Developing tree-ring chronologies from New Zealand matai *(Prumnopitys taxifolia)* and miro (*Prumnopitys ferruginea)* for archaeological dating: progress and problems

Gretel Boswijk[1], Neil J. Loader[2], Giles H.F. Young[2,3], Alan Hogg[4]

[1] School of Environment, the University of Auckland

[2] Department of Geography, Swansea University

[3] Natural Resources Finland (LUKE), Helsinki

[4] Radiocarbon Dating Laboratory, University of Waikato

Corresponding author:

Gretel Boswijk
School of Environment,
The University of Auckland
Science Building 302,
23 Symonds Street
Auckland Central

g.boswijk@auckland.ac.nz

Abstract

This paper describes attempts to develop tree-ring chronologies from New Zealand matai (*Prumnopitys taxifolia*) and miro (*Prumnopitys ferruginea*). These tree species have been recovered from Māori archaeological contexts, including as objects such as canoes and palisade posts. Dendrochronology offers the potential to establish accurate and precise calendar dates for wooden objects but relies on cultural use of species that are also suitable for tree-ring analysis, and the availability of calendar-dated reference chronologies for crossdating wood of unknown age. We used archived cross-section and core samples from seven sites in central North Island, and nineteen core samples collected in 2019 from matai and miro trees at Pureora Forest Park for our analysis. Some of these samples came from long lived trees, with ring counts indicating ages up to 800 years old. We found that both matai and miro exhibit considerable variability in ring clarity and ring width. They also have ring anomalies affecting the reliability of ring-width series. Miro was very challenging, and no tree sequences were built for this species. Tree-ring sequences were built for several matai samples but no secure inter-tree matches were identified. Further analysis of matai samples is required to establish reliable tree ring patterns for inter-tree and inter-site crossmatching.

Keywords

Archaeology, dendrochronology, matai, *Prumnopitys taxifolia*, miro, *Prumnopitys ferruginea*,

Introduction

Preserved culturally modified wood has been recovered from Māori archaeological contexts in New Zealand including artefacts such as sections of canoes (waka) and palisade posts. Radiocarbon dating is commonly used to establish the age of such objects. However, variations of atmospheric radiocarbon over the past 800 years (the period of human settlement in Aotearoa-New Zealand) can result in broad calendar age ranges and reduced dating precision. These constraints limit understanding, making it difficult to resolve key aspects in the manufacturing and use of cultural artefacts: such as temporal changes and the (relative) timing of spatial differences. Dendrochronology offers the potential to establish accurate and precise calendar dates for wooden objects, but relies on the cultural use of species that are also suitable for tree-ring analysis, and also the availability of calendar-dated reference chronologies for crossdating wood of unknown age. Archaeological evidence indicates that Māori used a wide range of tree species for structures and implements, including conifers such as 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 there appear to be no established tree ring chronologies for the other three species.

In this paper, we describe attempts to develop tree ring chronologies from matai and miro. These two species were selected because preserved miro palisade posts (Hogg *et al,* 2017) and artefacts made of matai including the remains of an early ocean-going canoe (Johns *et al*, 2014), structures, palisade posts, and agricultural implements, have been previously recovered or identified in archaeological contexts. These finds raised the question whether dendrochronology could be applied to absolutely date these artefacts. Researchers in the 1970s and 1990s identified that matai and miro have clear, sharp rings, and suggested that the species had potential for dendrochronology (Dunwiddie, 1979; La Marche *et al*, 1979; Lusk & Ogden, 1992). Various ecological projects have obtained ring counts from matai and miro to establish tree age (e.g., Bellingham, 1982; Lusk, 1989; Lusk & Smith, 1998; Wells *et al*, 2001; Cullen et al 2003; Willems, 1999) but did not apply standard dendrochronological techniques to develop tree-ring chronologies. To be suitable for tree-ring dating, tree species require well-defined annual rings, growth limited by a dominant environmental factor, usually climate, and a shared common growth pattern, enabling statistical crossmatching between trees and construction of tree-ring chronologies. Here, we describe the tree-ring characteristics of matai and miro, test intra- and inter-tree crossmatching, and outline issues impacting the suitability of these two species for classic dendrochronology.

Growth range and ecological characteristics of matai and miro

Matai and miro are members of the Podocarpaceae and belong to the same family (*Prumnopitys*). Both species are widely distributed throughout the North and South Island of New Zealand offering the prospect of a national network of tree ring chronologies (Figure 1). Within that wide distribution, and prior to extensive logging, matai was most abundant on the pumice soils of central North Island, and locally abundant on well-drained, but moist, alluvia of the west coast of South Island (Hinds & Reid, 1957; Clifton, 1994). Miro was abundant on the alluvial soils of the west coast of South Island and locally abundant or scattered elsewhere, including on Stewart Island. Land-use change, particularly since European colonisation, and 20th century logging have reduced the distribution of both species. Mature forest survives in parts of central North Island and the west coast of South Island.

The two species have different ecological characteristics. Matai is a light demanding species and Ogden & Stewart (1995) hypothesised that following major canopy disturbance, establishment of matai occurs early in the regeneration cycle in association with other light demanding podocarps such as totara. Juvenile trees have a shrub-like form with photosynthetic twigs and sparse leaves. As the trees mature, they develop a conical shape during the pole stage and then a spreading crown at maturity (Ogden & Stewart, 1995). Mature trees are tall and slow growing. The leaves of mature trees are 1.5 – 2 cm long, and straight or slightly curved (Figure 2). Podocarpacae leaves appear to be functional for at least three years and are shed in conjunction with small twigs (Ogden & Stewart, 1995). Matai are dioecious and produce a round, fleshy fruit like a drupe. In contrast, miro is a shade tolerant species, establishing under the canopy and forming a component of the sub-canopy. Ogden & Stewart (1995: 116) suggest that after major disturbance, miro will become established late in the sequence of podocarp regeneration. The leaves of mature trees are 1.3 –2 cm long, slightly longer on juvenile trees (Poole & Adams, 1994) (Figure 2). Miro are also dioecious and produces a reddish-purple oblong fruit.

Tree-ring analysis

An assemblage of archived matai and miro samples (cross-sections and cores) and tree cores collected in 2019 was used to investigate potential for chronology development. The samples were from seven sites in the Waikato, Bay of Plenty and Manawatu-Whanganui regions of central North Island (Figure 3a, Table 1). The elevation of the sampling sites ranges from 300 m to approximately 750 m above sea level. In general, across this wide area, summers are warm, with average daily maximum temperatures over 20°C, while winters are cool with frosts occurring inland of the coast. Sunshine hours vary from >2100 hours in the Coromandel Range to <1750 hours per annum for the Manawatu-Whanganui region (Chappell 2013a, 2013b, 2015).

The archived assemblage included three matai cross-sections, two sets of matai tree cores, and two sets of miro cores which were collected at different times between 1977 and 1999 for various dendroclimatological or ecological studies. These were held in the School of Environment Tree-Ring Laboratory (TRL) archive or at the Laboratory of Tree-Ring Research (LTRR), University of Arizona.

Several matai and miro cores in the TRL collection were collected between 1994 and 1999 as part of an ecology field school held near the Waipapa Loop Walk, Pureora Forest Park, Waikato. In February 2019, this area was revisited to collect new matai and miro cores from living trees (Figure 3b; 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) associated with the forest. This site was selected because of the availability and accessibility of mature trees, and because there was an existing assemblage of matai and miro tree cores. There were no records available indicating exactly which trees had been sampled during the 1990s, but it is possible (if unlikely) that we resampled some of the same trees in 2019. Two cores per tree were obtained from ten matai and ten miro trees using a 5 mm increment borer. Sampling was guided by the needs of an associated project examining the stable oxygen and carbon isotope signal in selected New Zealand species. Consequently, the cores were taken from same side of the tree, one above the other at approximately 10 cm apart.

Prior to ring width measurement, the cross-sections were reduced to up to four radial strips per tree. All samples were sanded (or resanded) to a fine polish to show the individual growth rings clearly. Ring widths were measured using a set-up comprised of a low power binocular microscope and a travelling stage linked to a computer. Ring-width data were recorded using the program TSAP-Win Scientific 4.69i (Rinntech 2002-2015). The same program was used for intra- and inter-tree comparison of ring width series using a combination of statistical crossdating programs and on-screen visual matching of line graphs. The statistical crossdating approach used follows the 'Belfast Method' (Cros73, Baillie & Pilcher, 1973) where ring width data are transformed using a high pass filter removing biological trends and enhancing the underlying common annual signal. Pearson's correlation coefficient 'r' indicates goodness of fit and a Baillie-Pilcher t value (BPt) is reported as a measure of statistical significance (Fowler *et al,* 2017).

The raw ring-width series were observed to have pronounced multi-decadal growth trends towards wider or narrower rings that underlie the shorter year-to-year changes assumed to reflect climate forcing (Figure 4). These longer-term trends may relate to growth in closed canopy forest, competitive effects, or injury and appear to be tree specific. They affect visual matching of the raw ring series, which at this exploratory phase is a critical step to intra- and inter-tree crossmatching and chronology development. To aid (visual) crossmatching, the ring-width series were standardised to remove biological and endogenous trends. The approach followed Fowler *et al* (2004; 2012) who demonstrated that smooth growth curves (splines) fitted to kauri tree-ring data were effective in removing endogenous noise and enhancing the year-to-year signal. The tree-ring series were converted to indices by dividing the actual ring widths by the corresponding value from the fitted spline. Here, it was found a 10-year spline improved ring-width series for visual matching (Figure 4).

Intra-tree comparison was undertaken to ensure that all growth rings were present on same-tree radii or cores. The width and clarity of the growth rings of matai and miro were variable, with periods of wide, clear rings, and very narrow rings and suppressed growth (Figure 5). It was evident early on that both matai and miro have growth anomalies that disrupt the ring width pattern. False rings, when growth is disturbed during the growing season causing density fluctuations or forming an apparent late wood boundary, occurred in samples from young and mature trees. Wedging rings that became locally absent around the tree circumference and/or up the stem also occurred, often in conjunction with periods of suppression. The sapwood of both species was pale yellow, and the growth rings in this section could be indistinct and ring boundaries faint. Resin pooling at the heartwood/sapwood transition was observed on some matai and miro samples, blurring the ring boundaries and impacting upon the accurate measurement of the growth rings.

Where possible, ring issues identified between same-tree samples were resolved by careful inspection of the samples under the microscope and comparison of ring width graphs. This enabled correction of misidentified false rings and identification of the likely location of locally absent rings. In the latter case, if the ring was wholly absent from the sample, a marker value of 0 was inserted at the appropriate position in the ring width series. After reconciliation, the same-tree series were averaged to produce a tree-ring sequence for individual trees. These were used for intra-tree cross-matching to identify if ring sequences from different trees could be aligned enabling construction of a tree-ring site chronology and accurate calendar dating of each ring. Following the Schulman convention (1956, p 130), in the Southern Hemisphere the annual ring is dated according to the year growth begins, e.g., the 2017-18 growth ring is labelled as year 2017.

Results

The outcomes of tree-ring analysis are described for each species separately.

Matai

The matai assemblage included samples from young (<100 rings) and old (>500 rings) trees (Table 2). The average series length for the entire assemblage was 297 rings. The shortest and longest ring-width series were from the Waipapa Loop Walk (WLW), Pureora Forest, where PUR951 had only 36 rings and MAT007 had 815 rings. The mean ring-width of individual matai samples ranged from 0.40 mm to 3.99 mm. Young trees tended to be fast growing, with wide rings and complacent ring patterns. Trees >300 years old showed a noticeable reduction in mean ring-width to <0.7 mm per annum, with more sensitive ring patterns.

The clarity of matai growth rings was variable. Young trees (<100 years) tended to have clearly defined, wide rings that were easy to identify and measure accurately. In contrast, many older samples had sections with distinct annual rings but during periods of suppressed growth, the rings could reduce to only a few cells wide with the ring boundary marked by only a single row of latewood cells (Figure 5). Very narrow rings could present as a band of latewood cells only. Ring anomalies, described previously, were more common in samples from larger, mature, slow growing trees. In particular, suppressed growth, where the rings became very narrow and poorly defined or locally absent, disrupted the ring pattern. Consequently, it was not always possible to securely reconcile same-tree ring-width series across their entire length.

Despite the occurrence of ring anomalies (and with some persistence), intra-tree crossmatching resulted in development of tree-ring sequences for the HMA, KAU, and WHC matai cross-sections, and for nine of ten sample pairs from the 2019 WLW matai assemblage (Table 3).

The WLW tree-sequences and radial series were compared against each other to identify intra-tree crossdating. It was anticipated that crossdating might be identified at least between samples from these two collection phases, and against the single sample from the Waihora Catchment, also located in Pureora Forest. We would expect that the trees would have similar growth patterns, as they were from the same area and experienced the same or similar environmental conditions. There was also the possibility that we had resampled trees at WLW which would be identified through crossmatching of ring width series. Unfortunately, the young trees had complacent growth patterns and secure crossmatching between different trees from this location was not forthcoming. Comparison of longer tree-sequences also did not yield reliable results. There were sections when the growth patterns of some of the Pureora tree sequences appeared to be synchronous, but these were often short, interspersed with longer periods that showed little or no similarity (Figure 6).

Resolving crossdating issues was difficult because of the nature of the samples. The 2019 WLW core pairs were from one side of the tree only and the narrow cores presented only a restricted field of view. Often it was difficult to determine with confidence the exact location of absent rings, and although tree-sequences were built for nine sample pairs, there is a high level of uncertainty regarding the reliability of the ring-width patterns because of the sometimes high number of locally absent rings (Table 3). The likely occurrence of additional unidentified absent rings impacts inter-tree crossmatching, as shown in Figure 6. Consequently, at this stage, reliable and consistent matching has not been identified between the WLW trees or between ring width sequences from any of the matai sites, and it was not possible to develop a calendar-dated master tree-ring chronology for this species.

Miro

Similar to the matai assemblage, the miro assemblage included three samples from young trees (<100 years) with the most samples from trees >200 years (Table 4). The shortest series had 69 rings (PUM961) and the longest series had 563 rings (MIR006a), with an average series length of 345 rings. Ring width was variable across the data set. Some samples exhibited very narrow rings (e.g., MAM293 had a minimum ring width of 0.04 mm) to rings over 3 mm wide (e.g. PUM962). Overall, the miro tended to be slower growing with more sensitive ring patterns than the matai.

The miro growth rings were physically similar in character to matai. Some samples had well defined rings, which could be easily and accurately measured. However, miro also exhibited anomalies such as suppressed growth, locally absent rings, and false rings. In some cases, such as for the HAK cores, the core samples were not measurable because of a combination of narrow rings and strong density fluctuations. Ring anomalies also impacted intra-tree crossmatching. For example, only two cores from the same quarter of tree MAM293 could be crossmatched (Table 5). Cores from the opposite side of the tree had suppressed growth and indistinct ring boundaries. Similarly, the two MAM301 cores were from the same half of the tree; both samples had >450 rings present, but suppressed growth and indistinct ring boundaries in the outer 200 rings affected the reliability of measurements and a truncated tree-sequence only could be made (Table 5). The same type of ring anomalies was also evident in both Pureora Forest assemblages, affecting the synchronicity of the ring patterns. Intra-tree comparison of series from the 2019 collection showed that samples from the same side of the tree could have multiple rings missing between the cores. This, combined with the narrowness of the rings and variability in growth, made reconciling same-tree series very challenging and only one tree sequence could be made (MIR010) (Table 5). As a result, confidence in the reliability of the ring patterns was reduced, and it was not possible to test inter-tree crossmatching or develop a miro tree-ring chronology.

Discussion and conclusion

This investigation of matai and miro has been valuable for informing our understanding of the suitability and potential of these species for dendrochronology and archaeological dating. There are five findings from this research.

1) Many of sampled trees from Pureora Forest were 400 – 500 years old, with some matai exceeding 700 years. The long-lived nature of these trees means that, theoretically, master chronologies constructed from living trees could span much of the period of human occupation in New Zealand. There is also potential for regional coverage from the North and South Islands which would be beneficial for investigating the distance over which trees express a common signal, and for dating archaeological material, particularly craft such as canoes which may be found at some distance from their site of origin.

2) Previously, researchers such as Dunwiddie (1979) noted that matai and miro had clear, sharp rings. In the samples studied here, the clarity of matai and miro growth rings was variable. Sometimes the rings were very clear and ring width measurement was straightforward, but both species exhibited false or poorly defined rings. Locally absent rings often coincided with episodes of suppressed growth. These characteristics, and the frequency of their occurrence, impacted measurement accuracy and the reliability of the ring width series. Our observations support an earlier comment by Bellingham (1982) that blocks of locally absent rings could impact ring counts.

3) The tree-ring series exhibit tree-specific episodes of suppression and release which may reflect local environmental conditions or perhaps biological influences, such as fruit production. For development of tree-sequences and inter-tree crossdating, standardisation of the ring-width data is necessary to remove these long-term trends and enhance the year-to-year signal, making (visual) matching more feasible. The method used here (a 10-year spline) was helpful for visual matching but further testing of other approaches to standardisation would be beneficial to aid crossmatching.

4) Although the young matai trees (~100 years old) had wide, clear rings, they commonly exhibited a complacent growth pattern and secure crossmatching between the tree sequences was not achieved. It is possible that young trees which, perhaps, have not yet reached canopy height are less responsive to a common forcing, limiting their suitability for crossmatching. The identification of some partial overlaps between tree sequences from mature Pureora Forest matai, based on visual matching of line graphs, hints that there is a common signal shared by different trees. This suggests that there is potential for crossmatching and development of master chronologies, although the occurrence of locally absent rings and false rings means that

considerable time and effort will be required to securely reconcile ring width series and achieve a reliable matai record. Having multiple cores from around a tree circumference would assist with resolving ring issues.

5) Reconciling same-tree series from the miro was difficult because of ring anomalies, particularly the high number of locally absent ring. Experience suggests that this is a more challenging species for crossmatching than matai and that it may be best placed in the ‘too hard’ basket for now.

The findings from this exploratory research have implications for dendrochronological dating of Māori artefacts made using matai or miro. Essentially, the combination of growth characteristics of these species, and difficulty in developing reliable tree-ring records means that classic tree-ring dating of wooden artefacts, such as waka or palisade posts is not feasible at this time. From a dendrochronological perspective, we need to understand more about factors influencing the growth of these species, such as the length of the growing season and biological and ecological factors influencing ring width. Analysis of additional cross-sections may be helpful for establishing reliable tree ring patterns as a starting point for inter-tree and inter-site crossmatching. And further exploration of methods for preparing cores to show rings clearly and of standardisation methods would be beneficial to aid crossmatching and chronology development. It is also possible that alternative tree-ring based approaches may yield results. The samples collected from Pureora Forest Park in 2019 were for a project investigating the stable oxygen and carbon isotope signal in selected New Zealand tree species. In Britain, annual stable oxygen isotope chronologies have been constructed for oak and employed to date timbers from standing buildings (Loader *et al* 2019; Miles *et al* 2019). Research is underway to develop a master isotope chronology for New Zealand from historic kauri and test its use for dating wood of unknown age. Identification of a similar stable isotopic signal in matai and/or miro could offer an alternative route for development of tree-ring chronologies and for the dendroarchaeological dating of Māori artefacts.

References

Baillie, M.G.L., Pilcher, J.R., 1973. A simple cross-dating program for tree ring research. *Tree Ring Bulletin* 33, 7-14.

Bellingham, P. 1982. Some ecological aspects of Matai (*Podocarpus spicatus* R. Br. ex Mirbel) in west Taupo indigenous forests, 1982.

Boswijk, G., Fowler, A.M., Palmer, J.G., Fenwick, P., Hogg, A., Lorrey, A., Wunder, J. 2014. The late Holocene kauri chronology: assessing the potential of a 4500-year record for palaeoclimate reconstruction. *Quaternary Science Reviews* 90: 128-142.

Boswijk, G., Johns, D., Hogg, A., 2019. Dendroarchaeology in New Zealand: assessing potential to extend the suite of useful tree species beyond kauri (*Agathis australis*). *Journal of Pacific Archaeology*, 10 (1), 33-44.

Chappell, P.R. 2013a. The climate and weather of Waikato. *NIWA Science and Technology Series* 61, 40 pp.

Chappell, P.R, 2013b. The climate and weather of Bay of Plenty. *NIWA Science and Technology Series* 62, 40 pp.

Chappell, P.R., 2015. The climate and weather of Manawatu-Wanganui. *NIWA Science and Technology Series* 66, 40 pp.

Clifton, N.C., 1994. *New Zealand timbers: the complete guide to exotic and indigenous woods*. Revised edition, Wellington: GP Publications Ltd.

Cullen, L.E., Duncan, R.P., Wells, A. & Stewart, G.H. 2003. Floodplain and regional scale variation in earthquake effects on forests, Westland, New Zealand. *Journal of the Royal Society of New Zealand*, 33, 693–701.

Dunwiddie, P.W. 1979. Dendrochronological studies of indigenous New Zealand trees. *New Zealand Journal of Botany*, 17, 251–266.

Fowler. A., Boswijk, G., Ogden, J. 2004. Tree-ring studies on *Agathis australis* (kauri): a synthesis of development work on late Holocene chronologies. *Tree-Ring Research* 60, 15-29.

Fowler, A.M., Boswijk G., Lorrey, A.M., Gergis, J., Pirie, M., McCloskey, S.P.J., Palmer, J.G., Wunder, J. 2012. Multi-centennial ENSO insights from New Zealand forest giants. *Nature Climate Change* 2, 172-176.

Fowler, A.M., Bridge, M.C., Boswijk, G., 2017. An empirical resampling method for determining optimal high-pass filters used in correlation-based tree-ring crossdating. *Dendrochronologia*, 44, 84-93.

Hinds, H.V., Reid, J.S., 1957. *Forest trees and timbers of New Zealand*. Wellington, N.Z, Government Printer.

Hogg, A., Gumbley, W., Boswijk, G., Petchey, F., Southon, J., Anderson, A., Roa, T., Donaldson, L. 2017. The first accurate and precise calendar dating of New Zealand Māori Pā, using Otāhau Pā as a case study. *Journal of Archaeological Science: Reports* 12: 124-133.

Johns, D. A., Irwin, G.J., Sung, Y.K. 2014. An early sophisticated East Polynesian voyaging canoe discovered on New Zealand's coast. *Proceedings of the National Academy of Sciences, USA,* 111(41): 14728-14733.

LaMarche, V.C. 1979. Tree-ring chronologies of the Southern Hemisphere, Tuscon, Tuscon: Laboratory of Tree-Ring Research, University of Arizona 1979.

Loader, N.J., McCarroll, D., Miles, D., Young, G.H.F., Davies, D., Bronk Ramsey, C., 2019. Tree ring dating using oxygen isotopes: a master chronology for central England. *Journal of Quaternary*

Science, 34 (6), 475-490.

Lusk C.H., 1989. Age structure and dynamics of podocarp/broadleaved forest in Tongariro National Park. Unpublished PhD Thesis, The University of Auckland.

Lusk, C. & Ogden, J. 1992. Age Structure and Dynamics of a Podocarp — Broadleaf Forest in Tongariro National Park, New Zealand. *Journal of Ecology*, 80, 379–393.

Lusk, C.H. & Smith, B. 1998. Life history differences and tree species coexistence in an old-growth New Zealand rain forest. *Ecology*, 79, 795–806.

Miles, D., Loader, N.J., Young, G.H.F., McCarroll, D., Davies, D., Bronk Ramsey, C., James, J.G. 2019. Stable isotope dating of historic buildings. *Vernacular Architecture*, DOI: 10.1080/03055477.2019.1660955

Ogden, J., Stewart, G. 1995. Community dynamics of the New Zealand conifers. In, N.J. Enright, R.S. Hill (eds) *Ecology of the southern conifers*. Carlton, Vic. Melbourne University Press.

Poole, A.L., Adams, N.M. 1994. *Trees and shrubs of New Zealand*. Lincoln, Manaaki Whenua Press, Landcare Research.

Rinntech, 2002-2015. TSAP-Win™ Time Series Analysis and Presentation for Dendrochronology and Related Applications. Version 4.69i for Microsoft Windows. Heidleberg, Frank Rinn.

Schulman, E. 1956. *Dendroclimatic changes in Semiarid America*, University of Arizona Press, Tucson, p 142.

Wells, A., Duncan, R.P. & Stewart, G.H. 2001. Forest dynamics in Westland, New Zealand: the importance of large, infrequent earthquake-induced disturbance. *Journal of Ecology*, 89, 1006–1018.

Willems, N. 1999. Forest structure and regeneration dynamics of podocarp/hardwood forest fragments, Banks Peninsula, New Zealand. Unpublished MSc thesis, Lincoln University.

Acknowledgements

We thank the Department of Conservation and Te Hau Kainga o Pureora for permission to collect core samples from matai and miro trees at the Waipapa Loop Track, Pureora Forest Park. In particular, we acknowledge Frances Hughes, Te Hau Kainga o Pureora, for her support of the project and Leigh Roderick, DOC, for help with sampling. GB thanks the Laboratory of Tree-ring Research, particularly Peter Brewer, Charlotte Pearson, and Ron Towner, for the opportunity to access the New Zealand collection as an Agnese N. Haury Visiting Scholar in 2018, and to Tomasz Wazny for discussion about the difficulties of these species. This work was supported by the Royal Society of New Zealand Catalyst: Seeding award (CSG-UOA1705).

Figures

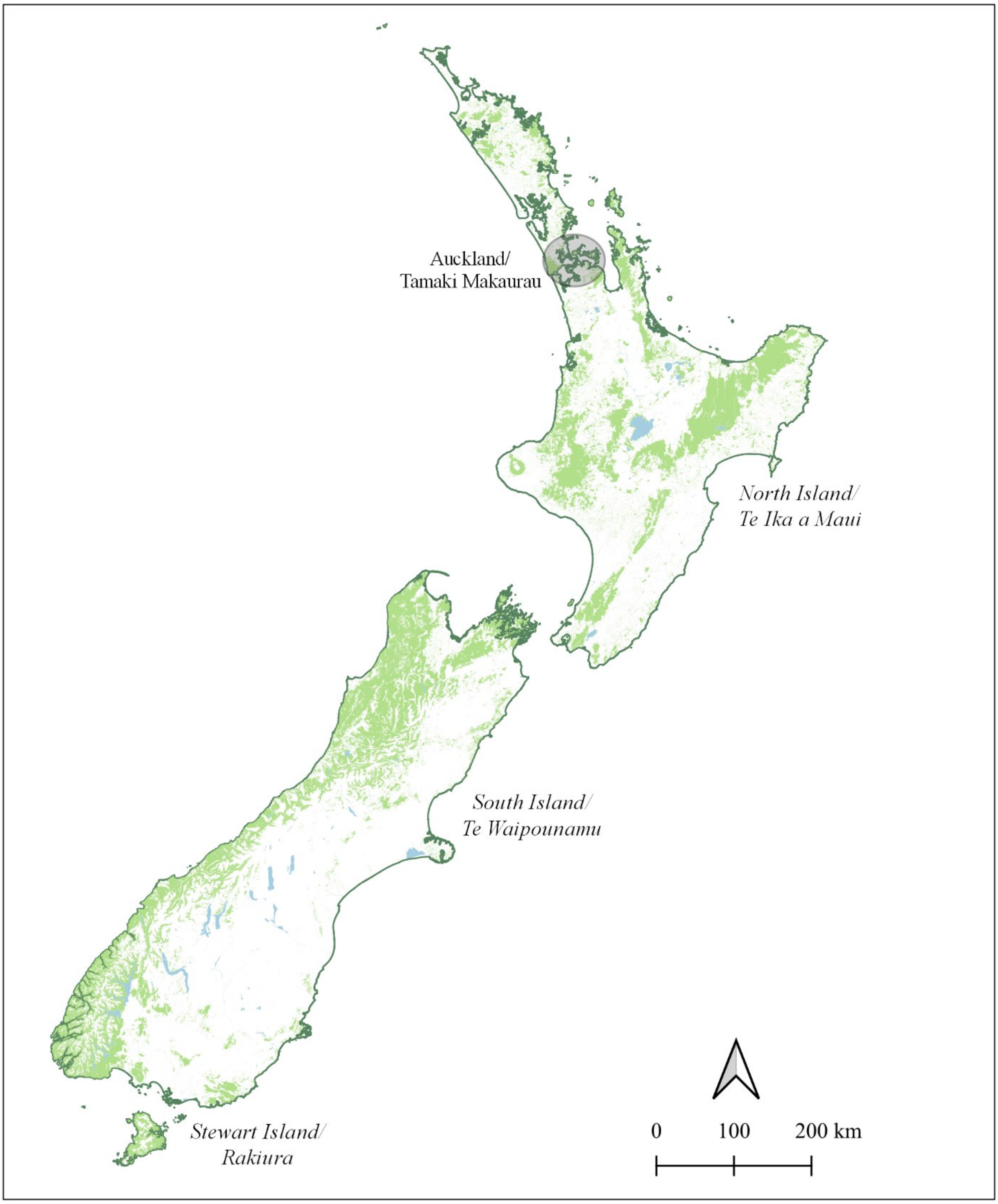

Figure 1: Modern distribution of native forest in New Zealand (green). Matai and miro were widespread across the islands. There were denser areas of matai in central North Island/Te Ika a Maui and of miro on the west coast of South Island/Te Waipounamu, and a gap in distribution in both species on the east coast of South Island/Te Waipounamu. Map data sourced from the *LINZ Data Service* and licensed for reuse under the Creative Commons (CC) BY 4.0 licence.

Figure 2: a) Matai tree and b) mature matai leaves. c) Miro tree and d) miro leaves. Images a, b, and d by 'Kahuroa' and c by 'Rudolph89' from Wikimedia Commons, reproduced under CC Attribution-Share Alike license 4.0.

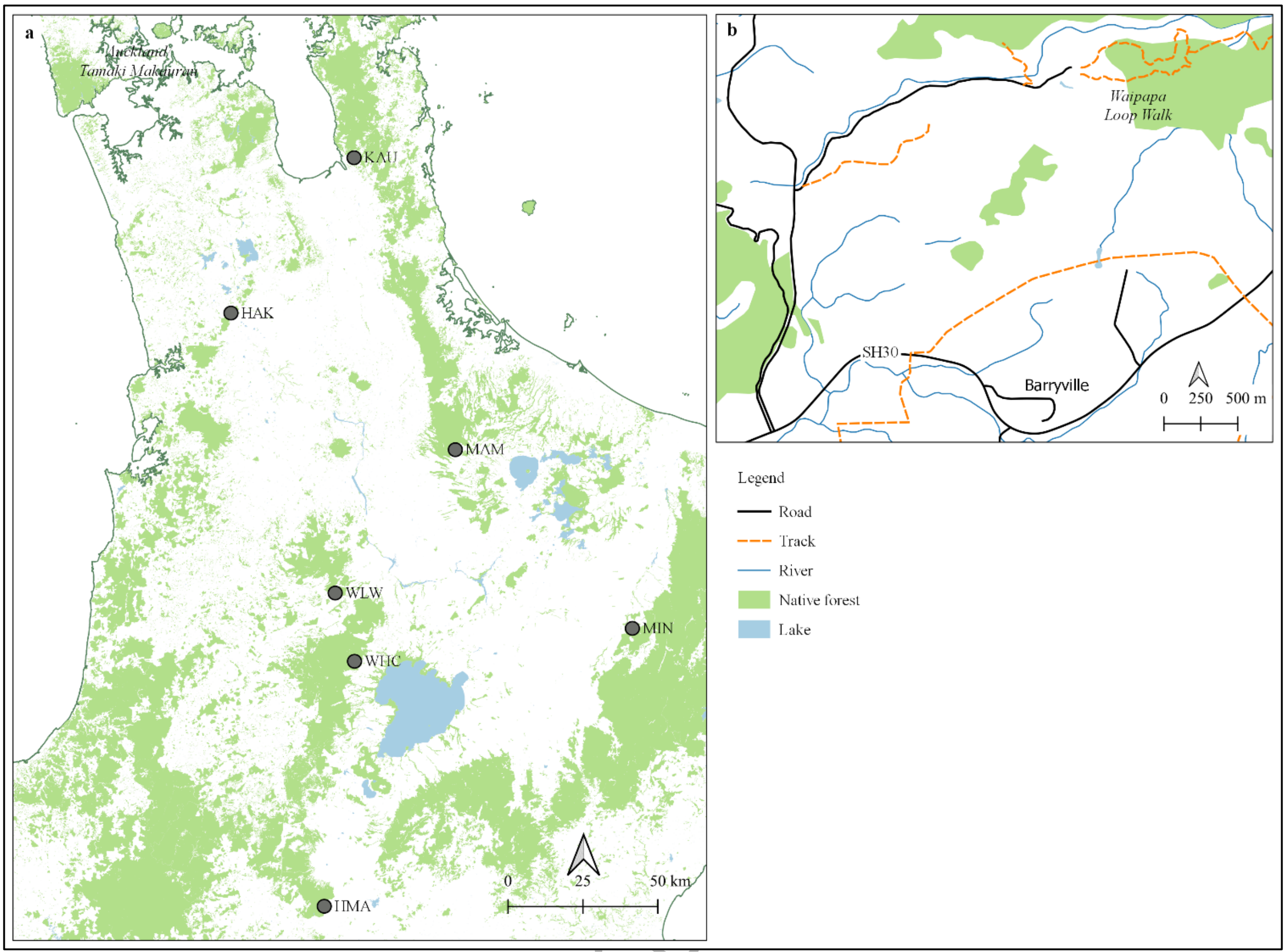

Figure 3: Location of: a) North Island/Te Ika a Maui matai and/or miro collection sites (1977 to 1999; see Table 1 for site listing); b) Waipapa Loop Walk (WLW), north Pureora Forest, revisited in 2019. Map data sourced from the *LINZ Data Service* and licensed for reuse under the CC BY 4.0 licence.

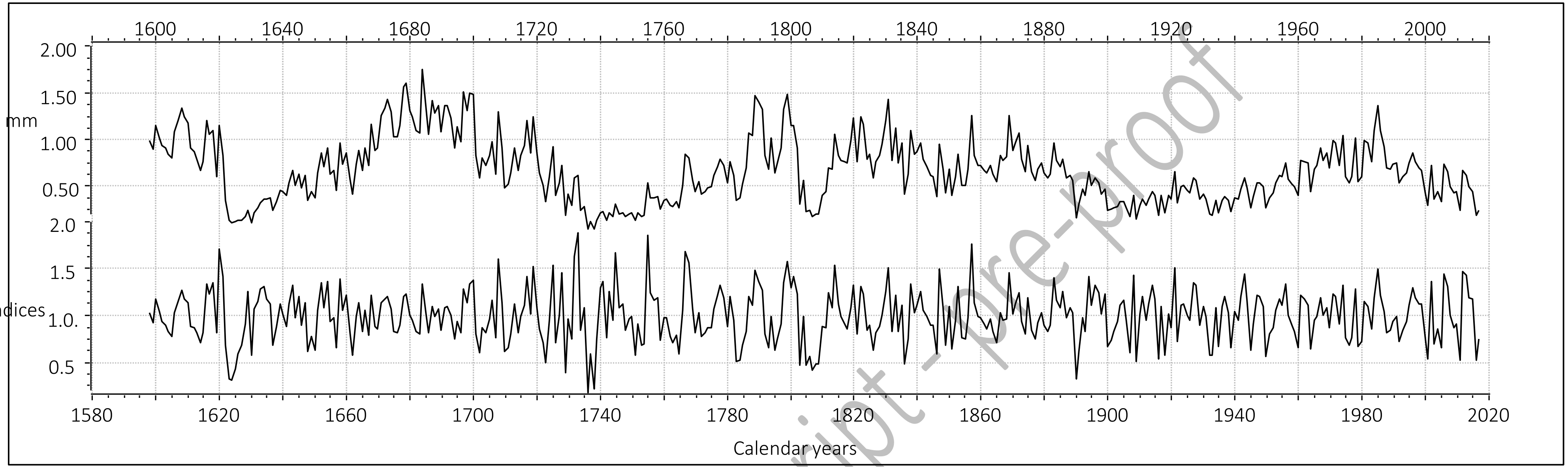

Figure 4: Example of matai (MAT005) raw ring width series (upper) and standardised series (lower). Calendar years are estimated based on ring counts only.

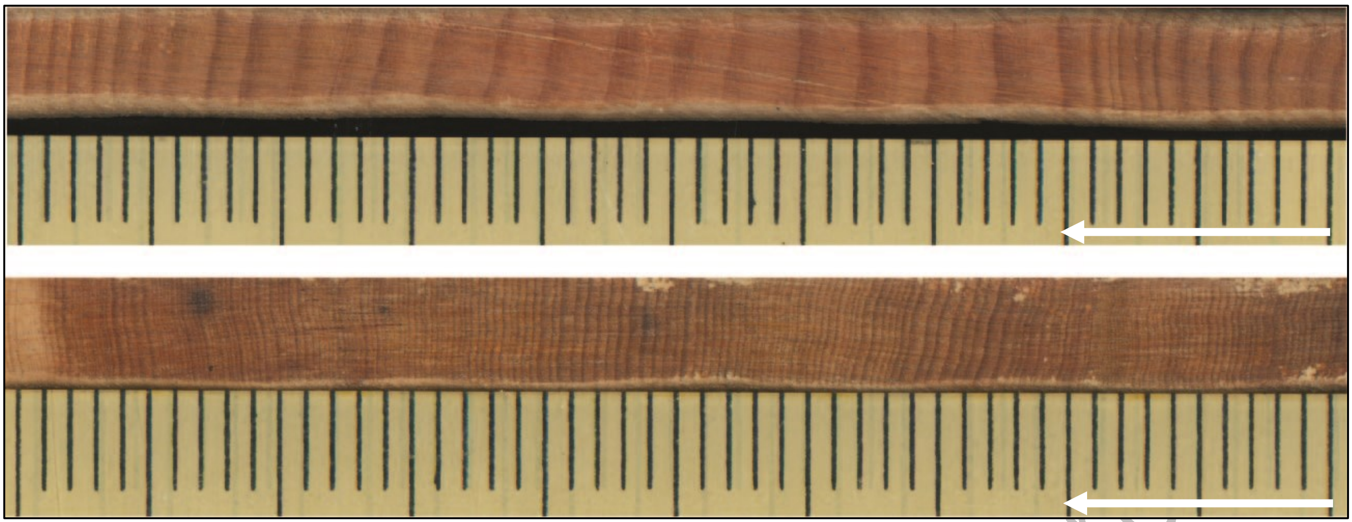

Figure 5: Sections of a single core showing the variability in width and clarity of matai growth rings. Miro growth rings (not shown) have similar variability. The arrow indicates the direction of growth with the youngest rings on the left side of the images. The scale is mm; the arrows are 10 mm long.

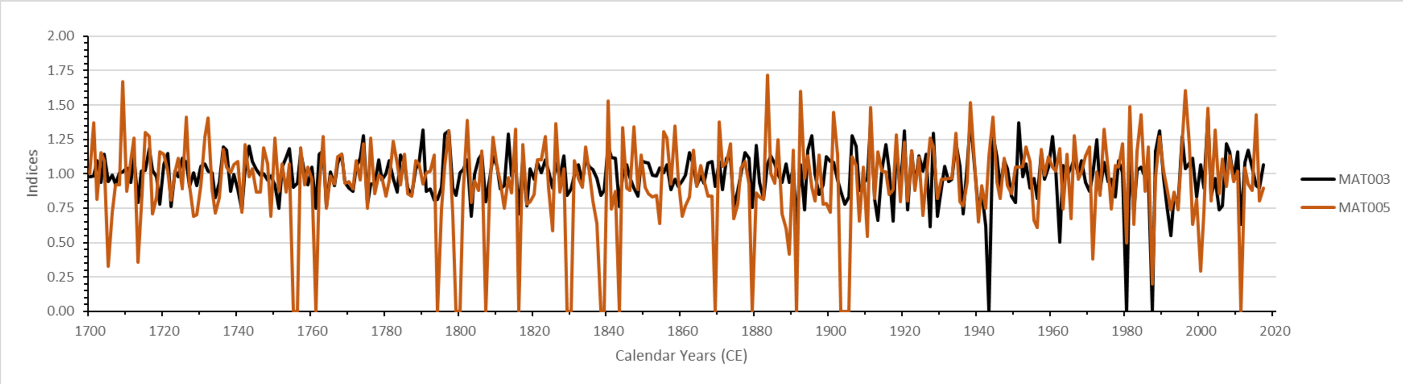

Figure 6: This graph illustrates a 300-year overlap between two WLW matai tree-sequences (MAT003, MAT005). Across this period there are sections where the ring series are appear similar, e.g., 1720 to 1780, 1900 to 2017. However, reconciliation required the addition of three locally absent rings to MAT003 and 19 locally absent rings to MAT005, reducing confidence in the reliability of the crossmatching.

Table 1: Location and site details of archived and new matai and miro samples.

Site Code	Name	Region	Lat (S), Long (E)	Elevation	Sample type	Notes
Matai						
HMA	Haere Maere, National Park	Manawatu-Whanganui	-39.36, 175.36	~750 m	1 cross-section	Collected by C. Lusk (1989) for his PhD research on the age structure and population dynamics of a podocarp forest in Central North Island. Samples were cut from tree stumps after the trees were felled as part of a realignment of the main trunk railway line.
KAU	Kauaeranga Valley	Waikato	-37.06, 175.67	-	1 cross-section	Collected February 1983 by John Ogden (?). Approximate location only.
MIN	Minginui, Whirinaki Forest	Bay of Plenty	-38.40, 176.45	350 m	2 trees (8 cores)	Collected 1977 by Peter Dunwiddie for the Southern Hemisphere sampling program led by Dr Valmore LaMarche, Laboratory of Tree-Ring Research, University of Arizona (La Marche et al 1979, Dunwiddie 1979). The cores and associated field notes are held in the Laboratory of Tree-Ring Research archive, University of Arizona, Tucson, USA.
WHC	Waihora, Pureora Forest	Waikato	-38.63, 175.67		1 cross-section	Collected in 1981 by Peter Bellingham from the North Waihora Block, eastern Pureora Forest. The area was dense rimu-dominated podocarp forest, with 20% matai and 10% miro over the whole area and was logged in September 1981. Bellingham sampled stumps to investigate age structure, taking slices at ~60 cm height. Approximate location only.
WLW	Waipapa Loop Walk, North Pureora Forest Park	Waikato	-38.47, 175.56	~550 m	14 cores	Collected by John Ogden between 1994 and 1999 for an ecology field school held at Pureora Forest. The collection includes cores from young and mature matai trees, some of which may have been repeat cored in successive years. (Core ID PUR)
					10 trees (20 cores)	Collected by the authors in February 2019. Two cores per tree, from the same side ~10 cm apart. (Core ID MAT)
Miro						
HAK	Hakarimata Reserve	Waikato	-37.40, 175.10	~300 m	1 tree (2 cores)	Collected 1977 by Peter Dunwiddie for the Southern Hemisphere sampling program. Details as above for Minginui. Location details from La Marche et al 1979.
MAM	Mamaku	Bay of Plenty	-38.08, 176.07	305 m	2 trees (4 cores)	Collected 1977 by Peter Dunwiddie for the Southern Hemisphere sampling program. Details as above for Minginui.
WLW	Waipapa Loop Walk Pureora Forest					

PUM	Waikato	-38.47, 175.56	~550 m		Collected by John Ogden between 1994 and 1999 for an ecology field school held at Pureora Forest. The collection includes cores from young and mature miro trees, some of which may have been repeat cored in successive years.
MIR	Waikato	-38.47, 175.56	~550 m	10 trees (19 cores)	Collected by the authors in February 2019.

Table 2: Details of sampled matai. The calendar dates are based on ring counts only and have not been securely established via crossmatching.

Sample code	DBH	# Rings	Minimum ring width (mm)	Mean ring Width (mm)	Maximum ring width (mm)	Standard deviation	Auto-Correlation [Lag=1]	Mean Sensitivity (%)	Minimum date span	Comments
HMA										
HMA449		511	0.08	0.62	1.75	0.31	0.89	20	~1474-1984	Estimated dates
KAU										
KAU001		111	0.19	1.77	4.06	0.86	0.86	24	1870-1980	
MIN										
MIN316		360	0.07	0.64	2.00	0.32	0.85	22	-	
MIN317		233	0.11	1.04	2.48	0.46	0.77	27	-	
WHC										
WHC001		586	0.60	0.62	2.70	0.39	0.92	21	~1382-1967	Estimated dates; outer rings truncated.
WLW (1994-99)										
PUR941		595	0.50	0.48	1.63	0.31	0.86	27	1398-1992	
PUR942		51	0.17	1.21	3.83	0.80	0.74	30	1942-1992	
PUR943		58	1.36	3.34	5.85	1.03	0.80	17	1935-1992	
PUR944		46	0.44	1.17	2.51	0.65	0.88	21	1947-1992	
PUR951		36	1.70	3.36	4.96	0.78	0.56	18	1958-1993	
PUR952		61	1.24	2.56	4.06	0.61	0.73	13	1933-1993	
PUR953		55	0.46	2.18	3.56	0.68	0.79	16	1939-1993	
PUR961		333	0.08	0.51	1.52	0.30	0.85	27	1662-1994	
PUR962		66	0.55	2.48	4.70	0.98	0.86	17	1929-1994	
PUR971		58	0.62	2.26	3.80	0.67	0.61	20	1938-1995	
PUR972		75	0.46	1.69	3.28	0.75	0.81	22	1921-1995	
PUR991		91	1.10	3.99	6.30	1.00	0.67	17	1907-1997	
PUR993		412	0.07	0.43	1.24	0.23	0.80	28	1586-1997	
PUR994		768	0.08	0.40	1.82	0.27	0.84	25	1230-1997	
WLW (2019)										
MAT001	18.4	107	0.33	2.40	4.62	1.10	0.92	18	1911-2017	Reconciled
MAT002	54.1	104	0.36	2.47	4.39	0.96	0.91	14	1914-2017	Reconciled
MAT003	107.2	740	0.03	0.50	2.68	0.42	0.91	28	1278-2017	Reconciled
MAT004	131.5	611	0.05	0.47	2.18	0.38	0.87	33	1407-2017	Core A

MAT005	110.1	458	0.11	0.69	1.92	0.37	0.89	22	1560-2017	Reconciled
MAT006	44.2	89	0.54	2.24	3.73	0.59	0.89	10	1929-2017	Reconciled
MAT007	108	815	0.03	0.43	2.17	0.27	0.82	28	1203-2017	Reconciled
MAT008	93.5	420	0.04	0.66	1.75	0.34	0.79	29	1606-2017	Reconciled
MAT009	14.6	119	0.34	1.94	3.82	0.78	0.87	19	1899-2017	Reconciled
MAT010	108.5	630	0.30	0.45	1.89	0.30	0.78	38	1323-1952	Reconciled; outer rings truncated

Table 3: Intra-tree crossmatching between matai series. Calendar dates are based on ring counts. The location of locally absent rings (LARs) in each series was based on careful checking of the sample and identification of the ring away from the measurement track or based on presence on another radius and comparison of ring width patterns from the same tree.

Series 1	Series length	Series 2	Series length	*t*-value (BP)	r	Overlap (years)	Common period (CE)	Comments
KAU001A	107	KAU001B	108	8.4	0.49	111	1870-1980	
WHC001As	513	WHC001B	416	9.4	0.47	416	1437-1852	A: LARs at 1745, 1748.
WCH001As	513	WHC001C	528	9.8	0.46	455	1440-1894	B: LARs at 1601, 1602, 1604, 1606, 1620, 1802, 1803, 1812, 1813, 1816, 1817.
WCH001B	416	WHC001C	528	11.0	0.70	413	1440-1852	C: LARs at 1606, 1620, 1659, 1761,1816, 1834.
HMA449B	511	HMA449A_s	459	11.0	0.52	459	1526-1984	A: LARs at 1706, 1707, 1887, 1909. Series truncated.
HMA449B	511	HMA449C_s	356	7.6	0.46	356	1526-1881	B: LAR at 1766.
HMA449B	511	HMA449D_s	352	10.9	0.36	352	1526-1877	
HMA449A_s	459	HMA449C_s	356	7.4	0.46	356	1526-1881	C: LARs at 1666, 1667, 1669, 1708, 1739, 1740. Series truncated
HMA449A_s	459	HMA449D_s	352	7.3	0.38	352	1526-1877	D: LARs at 1708, 1751, 1752, 1766. Series truncated
HMA449C_s	356	HMA449D_s	352	10.2	0.33	352	1526-1877	
MAT001A	107	MAT001B	101	29.1	0.94	101	1917-2017	
MAT002A	104	MAT002B	98	16.0	0.80	98	1920-2017	
MAT003B	740	MAT003A	734	27.6	0.74	734	1284-2017	A: LARs at 1356, 1369, 1715, 1716, 1724, 1732, 1972. B: LARs at 1405, 1408, 1988, 2001.
MAT004A	611	MAT004Bi	192	16.3	0.76	192	1504-1695	MAT004B cut into two sections due to an unmeasurable band of rings
MAT004A	611	MAT004Bo	144	6.6	0.52	144	1711-1854	
MAT005B	384	MAT005Am	286	18.9	0.76	286	1635-1920	MAT005 cut into three sections due to ring issues. Central section matched to MAT005B
MAT006B	89	MAT006A	86	16.2	0.84	86	1929-2017	
MAT007B	815	MAT007A	626	25.1	0.74	626	1354-2017	A: LARs at 1435, 1697, 1934, 1938. B: LARs at 1614, 1851, 1881.
MAT008B	420	MAT008A	412	38.0	0.90	412	1606-2017	A: LARs at 1736, 1739.
MAT009B	119	MAT009A	114	10.5	0.73	114	1904-2017	
MAT010B	630	MAT010A	616	32.8	0.83	616	1340-1955	A: LARs at 1522, 1528, 1548, 1551, 1604, 1682, 1832, 1842. Outer ~65 rings unmeasurable. B: LARs at 1494, 1499, 1577, 1584, 1694, 1820, 1822, 1870, 1879, 1885. Outer ~65 rings unmeasurable.

Table 4: Details of miro samples. Note that all calendar dates are based on ring counts only and have not been securely established via crossdating.

Sample code	DBH (cm)	# Rings	Minimum ring width (mm)	Mean ring width (mm)	Maximum ring width (mm)	Standard deviation	Auto-Correlation [Lag=1]	Mean Sensitivity (%)	# Locally absent rings	Minimum date span (rel/CE)	Comments
HKM											
HAK255		-	-	-	-	-	-	-	-	-	A & B cores unmeasurable
MAM											
MAM293		410	0.04	0.47	1.23	0.20	0.53	34		1-410	A & C cores only
MAM301		240	0.09	0.74	1.90	0.38	0.83	28		1-240	Truncated
WLW (1994-99)											
PUM942		252	0.09	0.62	1.60	0.31	0.61	36		1741-1992	
PUM943		226	0.08	0.75	2.42	0.40	0.60	29		1767-1992	
PUM952		222	0.09	0.72	1.76	0.43	0.71	28		1772-1993	
PUM961		69	0.58	1.60	3.39	0.60	0.77	21		1889-1993	
PUM962		71	0.09	0.82	1.85	0.44	0.64	33		1924-1994	
PUM963		130	0.11	1.20	2.29	0.60	0.70	35		1 - 130	Core broken
PUM971		71	0.21	1.49	3.07	0.79	0.79	31		1925-1995	
WLA (2019)											
MIR001	100.5	-	-	-	-	-	-	-	-	-	Not measurable
MIR002A	85	468	0.07	0.50	1.66	0.31	0.74	35	~14 rings	1550-2017	
MIR002B	85	460	0.11	0.49	1.75	0.32	0.75	35	different	1558-2017	
MIR003	89	-	-	-	-	-	-	-	-	-	Not measurable
MIR004A	78.5	296	0.10	0.64	2.08	0.33	0.67	36	~ 12 rings	1722-2017	
MIR004B	78.5	303	0.09	0.64	1.72	0.47	0.64	34	different	1715-2017	
MIR005A	108.8	523	0.09	0.64	3.67	0.47	0.73	37		1495-2017	
MIR006A	110.4	563	0.08	0.61	1.86	0.38	0.74	38	~ 9 rings	1455-2017	
MIR006B	110.4	562	0.06	0.65	1.94	0.38	0.69	39	different	1456-2017	
MIR007A	63.6	415	0.10	0.62	2.02	0.36	0.66	37	~10 rings	1574-1988	
MIR007B	63.6	402	0.08	0.64	2.11	0.39	0.63	37	different	1616-2017	
MIR008A	85	496	0.08	0.62	2.38	0.37	0.74	39	~13 rings	1522-2017	
MIR008B	85	457	0.07	0.64	1.88	0.37	0.71	39	different	1561-2017	
MIR009A	69.3	513	0.07	0.55	1.73	0.37	0.71	40	Unknown #	1505-2017	
MIR009B	69.3	318	0.07	0.65	1.88	0.39	0.64	42	rings	1700-2017	
MIR010	103	478	0.07	0.75	2.54	0.38	0.59	40		1540-2017	Reconciled

Table 5: Intra-tree crossmatching between miro series

Calendar dates are based on ring counts. The location of locally absent rings (LARs) was based on careful checking of the sample and identification of the ring away from the measurement track, or based on presence on another radius and comparison of ring width patterns.

Series 1	Series length	Series 2	Series length	*t*-value (BP)	r	Overlap (years)	Common period (rel/CE)	Comments
MIR010A	478	MIR010B	430	23.2	0.81	430	49-478	Relative years
MAM293a	410	MAM293b	373	12.9	0.29	373	1566-1975	A: LARs at 1651, 1711,1753, 1754, 1769, 1776, 1787, 1800 C: LARs at 1634, 1681, 1684, 1849, 1968, 1969.
MAM301b_s	241	MAM301a_s	237	16.8	0.89	240	2-238	Relative years; A: LARs at relative year 221