calibration during recent centuries. Red squares are for 5-ring block measurements of New Zealand kauri completed for the Rua Mātītī Rua Mātātā Swamp Pā project.

(*Podocarpus totara* (G.Benn. ex D.Don var. totara)) (Boswijk et al., 2019). Of these, totara is probably the most important species found in archaeological contexts. Unlike kauri, its ecological range is spread across NZ, and it was used widely by pre-European contact Māori for a range of purposes. Matai and miro also have a wide geographic distribution. Matai is known to have been used early in the settlement period for the construction of canoes, including a large ocean-going waka (Johns et al., 2014) and miro has been found as pā palisading (e.g. Hogg et al., 2017; McBride, 2024).

At present, however, kauri is the *only* species occurring in the archaeological record for which we have a network of multi-centennial calendar-dated tree-ring chronologies (Boswijk et al., 2014). So far, attempts to tree-ring date kauri objects such as the Muriwai waka have been unsuccessful due to very short ring sequences (<30 rings) and complacent (invariant) growth rings, and/or difficulties extracting useable core samples (Boswijk and Johns, 2018). A further constraint is that the natural range of kauri is limited to the upper North Island only.

Establishing a network of tree-ring chronologies for other culturally relevant species including matai, miro and totara would offer greater opportunities to apply dendrochronological methods to date wooden artefacts from throughout NZ. Prior research into the suitability of matai and miro for ring width dendrochronology indicates there is some potential, but that growth ring characteristics make the construction of reliable ring-width chronologies challenging (Boswijk et al., 2021). These include locally absent rings that affect intra- and inter-tree synchronicity and density fluctuations which can make the identification of true annual ring boundaries difficult. Additionally, the clarity and consistency of the ring series can be affected by suppression events, non-concentric growth, and resin pooling at the heartwood-sapwood transition. Research on totara is underway, with early results suggesting this species expresses similar characteristics to matai and miro (Sharp pers. comm. 2025). It is clear that development of a network of site chronologies, and regional master chronologies, for these podocarps will be a challenging and time-consuming process.

These limitations to classic dendrochronology associated with species suitability, series length and growth characteristics, led us to investigate whether stable isotope (SI) dendrochronology would be a valuable additional approach. This method of cross-dating exploits the time-specific annually resolved pattern in oxygen isotope ratios ($^{18}O/^{16}O$) to determine a calendar date for samples of unknown age (Dominguez-Delmas, 2020; Loader et al., 2019; Pearl et al., 2020; Sano et al., 2022; Shi et al., 2025). The approach is similar to conventional tree-ring dating but importantly does not require the trees to be physiologically stressed to record a dating signal. In the United Kingdom, Japan and China, stable isotope-based dating has been successful in providing accurate calendar dates from wood from historic buildings and archaeological contexts (Miles et al., 2019; McCarroll et al., 2019; Loader et al., 2020; Sano et al., 2022, 2023; Shi et al., 2025). Its use with wiggle-match ^{14}C dating and tree-ring dating to precisely date problematic sites, demonstrates the complementary nature of these methods (Bridge et al., 2019, Davies et al., 2024).

Previously, carbon (Jansen, 1962, Grinsted and Wilson, 1979) oxygen and hydrogen (Brookman, 2014; Lorrey et al., 2016; Pauly et al., 2020) stable isotopes in kauri tree rings have been used to explore climate reconstruction potential. A pilot project focused on testing the potential for stable isotope dating in NZ began in 2018, using modern kauri and matai. Even though matai was found to be challenging for classic dendrochronology, the pilot study demonstrated high potential for building annual isotopic chronologies for this species. Loader et al. (2022) developed a unique matai oxygen isotopic series (1930–2019 AD) and the testing of matai from geographically distant sites (~250 km) demonstrated a common isotopic signal. This finding points to the potential for stable isotope-based matching of material from geographically disparate sources, useful for analysis of portable objects such as canoes that may be found distant from their place of manufacture. Presently, further research is underway to extend the matai isotopic record back further in time using modern material and archived wood.

For our current project we are focusing mainly on kauri. This species offers the opportunity to make faster progress towards a multi-centennial stable isotope chronology as it is well understood dendrochronologically and there is a greater quantity of calendar-dated wood from buildings available. Proof of concept data identify that there is a strong inter-annual signal in the kauri isotopes, meaning that fewer than 10-tree replication may be required for secure dating (Fig. 4). However, the project will aim for enhanced replication (10-trees replication across the study period) to ensure that the master kauri (and matai) isotope chronologies are representative of a regional signal and free from inter-tree or site-specific bias.

Fortunately, we have sufficient archived wood and access to living trees to support our target level of replication. At present, collecting core samples from living kauri in the conservation estate is not feasible as the trees are suffering dieback due to a soil-borne fungal pathogen, *Phytophthora agathidicida* (Bradshaw et al., 2020). Some kauri forests in the conservation estate are closed to the public and there are restrictions on access in others. However, the University of Auckland owns a small scientific reserve containing mature kauri that are pathogen free. In 2019, we collected core samples from ten mature kauri trees at the Huapai Scientific Reserve, in west Auckland. As the trees in this reserve have been previously sampled for dendrochronology, the ring width patterns for individuals could be cross checked against prior measurements from the same trees, and the Huapai site chronology. The sample set has since been increased with the addition of 28 building timbers buildings that overlap with the modern trees and extend the record back in time. In some cases, the same parent timbers sampled for the radiocarbon calibration work have been specifically selected. This combination of modern trees and archived wood should enable near consistent replication across the entire time period to be achieved.

The calendar-dated modern cores and wood samples are presently being analysed at the stable-isotope facility at Swansea University for stable oxygen (and carbon) isotopes. There, each wood sample is processed individually to derive a single oxygen series per tree that can be subsequently used for building a master isotopic chronology. This involves the manual subdivision of individual rings from the wood samples, and preparation of each complete ring to alpha-cellulose. The dry alpha-cellulose (0.35 mg) is then pyrolised (at 1400C) to CO with $\delta^{13}C$ and $\delta^{18}O$ measured simultaneously using a Delta V isotope ratio mass spectrometer. Typical analytical precision of the method (σ_{n-1}, n = 10) is better than 0.12 ‰ ($\delta^{13}C$) and 0.30 ‰ ($\delta^{18}O$).

Using both modern cores and building timbers, we are now making excellent progress towards a well-replicated annual kauri stable oxygen isotope reference chronology spanning ~400 years (1600–2018 AD). Once this chronology is completed, we will be undertaking testing and verification of its usefulness for dating purposes, which is a three-step process.

1. *Blind test*: Dated and undated timber samples from a mid-19th century building (Scott Farmstead house) have been supplied to Swansea University, but the calendar dates of known-age material were not disclosed. Oxygen isotope series are being developed for each of these individual wood samples. As illustrated in Fig. 4 panel A, these series will be crossmatched against the kauri master chronology using ISODATE, a new tree-ring dating program specifically developed for stable isotope dendrochronology (Davies et al. 2025).

   As part of the crossdating process, the data are filtered to produce indexed stable isotope series and reference chronologies. Each indexed series is compared to the reference chronology at all possible positions of full overlap, following the protocol described by Loader et al. (2019). Pearson's correlation coefficients are calculated at each position and converted into Student's *t*-values with the degrees of freedom adjusted for autocorrelation and multiple testing (Fig. 4, panels C and D). Using this methodology, the probability of the chance occurrence of a *t*-value as high as that recorded at any position of full overlap against the master chronology can be calculated.

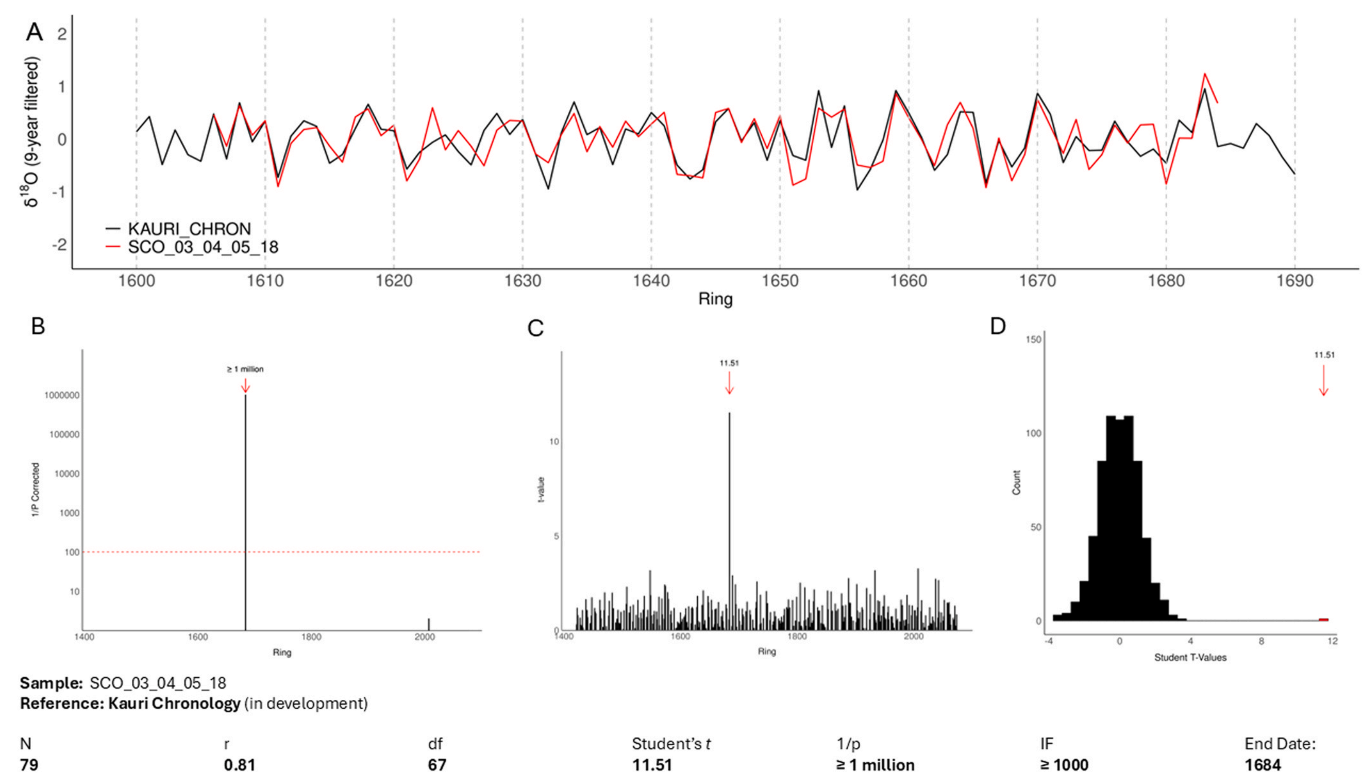

Fig. 4. An example of isotope dendrochronology dating for kauri demonstrating: A) The alignment of an independent average sequence from Scott Farmstead House (SCO) against the evolving kauri master chronology (Kauri Chron) (indices) at the position of best match; B) The relationship between the probabilities of error for the best match and the next best match (isolation factor); C) The distribution of Student's *t* values across the period of comparison; D) The distribution of all Student's *t* values returned with the position of the best match identified (red arrow).

The position of 'best-match' is defined by significance thresholds (Loader et al., 2019), refined for the target species. The resulting dates will be crosschecked against the known dendro-derived dates.

2. *Archaeological wood:* Our aim is to obtain isotopic series for archaeological wood, such as palisade posts and/or canoe samples if available. Currently, we are seeking suitable test cases made of kauri, with derived isotopic series to be compared to the master chronology to establish calendar dates.
3. *Inter-species cross-dating*: We also have access to palisade post samples collected from the Waikato region, of which some have been radiocarbon wiggle-match dated by McBride (2024). Use of such samples greatly reduces disturbance of culturally important sites and enables us to use real archaeological specimens of a known age previously dated by other methods. None of the posts were made of kauri but recent research in the UK, Japan and China has demonstrated that it is possible to crossmatch oxygen isotope series derived from different species (Loader et al., 2021, Nayling et al., 2024, Sano et al., 2022 Shi et al., 2025). The use of non-kauri archaeological material and the extension of the matai isotopic curve back in time provides the opportunity to test inter-species crossmatching. Additionally, as this material is currently from locations at the southern edge or south of the kauri region, we may also be able to examine the effect of geographic distance on the dating signal.

As with the radiocarbon work, the stable isotope analyses are currently in progress. The development of the kauri isotopic master chronology, and testing and verification, will be presented in a forthcoming paper.

4. Source water uptake in kauri trees

The isotopic chronology provides an annual record of variation in oxygen isotopes. This annual pattern is dependent on the isotopic composition of the source water (e.g., soil water, groundwater) taken up by the tree, evaporative enrichment in the leaves, and biological fractionation during the formation of photosynthetic sugars (Gessler et al., 2014; McCarroll and Loader, 2004; Treydte et al., 2014). We have, however, an imperfect understanding of the fractionation and exchange steps occurring along the pathway from source water to tree rings in kauri (Fig. 5).

To address this gap in our knowledge, we are monitoring a set of three small and four large kauri trees at the Huapai Scientific Reserve to identify where the trees obtain water from across seasons, to assess if there are any tree size related differences in tree water uptake depth, and to gain better insight into the fractionation processes. We have focused on kauri for this work because it is the primary species used for dendrochronology and radiocarbon dating, and we have access to trees at the University-owned reserve. Additionally, some of the selected trees previously have been sampled for a ring-width chronology (Fowler and Boswijk, 2001), monitored for climate-growth relationships (e.g. Wunder et al., 2013) and the oxygen stable isotope research described here.

Our current project encompasses collection of material and data at seasonal, monthly and sub-daily levels. Over 18 months, we conducted six seasonal collections of (a) leaves from the upper canopy of each tree, (b) tree cores at breast height using an increment borer, and (c) samples from the organic layer and mineral soil. The latter were from one location beneath each tree, sampled at 10–20 cm increments from 0 cm to 70–100 cm using a soil auger. Rainwater, throughfall and stream water has been collected on a monthly cycle. This coincides with data downloads from climate sensors measuring canopy temperature and humidity at 30 min intervals; tree growth data from point dendrometers installed on the selected trees; and probes beneath each tree recording soil moisture at different depths up to 1 m also at 30 min intervals.

The laboratory-based work for this part of the project includes extraction of water from leaves, xylem and soil using cryogenic vacuum distillation (Koeniger et al., 2011) and conducting $\delta^{18}O$ analysis using a

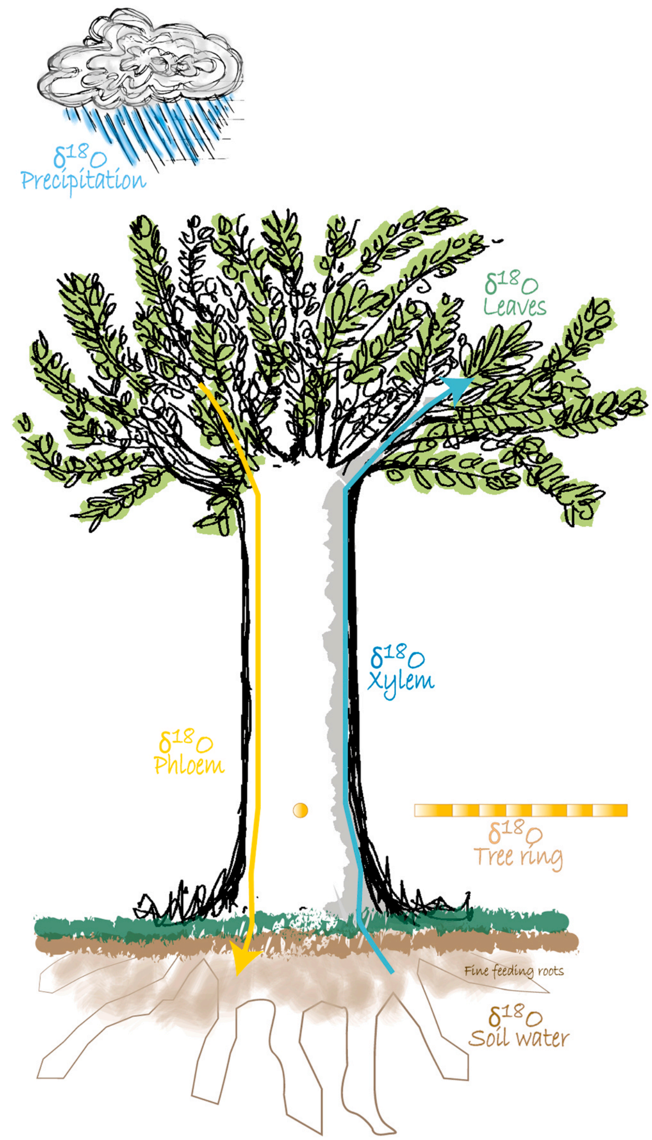

Fig. 5. Schematic of a kauri tree illustrating oxygen isotope variation from source water to tree ring (not to scale).

high temperature conversion/elemental analyser (TC/EA; Finnigan MAT, Bremen, Germany) linked to a Delta Plus XP isotope ratio mass spectrometer via a ConFlo III interface (Gehre et al., 2004). As the laboratory and statistical analyses of all data is still work in progress, the results will be presented elsewhere.

5. Outcomes and contributions

Our efforts are directed at producing an improved radiocarbon chronology for NZ and new stable isotope chronologies from kauri and matai for dating archaeological wood. The outcomes of this work are of national and international significance.

SHCal20 is the standard calibration curve used across the Southern Hemisphere. The addition of a high-resolution record for the last millennium will add higher resolution data to the calibration curve and should enable new insight into the variations in the inter-hemispheric gradient. Given NZ's short settlement history, new calibration information will have implications for understanding societal and environment change since human arrival in the thirteenth century.

The construction of the kauri and matai stable oxygen isotope chronologies and proof that reliable calendar ages can be obtained using this approach, opens up new options for dating archaeological materials especially if inter-species crossdating proves possible. There is the tantalising possibility of obtaining calendar dates precise to the last growth measured ring on a sample. Some of the palisade posts sampled for the wetland pa project still retain the final growth ring (McBride, 2024). While 'wiggle match" radiocarbon dating can constrain ages to as little as ±4 years (Hogg et al., 2017), stable isotope-based tree ring dating has the potential to identify the specific year of felling. This would create a 'tighter' chronology, fixing events in time. We are aware, of course, that the manufacture of other objects such as waka or house components may involve the removal of outer (sapwood and heartwood) rings and there may be a time lag between felling and use. In these cases, any calendar dates will provide a *terminus-post-quem* after which time the event happened. In such cases, clear guidance on different categories of calendar dates provided by our methods is needed to ensure that end-users such as hapū and iwi groups, archaeologists and other heritage specialists understand how this information should be correctly interpreted.

The radiocarbon and stable oxygen (and carbon) chronologies derived from tree-rings also have application to climate reconstruction. Atmospheric radiocarbon data provides evidence of solar activity, geomagnetic field changes and shifts in the carbon cycle (Heaton et al., 2021) while $\delta^{18}O$ chronologies can provides insight into hydroclimate conditions (Lorrey et al., 2016; Pauly et al., 2020; Treydte et al., 2024). A robust ^{14}C dataset and well replicated multi-centennial length annual $\delta^{18}O$ chronology, aided by improved understanding of source water uptake in kauri trees, would be valuable sources of sub-decadal environmental data and annual proxy climate data for the upper North Island for much of the period of human occupation of NZ.

As a final point, it should be emphasised here that our research is very much focused on chronology development, improving the radiocarbon calibration curve and advancing dating methods. It is not our intention to tell the stories of objects and places *per-se*, rather our research is geared towards providing another strand of knowledge that iwi and hapū may consider relevant and complementary to Mātauranga Māori. We anticipate that improved chronological resolution for NZ will be useful to iwi and hapū in their korero (conversation) with place and taonga, as well as to wider community, including the archaeologists and heritage practitioners responsible for the stewardship, curation and interpretation of these cultural artefacts, sites and places.

CRediT authorship contribution statement

Gretel Boswijk: Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Neil J. Loader:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Alan Hogg:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Luitgard Schwendenmann:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Melanesia Boseren:** Writing – review & editing, Methodology, Investigation. **Dilys Johns:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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