



# Developing tree ring chronologies from New Zealand matai (*Prumnopitys taxifolia* (D. Don) Laub.) for archaeological dating: Stable isotope dendrochronology

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## ABSTRACT

Aotearoa New Zealand has a rich cultural heritage but dating wooden objects using classic dendrochronology is challenging due to a paucity of master tree-ring width chronologies for species commonly identified in the archaeological record. This paper explores the potential for using a stable isotopic approach to dendrochronology for matai (*Prumnopitys taxifolia* (D. Don) Laub.). A total of six annual stable oxygen isotope ( $\delta^{18}\text{O}$ ) series for matai growing in the Pureora Forest Reserve, were analysed and their oxygen isotopes found to exhibit a level of coherence that enabled cross-dating. A provisional chronology covering the period 1930–2018 CE was developed and tested against a sample of matai from the Kauaeranga Valley (200 km to the north of Pureora) and a sample of miro (*Prumnopitys ferruginea* (D. Don) Laub.). Miro is another species common in the cultural archive, but also difficult to date using ring-width dendrochronology. Both the Kauaeranga matai and Pureora miro samples cross matched against the site chronology at the correct position, but with weaker dating statistics (Student's  $t$ : 4.26 and 4.11 respectively) compared to the results obtained for two (non-2019) sampled Pureora matai analysed in this study (Student's  $t$ : 6.80 and 5.66). These results nevertheless demonstrate the presence of a regional-scale dating signal which may be developed for future use as a precision dating tool.

## 1. Introduction

Archaeological evidence indicates Māori in Aotearoa New Zealand used a wide range of tree species for structures and implements, including kauri (*Agathis australis* (D. Don) Lindl.), totara (*Podocarpus totara* (G. Benn ex. D. Don)), matai (*Prumnopitys taxifolia* (D. Don) Laub.) and miro (*Prumnopitys ferruginea* (D. Don) Laub.) (Boswijk et al., 2019). Of these four species, well-replicated calendar-dated tree-ring chronologies have been established for kauri (Boswijk et al., 2014), but currently there are no tree-ring chronologies for dating the other three species. In a recent study, Boswijk et al. (2021) assessed the dendrochronological potential for two species commonly found in the cultural record; matai and miro. Both matai and miro exhibit growth characteristics which make ring-width dendrochronology extremely challenging. These characteristics include the formation of false rings, density fluctuations and wedging rings that became locally absent around the tree circumference and/or vertically along the stem. These

features often occur in conjunction with periods of suppression and are found in both juvenile and mature trees. Additionally, there is a tendency to ring complacency (invariant ring width) in the juvenile growth (c.100 years) and indistinct ring boundaries in the sapwood. Resin pooling at the heartwood/sapwood transition was also observed on some samples, blurring the ring boundaries and impacting accurate measurement. As a result of these features Boswijk et al. (2021) were unable to establish secure and consistent ring-width cross-matching between trees and sites across their study region. Significant effort, high levels of sample replication and independent verification would likely be required to overcome the problems of partial and wedging rings to develop robust reference chronologies from these species and whilst incorporation of young trees with faster growth may provide a solution, their growth is typically more complacent, making secure cross-dating difficult. Boswijk et al. (2021) concluded that it was not yet possible to develop a calendar dated master tree-ring width chronology given the high level of uncertainty regarding the reliability of the ring width

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patterns from these species.

Recent developments in stable isotope dendrochronology have demonstrated how isotopic coherence may be used as an independent technique for timber dating or to support ring-width dendrochronology (Leavitt et al., 1985; Loader and Switsur, 1996; Sakamoto et al., 2017; Yamada et al., 2018; Loader et al., 2019; Nakatsuka et al., 2020). The isotopic record preserved in a tree ring contains a strong environmental signal and this may be used to date samples through their objective comparison with a well-replicated regional master chronology. In Europe, the method has been shown to perform well for invariant and managed ring width samples across a range of species, where it can both date samples independently and also confirm the alignment of, and anchor, assemblages of temporally “floating” ring width data (Loader et al., 2019, 2021). In light of the advantages of this approach for dating invariant ring width series, if isotopic reference chronologies can be compiled for these culturally-relevant species, then this could support the development of ring-width reference chronologies for these and other challenging species across New Zealand through the provision of independent chronology.

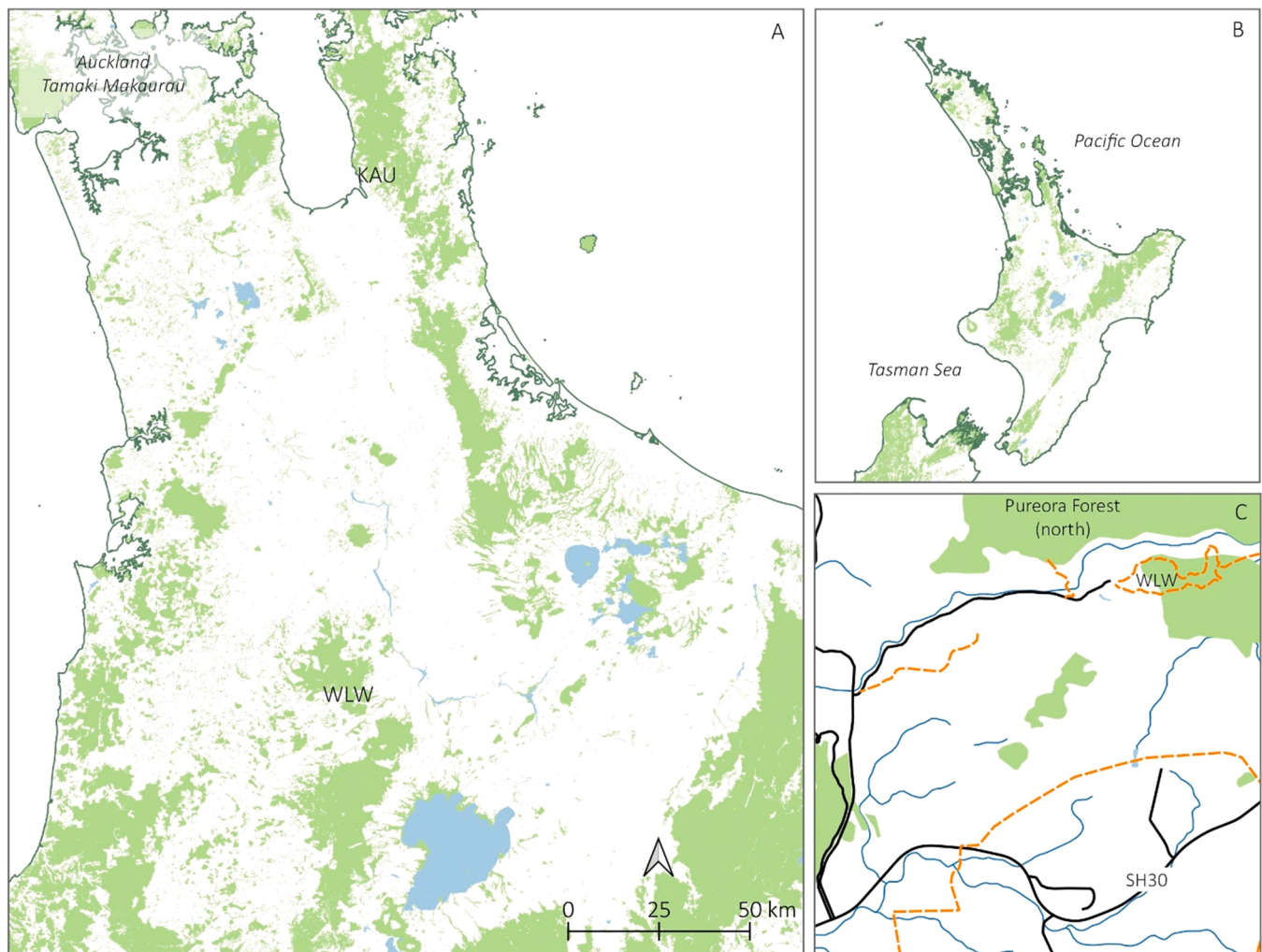
This paper explores the stable oxygen isotope signal preserved in matai trees growing at Pureora Forest, in the Waikato region of the North Island, New Zealand. It aims to compare the isotopic coherence within and between trees and between sites with a view to assessing the application of stable isotope analyses in the future development of isotopic reference chronologies. These may then be used to support isotope

dendrochronology and the development of ring width chronologies in matai, miro and other tree species of cultural relevance.

## 2. Material and methods

In February 2019, matai cores were collected from living trees at the Waipapa Loop Walk, Pureora Forest Park, Waikato (Fig. 1, NZ Topo50 BF34 2432 3864). The park is part of the national conservation estate and contains mature mixed podocarp-broadleaf forest. Permission to sample living trees at Pureora was granted by the Department of Conservation (Permit 67819-RES) and Te Hau Kainga o Pureora, the Māori iwi (tribe) who have mana whenua (territorial rights) over the forest. This site was selected because of the availability and accessibility of mature trees and because both matai and miro tree cores had previously been collected from the area between 1994 and 1999 (Ogden, pers. comm). Two cores per tree were obtained from ten matai and ten miro trees using a 5 mm increment borer.

The sampled trees and their ringwidth dendrochronologies are described by Boswijk et al., (2021). They found that whilst matai offered some cross-dating potential, by contrast miro was found to be more challenging and failed to provide any secure cross-matching so it was decided to focus this initial isotopic investigation on a sub-sample of the matai cores only. Of the 2019 matai, one core per tree from a sub-sample of 4 matai trees (MAT001, MAT003, MAT004, MAT006) were selected for isotopic analysis based upon their relatively wide rings and invariant



**Fig. 1.** Map showing the location of the sample sites. A: Pureora (Waipapa Loop Walk WLW), and Kauaeranga Valley (KAU). B: North Island of Aotearoa New Zealand. C: Pureora Forest (Waipapa Loop Walk WLW). Forest areas (green), lakes and rivers (blue), access trails (dashed orange lines (panel C only)).

inter-annual growth. Such growth is common in matai samples excavated from archaeological contexts (Hogg et al., 2017). Additionally, a second core from tree MAT006 was selected for isotope analysis to explore/confirm intra-tree isotopic variability. Two additional archived core samples collected during the 1994 and 1999 studies were also analysed along with a sample (KAU001) from a tree felled at the Kauaeranga Valley, Coromandel Peninsula (approx. 200 km north of Pureora) in 1982 to test inter-site coherence and isotopic dating potential.

Samples were surfaced for ring-width measurement using progressively finer abrasive paper. Ring widths were measured using a Lintab stage and TSAP software (Boswijk et al., 2021). The selection of cores for isotopic analysis specifically targeted relatively fast-grown invariant ring series. Aside from offering a practical advantage for isotopic analysis of these small diameter cores, such series are of the kind most often recovered from cultural constructions such as the palisade posts of pā (fortified settlements) and waka (canoes) (Boswijk and Johns, 2018; Hogg et al., 2017). Whilst younger juvenile growth is challenging to date dendrochronologically due to ring complacency, their greater ring width means that they generally displayed fewer wedging rings and provided sufficient wood for isotopic analysis.

Rings were manually excised as thin slivers of wood. The whole ring (early- and late-wood) was analysed and rings from the undated cores were divided based upon the assumption of one ring, one year, taking account of density fluctuations and indistinct latewood bands. Wood was prepared to  $\alpha$ -cellulose using an acidified sodium chlorite solution to oxidise lignin followed by a sodium hydroxide treatment to hydrolyse hemicelluloses (after Loader et al., 1997). The resulting cellulose was homogenised using an ultrasonic probe and freeze-dried ( $-40^{\circ}\text{C}$  0.001 Pa 48 h) prior to pyrolysis to at  $1400^{\circ}\text{C}$  over glassy carbon using a Flash HT elemental analyser and subsequent mass spectrometry of the resulting CO using a Thermo Delta V isotope ratio mass spectrometer. Analytical precision based upon replicate analysis of a commercial  $\alpha$ -cellulose standard is typically better 0.3 per mille VSMOW ( $\sigma_{n-1}$ ,  $n = 10$ ).

As the statistical properties of the isotopic signal in matai trees are not yet well established, data were prepared for isotope dendrochronology using methods developed for analysis of oak latewood. Data were first indexed using a simple 9-year rectangular filter by subtraction. The series were then cross-dated isotopically using the approach described in Loader et al. (2019). Dating results presented include the Student's  $t$  value, correlation coefficient, degrees of freedom (df, adjusted for filtering and multiple testing),  $1/p$  (the probability of a match of equivalent value occurring at an incorrect position), and IF (the ratio of the best to second best probabilities or Isolation Factor). The lack of a reference chronology means that these dates are reported based upon the individual series matches or composites and so ( $1/p$ , IF and df) relate to the series length at the position of strongest association. Given that the date of the last ring formed by the trees was known, the aim of cross-dating the series was first to establish whether the degree of coherence in the stable isotope signal was strong enough for inter-sample dating and second whether there was potential to use the isotopic signal in matai tree rings to develop isotope dating chronologies that could feasibly support ring width dendrochronology in New Zealand.

Studies of tree-ring isotopic variability, for plant physiological, palaeoclimate research and archaeology have demonstrated inter-species isotopic coherence which may be useful for precision dating (Fu et al., 2017; Loader et al., 2021). In light of the diversity of species identified in archaeological contexts and cultural artefacts, and in addition to the matai samples analysed in this study, a single miro sample (PUM961), collected from Pureora in 1991 with relatively clear wide rings, was also extracted to cellulose and analysed using methods identical to those used for the matai. Although this is only one relatively short series, the inclusion of this additional sample will help to establish whether these two species, which are often found to co-occur in the

archaeological record, yield a sufficiently coherent isotopic signal to enable future inter-species dating.

### 3. Results and discussion

#### 3.1. Intra-tree variability

Two isotope series were developed from two radii of tree MAT006. The indexed raw data series exhibit good visual coherence. They were statistically cross correlated ( $r = 0.78$ ) and found to cross match significantly at the correct position of overlap with a Student's  $t$  value of 9.46 (Table 1, Fig. 2). The two index series were averaged into a single tree series for subsequent comparisons covering the period 1930–2018. The high degree of coherence is to be expected, given previous research (McCarroll and Loader, 2004 and references therein), and that these cores are collected close to each other from within the same tree, however the series are not identical and the growth complacency in these relatively young trees would make them difficult to cross-match using ring widths alone (Boswijk et al., 2021). This result therefore indicates a potential advantage of the isotope approach for supporting core synchronisation in complacent samples.

#### 3.2. Inter-tree variability

The two core average from MAT006 was then compared against the isotopic data obtained from the three other trees (MAT001, MAT003, MAT004) sampled at Pureora in 2019 (single cores). Indices cross-correlate at the correct year and generally provide secure matching, although there is some variability ( $r$  ranging from 0.51 to 0.68). Comparison of trees MAT001 and MAT006 indicate a possible off-set of 1-year in their earliest section that could indicate a false ring mis-identified as two in MAT006. There is limited independent data and overlap with which to test this association, but removal of the ring in MAT006 and re-comparison of the series, resulted in an improvement in match statistics (Table 1). The 2019-sampled index series (using MAT006 adjusted) from the four trees were combined by averaging into a site chronology (PUREORA4).

The Pureora evolving site chronology was then compared against isotope data obtained from two additional matai cores, PUR952 and PUR943, collected previously for a forest ecology study (Ogden, pers. comm.). The two series were dated against the PUREORA4, cross-matching at the correct position. A comparison of the results obtained against the 4-tree average with and without the ring adjustment yields slightly stronger matches with the adjustment than without, however even in this additional test, overlaps are very short and so this adjustment should be considered preliminary and somewhat subjective. It is notable that ring width dendrochronology failed to date these six series securely, but here the stable isotopes are able to confirm the relative dating of the tree ring samples.

To help quantify the degree of inter-series coherence, the mean inter-series correlation ( $r_{\text{bar}}$ ) and expressed population signal (EPS) were calculated (Wigley et al., 1984). For the six individual indexed series from Pureora,  $r_{\text{bar}}$  is 0.567 ( $n = 6$  trees), which yields an EPS of 0.887. Similar results were found with the raw isotope data, which return an  $r_{\text{bar}} = 0.479$  ( $n = 6$ ) and an EPS of 0.846. In light of this agreement, the index series were combined into a new six-tree site chronology (PUREORA6) (Fig. 3). These results contrast with the  $r_{\text{bar}}$  (0.080) and EPS (0.343) calculated for the tree ring indices ( $n = 6$  trees).

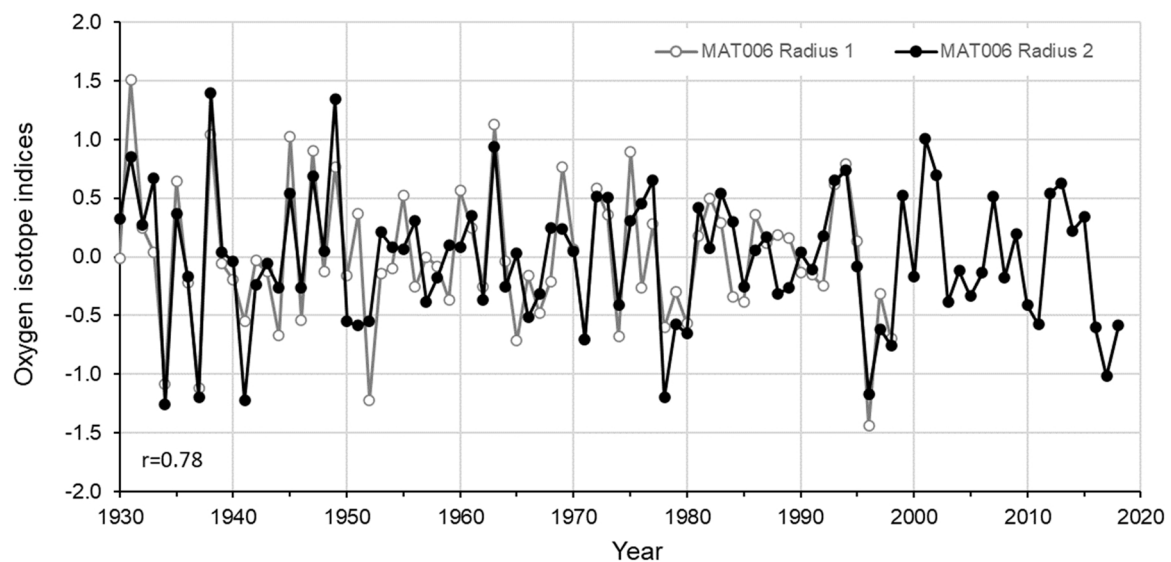
#### 3.3. Inter-site variability

The demonstration of isotopic coherence within and between trees is important as it provides essential proof of concept for future development of ring width and stable isotope chronologies in New Zealand. However, for dendrochronology to be most effective it should be possible to date samples beyond the single site-level. Here, the Pureora

**Table 1**

Results from cross-correlation of matai and miro cores from individual matai trees (MAT, PUR, KAU) and a single miro core (PUM961). Where series of indices are combined the working chronologies are reported as PUREORAX where X is the number of matai trees in that composite series. MAT004 (adjusted) has been modified for a potential partial ring. Statistics calculated with n adjusted for the number of pairs at the position of best overlap.

Series comparison	Species & Sampling information	Correlation Coefficient	No. paired observations	Degrees of freedom (df)	Student's t value	1/p	Isolation Factor (IF)
Radii A and B, MAT006	Matai (2019)	0.78	69	58	9.46	> 1 Million	> 1000
MAT004 v MAT001	Matai (2019)	0.68	81	69	7.77	> 1 Million	> 1000
MAT004 v MAT003	Matai (2019)	0.63	73	62	6.37	> 1 Million	> 1001
MAT004 v MAT006	Matai (2019)	0.50	89	76	5.06	700558	256
MAT004 v MAT006 (adjusted)	Matai (2019)	0.60	88	76	6.56	> 1 Million	> 1000
MAT001 v MAT003	Matai (2019)	0.54	73	62	5.11	601930	> 1000
MAT001 v MAT006	Matai (2019)	0.57	81	69	5.83	> 1 Million	> 1000
MAT001 v MAT006 (adjusted)	Matai (2019)	0.57	81	69	5.83	> 1 Million	> 1000
MAT003 v MAT006	Matai (2019)	0.51	73	62	4.67	95675	> 1000
MAT003 v MAT006 (adjusted)	Matai (2019)	0.51	73	62	4.67	95675	> 1000
PUREORA4 v PUR943	Matai (Archive sample)	0.70	58	47	6.80	> 1 Million	> 1000
PUREORA4 v PUR952	Matai (Archive sample)	0.63	58	49	5.66	434377	> 1000
PUREORA4 v KAU001	Matai (Inter-site test)	0.58	45	36	4.26	14397	> 1000
PUREORA6 v KAU001	Matai (Inter-site test)	0.58	45	36	4.31	16684	> 1000
PUREORA4 v PUM961	Matai & miro (Inter-species test)	0.57	43	36	4.11	9084	> 1000
PUREORA6 v PUM961	Matai & miro (Inter-species test)	0.52	43	36	3.66	2459	> 1000
PUREORA7 v PUM961	Matai & miro (Inter-species test)	0.53	43	36	3.74	3128	> 1000



**Fig. 2.** Comparison of oxygen isotope series from two sampled radii tree MAT006. The outer part of radius 1 was not measured isotopically due to poor preservation.

trees are all sampled from within a single forest, and so to explore the spatial “range” of the dating signal recorded at Pureora a sample of matai (KAU001) collected from the distant Kauaeranga Valley (200 km to the north of Pureora) was analysed for its stable isotopic signal and compared against the 4 and 6 sample Pureora isotope chronologies.

Remarkably, the Kauaeranga sample series (which spans the period 1910–1980) returns the correct end date when compared against the Pureora 4- or 6-tree means. The strength of the match is relatively low (Student's  $t = 4.26$  ( $r = 0.58$ ) and  $t = 4.31$  ( $r = 0.58$ ) respectively with

relatively low match probabilities and IF) which most likely reflects the low levels of sample replication in both reference series, the short temporal overlap and the distance between sites. However, confidence in the match warranted inclusion of the KAU001 series in a new working chronology; PUREORA7 (Fig. 4).

The evidence of long-distance matching provides encouraging proof-of-concept because it demonstrates a regional signal is preserved in the stable oxygen isotopes of matai. Additional work is necessary to explore these signals further and to strengthen these chronologies with new sites

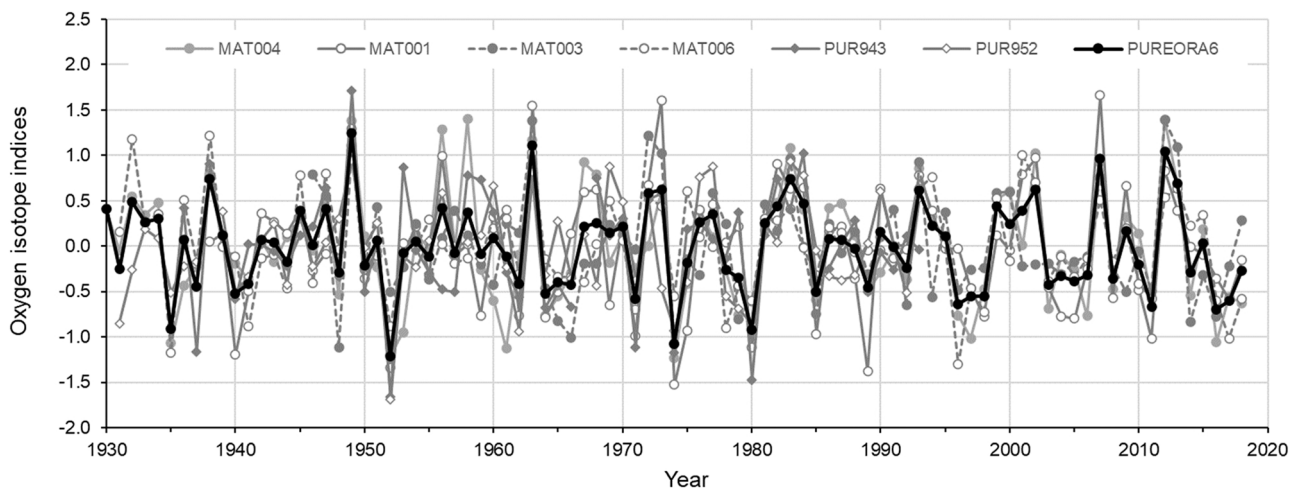


Fig. 3. Comparison of matai index series from Pureora (grey lines) and mean series (black line).

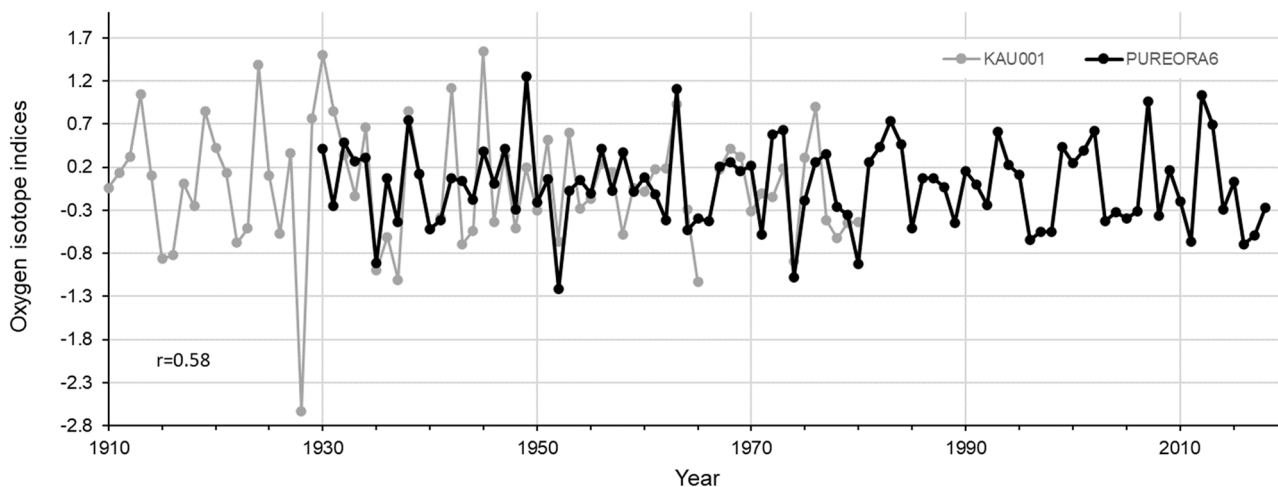


Fig. 4. Comparison of Kauaeranga (KAU001) indices with mean of 6 (PUREORA6) matai index series.

and sample replication.

### 3.4. Inter-species potential

The final test conducted, compared the isotopic variability attained between a single sample of miro, *Prumnopitys ferruginea* (PUM961) with

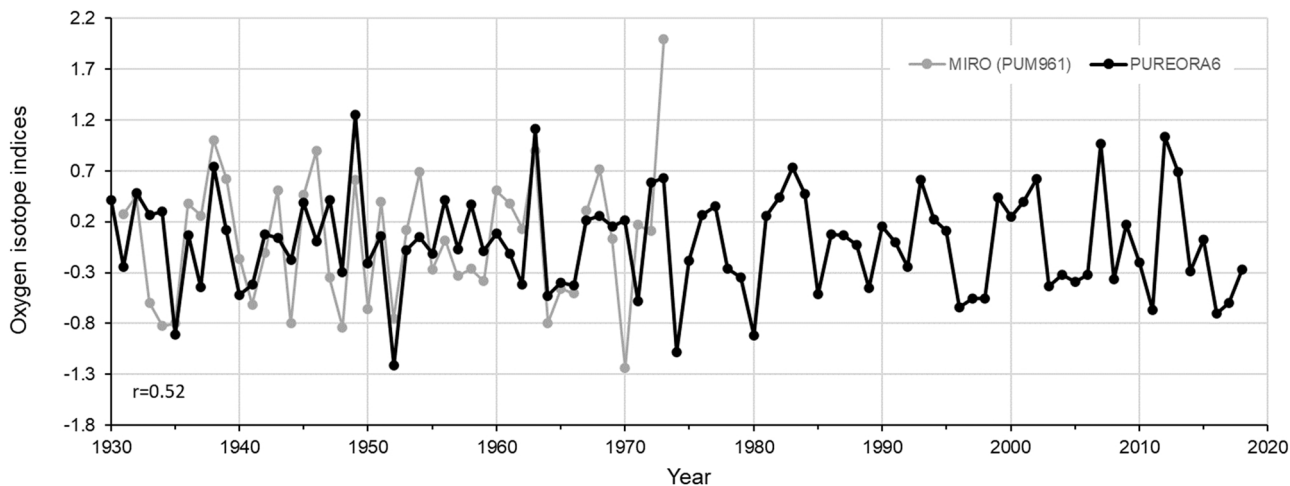


Fig. 5. Comparison of mean of 6 matai oxygen isotope series (PUREORA6) and miro (PUM961) isotope indices. The outer rings of PUM961 were not measured isotopically due to poor preservation and potential contamination.

the isotope data from the 4-, 6- and 7-tree matai chronologies. The miro sample cross-matches successfully, but match statistics are relatively low. There are a number of relatively extreme values, which will undoubtedly have impacted upon dating results, but without additional cores it is difficult to explain these further. The match is strongest with the 4- tree chronology (Student's  $t = 4.11$ ,  $r = 0.57$ ), and lowest with the 6-tree variant (Student's  $t = 3.66$ ,  $r = 0.52$ ). The match strengthens slightly from the 6-tree series with the addition of the KAU001 series to the Pureora dataset (Table 1). Boswijk et al. (2021) explored the dendrochronological potential of miro from Pureora and concluded that this species is currently more challenging than matai. Here the ability to cross-match matai and miro isotope data may provide an alternative approach for future chronology development and dating of this challenging species (Fig. 5).

### 3.5. Wider application and considerations

The oxygen isotopes in tree-ring cellulose are largely controlled by the isotopic composition of summer (growing season) precipitation. This signal is recorded more passively than annual growth which requires a limiting factor to preserve a coherent dating signal. Pureora is an old growth natural forest and it is likely that the ringwidth series record stand-specific disturbance and changes in canopy dynamics (e.g. competition, gap formation etc.) in addition to climate. Such changes are likely to be more localised than the more widespread isotopic signal contained in precipitation and this may help to explain why the ring-width measurements are so challenging for dendrochronological dating.

Work remains to establish the wider scope of the technique as applied in New Zealand, in terms of the statistical data treatment protocols and thresholds, geographical range (footprint) of the dating signal and the diversity of species that can be dated using a single master chronology. Statistical properties can be determined once a robust, well replicated chronology is established and from this the geographic range may be determined. Development of such a reference chronology would not be a trivial task due to the difficulties in establishing precise ring-width chronologies from this species, but once established and tested, such a chronology or network of chronologies would represent a very useful dating resource for the research community. It is likely, as for ringwidth dendrochronology, that best results will be obtained dating samples of the same species, but as we have shown here, where different genera share common characteristics, it may also be possible to achieve inter-species dating, although it is unlikely that a single reference chronology developed for a single species will be universally applicable.

## 4. Conclusions

New Zealand has a rich cultural heritage but dating wooden objects using classic dendrochronology is challenging because of a combination of species characteristics and paucity of master tree ring width chronologies for archaeologically useful species. Here, the potential of using stable isotopes to support dendrochronological dating was explored. A sample of 6 matai trees from Pureora forest were measured for their stable isotope composition and found to exhibit a level of isotopic coherence that enabled the correct alignment of the series based upon their stable isotopes. The performance of the isotopes is stronger than the ring widths for these samples which was unable to cross date the series securely. The resulting chronology was then tested against a sample of miro and a distal sample of matai from Kauaeranga Valley. Both samples cross match at the correct position confirming the presence of a larger-scale dating signal which may also provide valuable palaeoclimate information and evidence for isotopic coherence between species that may facilitate wider application of the approach in this region. These findings demonstrate the potential for building isotope chronologies for precision dating and provide a new tool to support the development of ring width chronologies from matai, miro and other species of socio-cultural importance in Aotearoa/New Zealand.

Future application of the isotope approach for dendrochronology will require replication of these results through the incorporation of additional longer-lived trees sampled from across a number of sites to increase sample replication and temporal coverage. Indeed, given the propensity of these species for wedging and partial rings, it is possible that methods adopted for identifying double/missing rings in ring width chronologies (e.g. COFECHA, Holmes, 1983) may need to be employed for additional quality control when developing isotope reference series for these species. To ensure robust reference chronologies, increased replication and longer timeseries than presented in this proof-of-concept paper will be essential.

The isotope coherence reported for the Pureora matai was developed from relatively wide-ringed trees with invariant growth, this may be useful when determining maximum tree age or developing/extending initial chronologies from longer-lived trees. This is because it is often the slower older growth (rather than the rings formed when the tree was young) that appear to be more prone to growth disturbance in this species. The long-lived nature of both matai and miro (Boswijk et al., 2021) means that given sufficient samples, it should be possible to develop an isotopic dating framework for these species relatively rapidly. It is also highly likely that once a cohort of precisely-dated tree ring isotopes have been established, that the associated ring-width measurements may more easily be cross-dated thereby reducing inter-tree growth variability (noise) to a point where it becomes possible to develop robust ring width chronologies for these challenging species.

The matching of a sample of miro with the matai series is a particularly encouraging result given the difficulty of dating this species using ring-width data. Further research and replication of this result is essential but it offers potential for developing chronology for samples of both matai and miro spanning the period since Māori arrival in the late 13th century. Both matai and miro trees are widely distributed across Aotearoa/New Zealand and there is potential for developing new chronologies for these species. Whilst the wood anatomy of these species is challenging, their cultural relevance and presence in the archaeological record make matai and miro, (and also totara) important and now more attainable targets for dendrochronology and science-based archaeology.

### 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.

### Data Availability

Data will be publicly archived as part of a larger dataset of isotopic analyses.

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