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A dendroarchaeological approach to the study of Iberian cultural heritage




HISTORIA FORESTAL, ABASTECIMIENTO DE MADERA Y ANILLOS DE CRECIMIENTO

Una aproximación dendroarqueológica al estudio del patrimonio cultural en la Península Ibérica

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A mis padres,

José Manuel y Pilar

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HISTORIA FORESTAL, ABASTECIMIENTO DE MADERA Y ANILLOS DE LOS ÁRBOLES
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Interior Jaen cathedral (photo: M. Domínguez Delmás)

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With this thesis concludes a dream that began 15 years ago, when doing an internship at the Ring Foundation in the Netherlands I got fascinated by the amount of information that could be extracted from wood by dendrochronology. During the seven months that I trained as a dendrochronologist at the Foundation, surrounded by the enthusiasm and supervision of Elsemieke Hanraets and Ute Sass-Klaassen, I had the opportunity to work with all types of wood, from ancient oaks of forests that had been buried thousands of years ago in Dutch bogs, to pines and spruces from Norway imported into the Netherlands during the Early Modern Period, as well as with timbers from historic buildings, and the most exquisite furniture and cabinets that are now exhibited at the Rijksmuseum in Amsterdam. That was the beginning of everything, and words cannot express how thankful I am to Elsemieke and Ute for those inspiring months. There was no turning back. There and then I decided that this would be my path, and that someday I would do my PhD thesis studying the cultural heritage of my own country by dendrochronology.

This journey has been long, and I have not traveled alone. In all these years I have had the fortune and pleasure to get in contact and learn from many dendrochronologists, all of them excellent researchers, who have become great colleagues and have helped me, in one or other way, to realize my dream. I am very grateful to:

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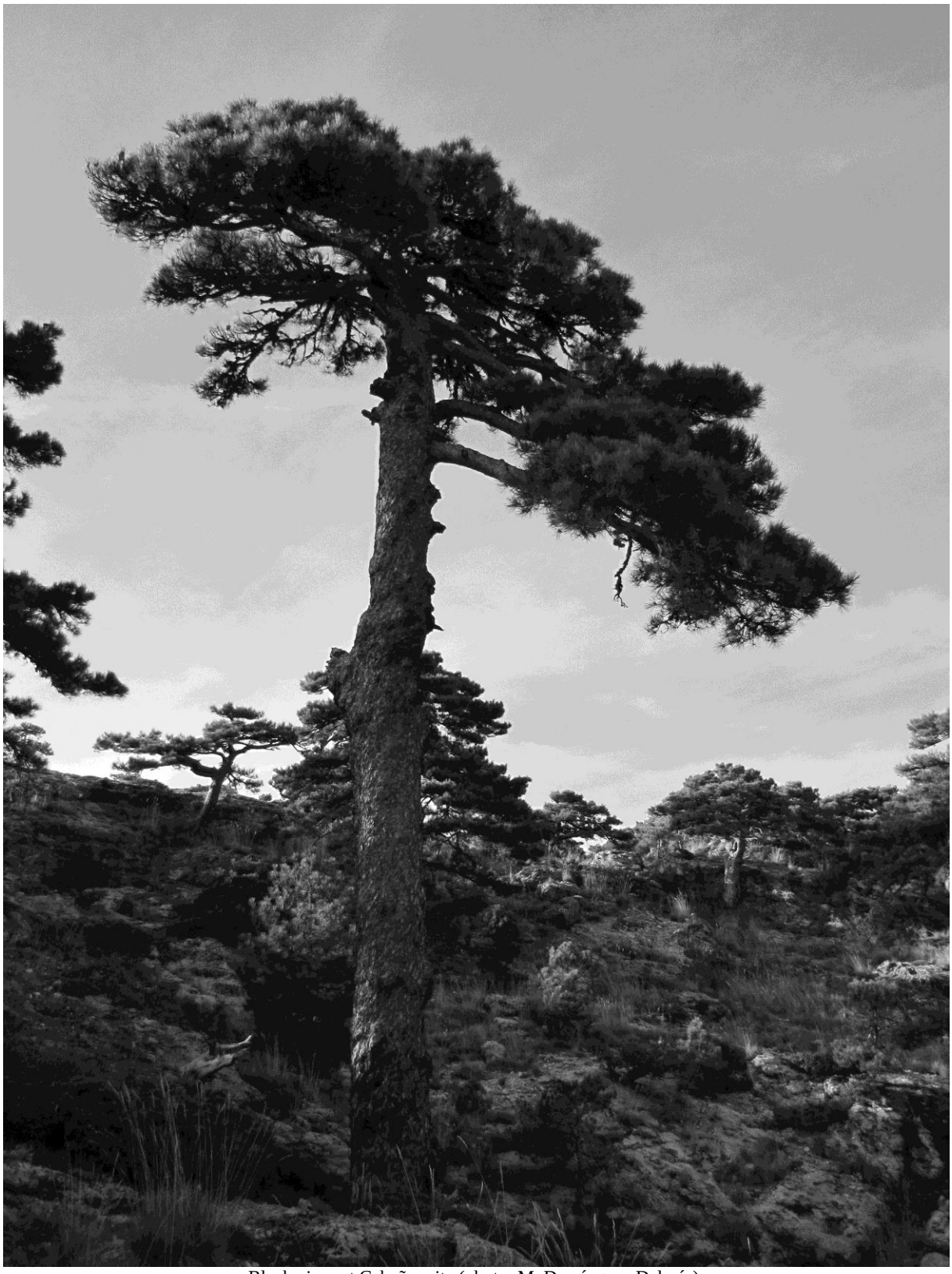
As we are free to dream, I dream that the conclusion of this journey is just the beginning of a new one, full of opportunities to keep on learning, exploring and discovering.

Marta, 18 September 2015



Black pines at Cabañas site (photo: M. Domínguez Delmás).

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Con esta tesis concluye un sueño que comenzó hace 15 años, cuando haciendo una estancia en la Fundación Ring en Amersfoort (Países Bajos) quedé fascinada por la cantidad de información que podía extraerse de la madera mediante la dendrocronología. Durante los siete meses que pasé allí formándome como dendrocronóloga, rodeada por el entusiasmo y la supervisión de Elsemieke Hanraets y Ute Sass-Klaassen, tuve la oportunidad de trabajar con todo tipo de maderas: desde robles de bosques antiquísimos que llevaban enterrados miles de años en las tierras holandesas que antaño fueron pantanos, hasta pinos y píceas de la Edad Moderna importadas a los Países Bajos desde Noruega, pasando por la madera de edificios históricos y de los más exquisitos muebles y aparadores que ahora se exponen en el Rijsmuseum de Amsterdam. Ese fue el principio de todo y cualquier palabra de agradecimiento es poca para dedicársela a Elsemieke y a Ute. No había vuelta atrás. Allí y entonces decidí que este sería mi camino, y que algún día haría el doctorado estudiando la madera del patrimonio cultural de mi país mediante la dendrocronología.

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Roof structure of the pyramidal roof above the choir at Jaen Cathedral (photo: M. Domínguez Delmás).

SUMMARY

This thesis is devoted to review, assess and validate the potential of dendroarchaeology in the Iberian Peninsula, to define strategies for its future development and implementation in this territory, and to illustrate the importance of its application in the study of cultural heritage made of wood. To accomplish these main goals, a review of the current state of dendroarchaeology in the Iberian Peninsula was carried out, together with four pilot projects directed at exploring every aspect covered by dendroarchaeological research. One of these projects consisted on the development of multi-century reference chronologies of black pine (*Pinus nigra* subsp. *salzmannii*) at different elevations in the Cazorla and Segura mountains (eastern Andalusia), to explore their suitability as dating and provenancing tools for historic timbers. The other pilot projects illustrate the application of dendroarchaeology to provide, in addition to absolute dates, information about the provenance of the wood, the organisation of timber supply, the transport and trade of timber, and the evolution of wood-working techniques during the Early Modern Period. For this, dendroarchaeological research was carried out on historic buildings (Jaen Cathedral and *Colegial del Salvador church* in Seville), selected art-historic objects (*Evangelistas* altarpiece at Seville cathedral) and shipwrecks (*Arade 1* shipwreck, found at the mouth of the Arade river in the south of Portugal, excavated, and later on conserved at the *Centro Nacional de Arqueologia Náutica e Subaquática*, in Lisbon).

The results have demonstrated that dendroarchaeological studies have a great potential in the Iberian Peninsula. Wood from historic buildings, art-historic objects and archaeological contexts is abundant in the territory and represents an historic, ethnographical and environmental archive that can be studied by means of dendrochronology. This thesis shows that to achieve a well replicated set of reference chronologies needed for dating cultural heritage from this geographical region, strategies for tree-ring data compilation should be directed at key source areas along elevation, latitudinal and longitudinal gradients, covering all possible environmental niches. To improve the replication of the earlier centuries of those chronologies and extend them back in time, timbers from historic buildings offer the best prospects, although the selection of buildings should be preceded by documentary research, in order to acquire as much information *a priori* as possible in what regards the origin of the wood.

As demonstrated in this thesis, the transport and trade of timber within the peninsula, and specially the import of raw timber and manufactured timber products into Spain and Portugal are questions that can be addressed by dendroarchaeology. They also provide a broader, international dimension to future research lines. Dendroprovenancing studies have a paramount role in this territory, hence multidisciplinary national and international collaboration is required to explore novel, high-resolution approaches to establish the provenance of historic wood.

Last but not least, campaigns of awareness about the potential of this discipline to increase our understanding of cultural heritage have proven effective in the short and medium term, but for dendroarchaeology to be fully established in Spain and Portugal, structural support and commitment from national and regional institutes, research centres and academic institutions is essential. Only then will dendroarchaology reach the full potential and high quality standards that have already been acquired in most of northern, central and eastern Europe.

Evangelistas altarpiece at Seville cathedral (photo kindly provided by A. Jiménez Martín).

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RESUMEN AMPLIADO

Desde la antigüedad, la madera ha sido una materia prima fundamental para el desarrollo y sostenibilidad de culturas e imperios. La historia forestal de la Península Ibérica está marcada por siglos de guerras, agricultura, pastoreo y la sobreexplotación de los bosques para la construcción de edificios, construcción naval y producción de carbón. La progresiva reducción de los bosques ocurrida durante la Edad Moderna acarreó la promulgación de leyes y políticas destinadas a proteger y recuperar los bosques en áreas clave del territorio, y dio lugar a la importación de madera procedente de naciones extranjeras. El legado de esta historia de deforestación e importación de madera forma ahora parte de nuestro patrimonio cultural, por lo que madera de diferentes épocas y zonas geográficas puede encontrarse por toda la península en yacimientos arqueológicos terrestres y subacuáticos, en artesonados, cubiertas, puertas y ventanas de edificios históricos, así como en muebles, pinturas sobre tabla y esculturas de madera de colecciones públicas y privadas. Además, la madera de bosques ibéricos utilizada para construir barcos en siglos pasados está conservada en algunos pecios alrededor del mundo. La dendrocronología permite recuperar el archivo histórico, etnográfico y ambiental contenido en dicho patrimonio cultural hecho con madera, contribuyendo así a ampliar nuestro conocimiento sobre las interacciones entre nuestros antepasados y su entorno natural en períodos específicos de tiempo.

La dendrocronología es la ciencia que estudia las variaciones anuales de crecimiento en la madera. Dichas variaciones son causadas principalmente por las condiciones climáticas y ecológicas, y también en parte por intervenciones antrópicas, por lo que las series de anillos en la madera representan registros anuales del entorno natural e histórico en el que crecieron los árboles. Dentro de la dendrocronología, la especialidad de dendroarqueología estudia los patrones de anillos de maderas históricas y prehistóricas para anclarlos en el tiempo e inferir una amplia gama de información. Las aplicaciones de esta ciencia en disciplinas relacionadas con el patrimonio cultural material (arqueología, historia del arte, historia de la arquitectura) son por tanto muy diversas. Más allá de la datación exacta de la madera puede obtenerse también información sobre la procedencia de la misma (‘dendroprocedencia’), la selección de especies, el tipo de bosque del que se sacaron los árboles, el transporte y comercio de la madera, así como sobre formas de procesarla. Además, a falta de dataciones dendrocronológicas absolutas, la datación cruzada relativa entre series de anillos de numerosas piezas de la misma estructura permite identificar fases constructivas, así como definir espacios temporales de ocupación de asentamientos antiguos, o deducir cómo se organizaba el abastecimiento de madera.

Para poder aplicar la datación dendrocronológica absoluta y la ‘dendroprocedencia’ se requieren cronologías de anillos de referencia para las especies arbóreas específicas que se están investigando. Además, dichas cronologías de referencia deben abarcar el período temporal de las muestras que se

investigan, así como la zona de donde se extrajo la madera. En la Península Ibérica la falta de este tipo de cronologías de referencia dificulta el empleo de la dendroarqueología, lo que hace que esta disciplina esté infrarrepresentada a pesar de la abundancia de madera histórica de diferentes épocas que puede encontrarse en todo el territorio ibérico. **El objetivo de esta tesis es por tanto revisar, evaluar y validar el potencial de la dendroarqueología en la Península Ibérica, definiendo estrategias para su desarrollo y futura aplicación en este territorio, e ilustrando la importancia de su uso en el estudio del patrimonio cultural hecho con madera.**

Con este objetivo principal en mente se diseñaron cinco objetivos específicos que dieron lugar a los cinco artículos que componen esta tesis (véase el Apéndice 1). El ***Artículo 1*** presenta una revisión del estado de la cuestión y las perspectivas futuras de la dendroarqueología en la Península Ibérica. Este artículo comienza describiendo la importancia y complejidad del territorio ibérico y su patrimonio cultural material para estudios dendroarqueológicos, ofreciendo una visión de la historia forestal peninsular y cómo quedó marcada por las diferentes culturas que poblaron el territorio desde la antigüedad; a continuación, se presenta el estado actual de la dendroarqueología, revisando los esfuerzos realizados hasta ahora para establecer esta disciplina en España y Portugal; y, por último, se proponen líneas de investigación y estrategias hacia la futura aplicación de esta ciencia en el estudio del patrimonio cultural hecho con madera en la Península Ibérica. El ***Artículo 2*** investiga el potencial de cronologías de pino salgareño (*Pinus nigra* subsp. *salzmannii*) de las montañas de Cazorla y Segura para servir como herramientas para la datación de maderas históricas. Para ello, cuatro cronologías de anillos de pino salgareño fueron creadas a lo largo de un gradiente altitudinal de casi 1.000 m en dichas montañas, y se analizó tanto su repuesta a los factores climáticos a lo largo del gradiente, como la sincronización (‘teleconexión’) de estas cronologías entre ellas y con otras cronologías de coníferas del resto de la Península, norte de África y cuenca Mediterránea. Los ***Artículos 3, 4 y 5*** representan estudios piloto que ilustran el potencial de la dendroarqueología aplicada en la investigación de edificios históricos (catedral de Jaén e iglesia Colegial del Salvador en Sevilla; ***Artículo 3***), objetos histórico-artísticos (retablo de los Evangelistas en la catedral de Sevilla; ***Artículo 4***) y pecios (pecio *Arade 1*, localizado en la desembocadura del río Arade, en el sur de Portugal, excavado, y posteriormente conservado en el *Centro Nacional de Arqueologia Náutica e Subaquática* en Lisboa; ***Artículo 5***).

Como se resume en el ***Artículo 1***, las guerras, la agricultura, los incendios forestales, el pastoreo, la industria y las reforestaciones han moldeado los bosques ibéricos tal y como los conocemos hoy en día. Los bosques antiguos que sobreviven son en muchos casos meras reliquias de lo que fueron, pero representan el punto de partida para el desarrollo de cronologías de anillos de referencia. El inventario de los datos dendrocronológicos disponibles para la Península Ibérica ha revelado que las cronologías existentes tienen una amplia cobertura geográfica, pero son a menudo demasiado cortas para permitir la datación dendrocronológica de piezas históricas. Sin embargo, diferentes estudios realizados desde

1984 en varios puntos de España sugieren que esta disciplina tiene un gran potencial en el territorio peninsular. Numerosos objetos y estructuras del patrimonio arqueológico, arquitectónico e histórico-artístico de España y Portugal contienen maderas históricas que podrían ser utilizadas para expandir retrospectivamente las cronologías de árboles vivos. A su vez, esas cronologías permitirían determinar la datación y procedencia geográfica de un mayor volumen de patrimonio cultural construido en madera.

Una cuestión importante a tener en cuenta es que dicha madera de objetos y estructuras del patrimonio cultural podría no tener su origen en los bosques de zonas cercanas. Por ejemplo, está bien documentado que, durante siglos, los pinares de salgareño de las montañas de Cazorla y Segura han proporcionado madera para la construcción de edificios o la fabricación de utensilios en pueblos cercanos y en ciudades como Jaén, Córdoba o Sevilla, situadas kilómetros rio abajo en el valle del Guadalquivir. Los ríos han sido tradicionalmente utilizados como vías de conexión entre los bosques en las montañas y los pueblos y ciudades en los valles. El transporte de madera por vía fluvial era mucho más rápido y fácil que el terrestre, por lo tanto, este último se reservaba sobre todo para cubrir la distancia entre el bosque y la vía fluvial más cercana. Fuentes documentales informan sobre el transporte de madera por flotación en los principales ríos ibéricos como el Ebro, el Tajo y el Guadalquivir y sus afluentes, así como en ríos medianos como el Júcar, o más pequeños como el Bidasoa. Además de este transporte de madera entre lugares del territorio peninsular, la importación de madera procedente de los mercados del norte de Europa para construcción naval y fabricación de obras de arte adquirió especial relevancia durante la Edad Moderna. Así, existen referencias al roble y pino ‘de Flandes’, ‘pino de Prusia’ o ‘pino Riga' en documentos relacionados con la construcción naval y con la contratación de retablos. Dichos contratos también informan durante este período sobre la importación desde las Américas de 'cedro de Indias’ y otras especies. Esta tesis ha proporcionado con métodos dendrocronológicos pruebas empíricas tanto del abastecimiento y transporte de pino de Cazorla y Segura para construcción de edificios en la región Andaluza, como de la importación de madera a Sevilla procedente de países extranjeros.

Las cronologías de pino salgareño desarrolladas en las montañas de Cazorla y Segura (***Artículo 2***) contribuyeron a este resultado. La longitud de las cronologías parece reflejar la intensidad de las actividades históricas de saca de madera en estas montañas, con la cronología más larga (abarca el intervalo temporal 1331-2010 d.C.) obtenida en la parte alta de las montañas (CBS, 1,755-1,953 m s.n.m.), y la más corta (1840-2009 d.C.) obtenida en la parte baja, y por tanto más accesible (LIN, 1,079-1,177 m s.n.m.). Las dos cronologías a cotas intermedias (PMB, 1,500-1,619 y NAV, 1,582-1,702), presentan una alta calidad estadística para intervalos de longitud variable (1544-2009 y 1698-2009, respectivamente). El análisis de las relaciones clima-crecimiento a lo largo del gradiente reveló diferencias significativas entre las cronologías que parecen ser causadas por fluctuaciones en el clima regional y la respuesta adaptativa de los árboles a diferentes cotas altitudinales. Estas diferencias

podrían obstaculizar la datación cruzada de elementos de madera obtenidos de árboles a cotas bajas con la cronología obtenida en la parte alta de las montañas. Sin embargo, las cronologías de cotas intermedias podrían actuar en tales casos como puentes para la datación cruzada, ya que muestran más similitudes con la cronología de las cotas bajas que con la de la cota superior. Además, dichas cronologías de cotas intermedias presentan muy buena teleconexión con otras cronologías de coníferas en la Península Ibérica (especialmente con cronologías de pino salgareño del Sistema Central) y el norte de Marruecos, lo que es muy conveniente para poder datar piezas históricas.

El potencial de datación de las cronologías de salgareño creadas se puso a prueba con maderas históricas de las cubiertas de la catedral de Jaén y la iglesia Colegial del Salvador en Sevilla (***Artículo 3***), ya que fuentes documentales informaban de que la madera de dichas cubiertas se extrajo de las montañas de Cazorla y Segura. Las estructuras de cubiertas estudiadas en la catedral de Jaén datan según los archivos de los siglos XVI (sacristía), XVII (cubierta sobre la cúpula del altar) y XVIII (cubierta piramidal sobre una de las bóvedas del coro), mientras que las de la iglesia Colegial del Salvador se completaron entre los años 1703 y 1709. Ambos edificios fueron construidos en los emplazamientos de mezquitas aljamas medievales, tras haber sido utilizadas éstas durante siglos para el culto cristiano. Por lo tanto, la hipótesis de partida en la investigación de estas cubiertas contemplaba la posibilidad de que pudiesen contener madera reutilizada de las mezquitas medievales. Dicha posibilidad, junto con el hecho de que se emplease madera de las sierras de Cazorla y Segura, hacían de estos edificios excelentes casos de estudio para investigar el suministro de madera para construcción de grandes inmuebles en diferentes siglos, permitiendo estudiar aspectos como la procedencia de madera, su transporte y la evolución de las técnicas de procesado a lo largo de los siglos.

Durante la inspección de las cubiertas se encontraron diferentes anotaciones de carpintero en la cubierta del siglo XVI de la catedral de Jaén, y en todas las estructuras investigadas se observaron en las maderas marcas de herramientas (sierra y distintos tipos de azuelas). En varias cubiertas también se encontraron maderas con muescas que indicaban que habían sido reutilizadas, y en dos cubiertas piramidales de la Colegial del Salvador se encontraron pruebas materiales que apuntaban a que los troncos de pino se transportaron por flotación en almadías, para ser procesados en piezas de la forma requerida una vez llegados al lugar de construcción. La investigación dendrocronológica tuvo como resultado la datación absoluta de todas las cubiertas investigadas en la catedral de Jaén con las cronologías de pino salgareño desarrolladas en esta tesis. Las dataciones obtenidas son consistentes con la información histórica sobre los años de compra de la madera y la conclusión de las cubiertas, y además sugieren que la madera para las cubiertas de los siglos XVII y XVIII se extrajo de zonas de las sierras situadas en cotas de altitud intermedias. Tales resultados ponen de manifiesto el potencial de las cronologías desarrolladas para la datación de maderas históricas y confirman que los árboles de distintas altitudes presentan diferentes señales dendrocronológicas, lo que permite determinar la

procedencia de la madera histórica extraída de estas montañas con alta resolución. Algunas maderas de la estructura del siglo XVI permanecen sin datar, por lo que la hipótesis de que podrían pertenecer a la antigua mezquita sigue todavía abierta. En la iglesia Colegial del Salvador sólo dos maderas pudieron ser datadas, lo que ilustra la complejidad de la señal dendrocronológica de las sierras de Cazorla y Segura, y de la organización del abastecimiento de madera para la construcción de este edificio a comienzos del siglo XVIII. Este resultado también refleja la necesidad de continuar desarrollando cronologías de referencia a diferentes altitudes en las montañas andaluzas para averiguar de dónde se sacó exactamente la madera para este edificio.

La inspección e investigación de cinco de los cuadros que componen el retablo de los Evangelistas de la catedral de Sevilla (***Artículo 4***) permitieron la reconstrucción del procesado de la materia prima (roble *borne*) hasta obtener el producto final (los tableros sobre los que se pintarían las imágenes). Las marcas observadas en el reverso de los tableros sugieren por un lado que las herramientas utilizadas para preparar las planchas fueron similares a las empleadas en talleres flamencos, y por otro, que se siguió un proceso de preparación de los tableros similar al de dichos talleres. Además, la investigación ha proporcionado una descripción empírica del producto de madera conocido como *borne* en la Península Ibérica. Dicho término se empleaba para referirse a un tipo específico de producto maderero conocido como '*wainscot*' en los mercados del norte de Europa. *Wainscots* eran tablas de roble de la mejor calidad (generalmente partidas al hilo, sin nudos y con grandes dimensiones) que se exportaron en grandes cantidades desde el sureste Báltico hacia Europa occidental hasta mediados del siglo XVII, principalmente desde el puerto polaco de Gdansk, así como desde Koningsberg en la antigua Prusia (conocida actualmente como Kaliningrado). Los *wainscots* aparecen con frecuencia en registros históricos como los documentos aduaneros del puerto de Gdansk. Mediante la investigación dendrocronológica también se ha podido verificar la fecha de construcción del retablo en el año 1555 d.C., y determinar que el roble *borne* empleado en su construcción es originario del suroeste de Suecia. Esta es la primera vez que dicha procedencia se documenta por medios dendrocronológicos en el estudio de roble empleado para pintura sobre tabla en el oeste de Europa, dado que los centros más importantes de producción artística del siglo XVI empleaban fundamentalmente roble del sureste Báltico. Este resultado ilustra cómo la dendrocronología puede proporcionar evidencias sobre rutas comerciales alternativas a comienzos de la Edad Moderna.

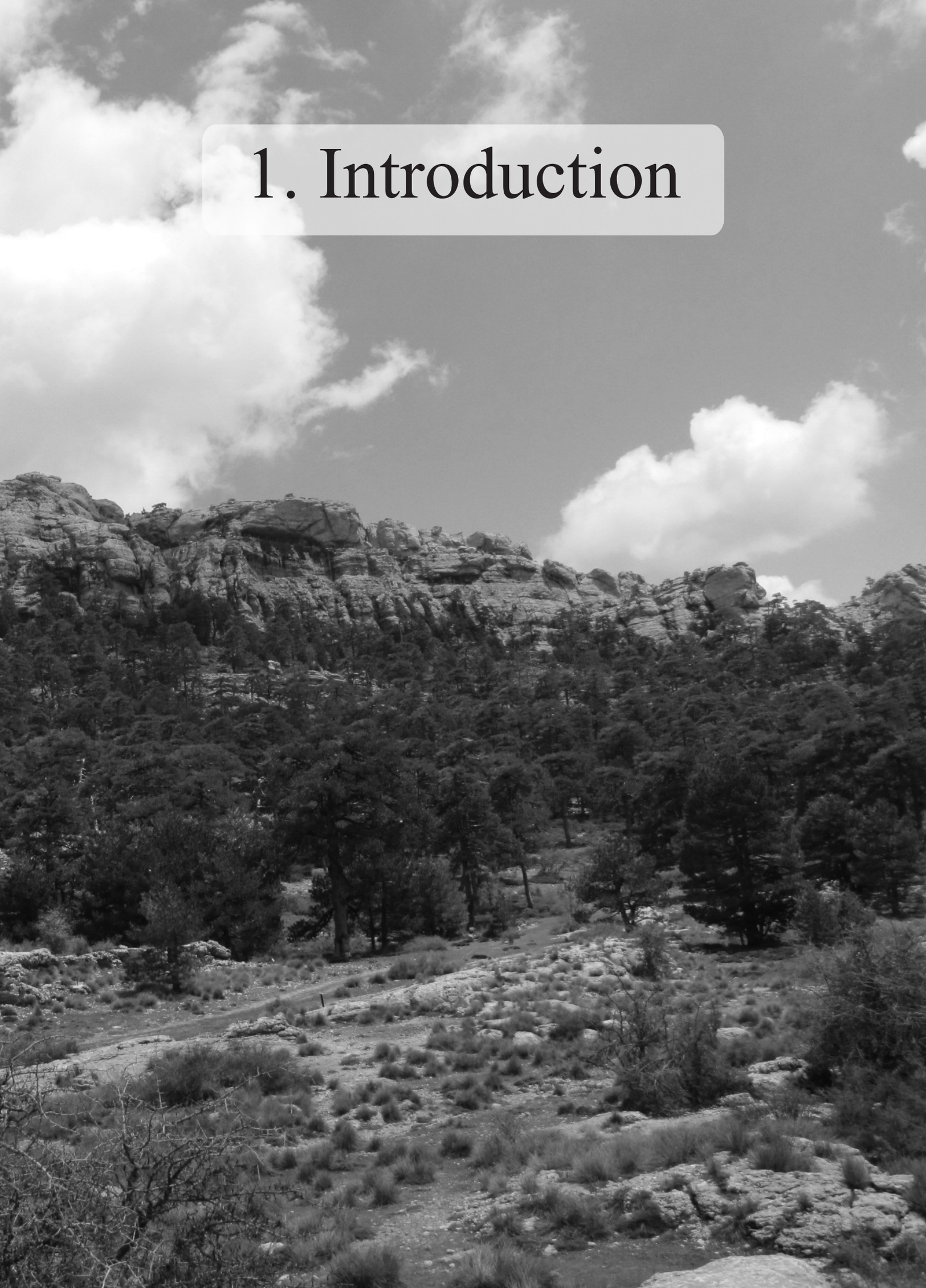
Por último, el pecio *Arade 1* (***Artículo 5***) (correspondiente supuestamente a un barco del siglo XVI, según indicios arqueológicos y datación por radiocarbono) fue seleccionado para investigación dendrocronológica dada la buena conservación de muchos de sus elementos estructurales (tablazón, genoles y varengas) y puesto que en años precedentes ya se había realizado un minucioso registro arqueológico del conjunto de la estructura, así como de las piezas individuales. Además, como parte de dichas investigaciones llevadas a cabo en años anteriores por distintos laboratorios, la madera de numerosos elementos había sido identificada como roble quejigo (*Quercus faginea*) y alcornoque

(*Quercus suber*). Este resultado había llevado a los arqueólogos a considerar como principal hipótesis que el barco se había construido con madera local/regional, por lo que las características constructivas se asociaron un tipo de construcción Portuguesa/Ibérica. Sin embargo, dichas identificaciones resultaban controvertidas, dada la dificultad (por no decir imposibilidad) que supone aun hoy en día la separación de robles caducifólios/marcescentes presentes en la Península Ibérica basándose en características de anatomía de la madera. Con el fin de re-analizar las muestras que dieron como resultado dichas identificaciones polémicas, además de nuevas muestras de elementos estructurales, se llevó a cabo la identificación de especie de un total de 54 piezas de madera. Cincuenta y dos de ellas fueron identificadas como roble de hoja caduca/marcescente (*Quercus* subg. *quercus*), sin que pudiese efectivamente afinarse la identificación a nivel de especie, y dos como castaño (*Castanea sativa*). De los 24 elementos estructurales seleccionados para la investigación dendrocronológica e incluidos en dichas identificaciones, 23 pudieron ser datados, estableciéndose la fecha de corta de los árboles entre la primavera/verano de 1579 d.C. y las mismas estaciones de 1583 d.C.. La homogeneidad en el crecimiento de los árboles que se emplearon para obtener las piezas datadas, sugiere que pertenecen a la estructura original del barco, por lo que la construcción del mismo debió tener lugar en 1583 d.C. o poco después. Asimismo, el origen de la madera pudo determinarse en el oeste de Francia, concretamente en el curso medio del valle del Loira. Dicha zona está comprendida en el área de distribución de los robles *Q. robur, Q. petraea* y en menor medida *Q. pubescens*, mientras que el *Q. faginea* y el *Q. suber* están totalmente ausentes en esta zona. Por tanto, las identificaciones proporcionadas por estudios previos quedaron definitivamente descartadas. Los resultados de la investigación dendrocronológica proporcionaron una datación precisa y la procedencia exacta de las maderas investigadas, permitiendo inferir también la fecha probable de construcción del barco. Sin embargo, la pregunta de dónde se construyó la embarcación sigue sin respuesta cierta. La procedencia de las piezas de roble y castaño en el curso medio del valle del Loira, implica que la embarcación se construyó bien en algún astillero francés, o en algún otro astillero ibero-atlántico que importaba madera francesa para construcción naval. Esta investigación ilustra plenamente el potencial de la dendroarqueología aplicada al estudio de pecios cuando se adopta una estrategia de muestreo apropiada. Tal estrategia debe incluir la inspección y análisis de numerosas piezas estructurales cuidadosamente seleccionadas. La existencia de una densa red de cronologías de referencia locales disponibles para el área de procedencia de la madera, así como la colaboración internacional, fueron las claves del éxito de esta investigación. Si la madera se hubiese extraído de zonas donde escasean las cronologías de referencia (como por ejemplo, la Península Ibérica), las muestras hubiesen quedado sin datar. El desarrollo de dichas cronologías de referencia en áreas de las Península Ibérica que suplieron de madera la construcción naval sigue siendo un paso muy necesario hacia la correcta evaluación y el estudio de pecios potencialmente ibéricos que yacen en fondos marinos por todo el mundo. Las maderas de los pecios son una excelente fuente de información para comprender tanto los cambios que

acontecieron durante la Edad Moderna en tradiciones de construcción naval ibero-atlánticas, como en las prácticas de manejo forestal y en las redes del comercio de madera.

En esta tesis se ha validado y demostrado que los estudios dendroarqueológicos tienen un gran potencial en la Península Ibérica. La madera de edificios históricos, objetos histórico-artísticos y de yacimientos arqueológicos abunda en el territorio peninsular y su estudio por métodos dendroarqueológicos puede desentrañar las interacciones de nuestros antepasados con esta materia prima tan preciada en siglos recientes y anteriores. Para lograr un conjunto de cronologías de referencia en España y Portugal que permitan el adecuado estudio del patrimonio cultural hecho con madera, estrategias futuras dirigidas a la compilación de series de anillos de referencia deben comenzar por el muestreo de árboles vivos en zonas históricas de abastecimiento de madera, cubriendo todos los posibles nichos ambientales a lo largo y ancho de gradientes altitudinales, latitudinales y longitudinales. Para mejorar la calidad y replicación de los siglos más antiguos de dichas cronologías y extenderlas retrospectivamente en el tiempo, se recomienda el muestreo de artesonados y cubiertas de techos de edificios históricos localizados preferentemente en las cercanías de las masas boscosas investigadas. La selección de inmuebles debería estar precedida por la investigación histórica, con el fin de adquirir tanta información *a priori* como sea posible sobre el origen de la madera empleada. Dicha estrategia maximizaría los esfuerzos dirigidos hacia la extensión retrospectiva de cronologías de referencia.

Esta tesis también ha puesto de manifiesto la posibilidad de estudiar por medios dendroarqueológicos cuestiones como el transporte de la madera en los ríos peninsulares, y sobre todo, la importación de productos madereros a España y Portugal, temas que dotan a las futuras líneas de investigación de una dimensión amplia e internacional. En este contexto de transporte y comercio de madera, los estudios de ‘dendroprocedencia’ tienen gran relevancia en la Península Ibércia, por lo que la colaboración multidisciplinar nacional e internacional adquiere un rol crucial para datar la madera y explorar nuevos métodos que permitan establecer su procedencia con alta resolución geográfica. Por último, campañas de sensibilización sobre el potencial de esta disciplina científica en el estudio del patrimonio cultural han demostrado ser eficaces a corto y medio plazo. Sin embargo, para asentar la dendroarqueología en España y Portugal y conseguir que su uso sea sistemático, es crucial contar con el apoyo estructural por parte de centros de investigación nacionales y regionales, así como de instituciones académicas. Sólo entonces alcanzará la dendroarqueología en estos países la relevancia, calidad y potencial que ha adquirido ya en la mayor parte del centro, norte y este de Europa.



1. Introduction

1. INTRODUCTION

1.1. Forest history, timber supply and cultural heritage

The importance of wood throughout human history can hardly be overestimated. Since ancient times people have used wood for artefacts, as construction material, and as fuel for heating in domestic contexts (e.g. cooking, heating) and industrial processes (iron melting, production of ceramics, etc.). In Europe, the size of forested areas has fluctuated over the past three millennia synchronously with shifts in population (Kaplan *et al*. 2009). As societies evolved, so did their needs for food and raw materials, and woodlands became increasingly exploited to gain pasture and agricultural land, as well as firewood and timber (Williams, 2006).

In Europe, the scarcity of this raw material in certain areas would trigger the transport of this material over large distances by the 2nd century AD (e.g. Domínguez-Delmás *et al*. 2014). From the 13th century onwards, and especially during the Early Modern Period (ca. AD 1450-1800), the demand of wood in highly populated areas of the west of the continent could not be sustained by local forests, and transport and trade of wood from central and north-eastern Europe first, and the Americas later on, acquired global relevance.

The forest history of the Iberian Peninsula is no exception, as centuries of wars, sheep breeding and overexploitation of woodlands led to the progressive depletion of forests. This prompted the enactment of laws and policies to protect and recover forested land in key areas of the territory, as well as to the importation of timber from foreign nations. The legacy of such history and trade has become part of our cultural heritage, and wood from different periods and diverse geographical origins has survived until today in archaeological sites from terrestrial and maritime contexts, historic buildings and works of art and furniture. Dendrochronology holds the key to unlock the historic, ethnographical and environmental archive contained in this material heritage made of wood, increasing our understanding of past human-environment interactions.

1.2. Dendrochronology: definitions and applications in cultural heritage studies

Dendrochronology is the science that studies the annual variations in growth rings of woody species. In temperate climates, tree growth activates in the spring and continues until the late summer or early autumn, depending on the elevation, latitude and longitude. The new annual ring is formed right under the bark, and its wider or narrower width will be mostly determined by climatic and ecological conditions (Fritts, 1976). Human interventions such as pruning and management practices also influence tree growth and induce variations that can camouflage in a higher or lesser degree the environmental signal contained in the ring widths (Schweingruber, 1996; Beeckman, 2005). Therefore, the sequences of tree rings, known as *tree-ring series* (Fig. 1), are records with annual resolution of the natural, historic and anthropogenic environment in which the trees grew.

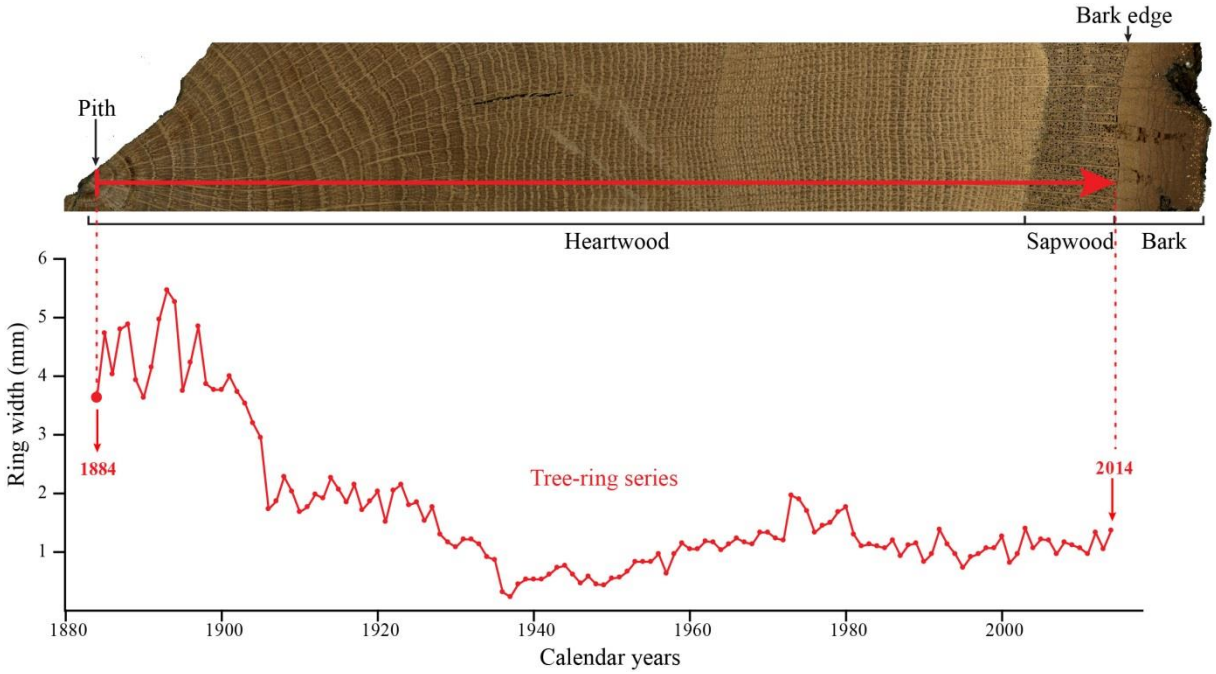


Figure 1. Tree-ring series of an oak sample from a tree that was cut in the autumn of the year 2014. Each dot in the series represents the tree growth (ring width) in millimetres in that specific year. M. Domínguez Delmás.

This science is based on the premise that trees of the same species growing in the same area and influenced by the same environmental conditions will produce tree-ring series with similar patterns. Assigning the year of the most recent growing season to the tree ring formed right under the bark, tree-ring series from living trees can be *crossdated*, i.e. matched against each other, and averaged to create *reference chronologies* representing the growth of specific species in specific areas (Fig. 2). Such reference chronologies can be used subsequently to absolutely date the tree-ring patterns of historic timbers (e.g. beams in wooden roof structures) from the same species and provenance, and covering the same temporal period. The fact that each growth ring in the wood is formed within a single calendar year, makes dendrochronology the most accurate method to absolutely date wood (Baillie, 1982). In return, the newly dated series from the historic timbers can be added to the reference chronologies to extend them back in time. If a historic tree-ring series remains initially undated, i.e. *floating*, it is subsequently compared with each new series and reference chronology produced from the same species, until it is eventually dated.

The most evident application of dendrochronology within the Humanities (e.g. archaeology, art history and architectural history) is the absolute dating of wood from artefacts and structures (Fig. 2). This subdiscipline is known as *dendroarchaeology*. Once the wood is absolutely dated, accurate information about the fabrication period of e.g. a panel painting, a ship, or a building can be inferred. Furthermore, the area of provenance of the wood can be determined with different degrees of resolution, provided the reference chronologies dating the wood represent well-defined geographical

areas. This subdiscipline is known as *dendroprovenancing* (Eckstein and Wrobel, 2007; Bridge, 2012). Therefore, a crucial step for the successful dating and provenancing of (pre)historic wood in a specific geographic region is the development of multi-century long site-specific reference chronologies for different species.

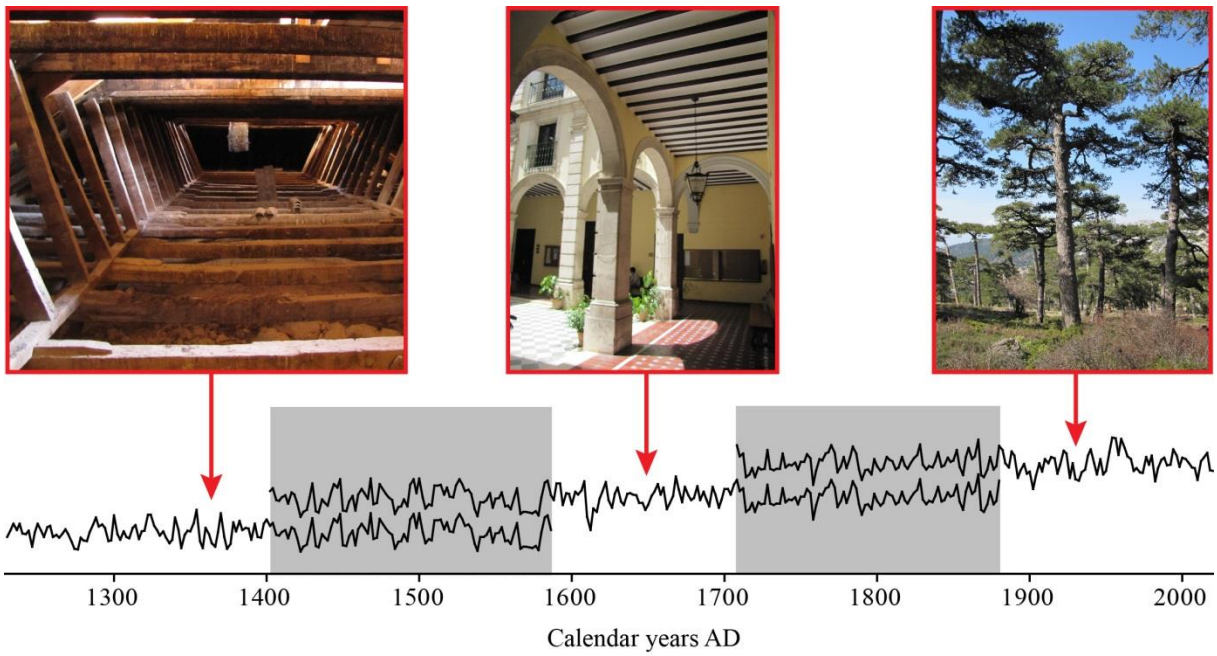


Figure 2. Crossdating and retrospective extension of chronologies from living trees. The shaded area indicates the overlapping periods. Chronologies from living trees can be prolonged back in time with tree-ring series of wood from historical buildings, provided the wood is of the same species, has the same provenance, and overlaps in time. Photos: M. Domínguez Delmás.

1.3. Dendroarchaeology beyond the dating: from the forest to the end product

Beyond the determination of felling dates and the provenance of wood, dendroarchaeological investigations can provide information about the type of forests where the trees grew, the selection of trees, transport of timber, ways to process the wood and the tools employed (e.g. Billamboz, 2003; Tegel, 2012). If the dendrochronological analysis provides a date for the investigated timbers, all this information will be framed in a specific temporal context. The relative crossdating of both absolutely dated and floating tree-ring series from numerous timbers of the same structure, also allows identifying construction phases, as well as defining the occupation timeline of ancient settlements, or inferring information about the organisation of wood supply (Billamboz, 2008; Mom *et al*., 2010). Additionally, the combined analysis of large sets of dendroarchaeological data can address interdisciplinary issues such as European-scale trade of specific timber products, changes in forest management practices throughout history, deforestation in different (pre)historic periods and climate

change (Haneca *et al*., 2005; Wazny, 2005; Fraiture, 2009; Büntgen *et al*., 2011; Crone and Mills, 2012; Domínguez-Delmás *et al*., 2014). In this manner, dendroarchaeology allows inferring information about the use, management and organisation of timber resources, contributing to the study of human behaviour and the evolution of natural resources and landscapes in specific periods of time.

1.4. The Iberian Peninsula: a blank spot in European dendroarchaeology

In the Iberian Peninsula, the application of dendroarchaeology has been remarkably underrepresented in comparison to disciplines dealing with ecological and climatological questions. The earliest dendroarchaeological studies in the territory date from the 1980s, when a Spanish-German collaboration was dedicated to develop a set of reference chronologies of pine (*Pinus* spp.) from living trees and timbers from historic buildings in the centre and east of Spain (Richter, 1988). More recently, dendrochronological studies in historic buildings in Galicia, the Basque Country and Andalusia have confirmed the potential of this field of research in different regions of this country (Domínguez Delmás, 2004; Susperregi, 2007; Rodríguez Trobajo, 2008). However, in spite of the abundance of cultural heritage made of wood that would profit from this type of research, its implementation is still far from optimal. Reasons for this could be a general lack of multi-century long reference chronologies to date historical timbers, or the lack of awareness of end-users (archaeologists, building historians or art-historians for example) about the broad possibilities of this science, together with the lack of expertise to conduct this type of research in national and regional institutions where study and conservation of cultural heritage made of wood is carried out.

Most dendrochronological research in Spain and Portugal is carried out at universities and research institutes with a focus in ecological and climatological questions. The work of these research groups has provided the dendrochronological map of the Peninsula with a large spatial coverage (see Fig. 6 in ***Article 1***, Appendix 1, p. 108). The species studied are also very divers and range from several pine species (*Pinus* spp.) and other conifers, to broadleaf species such as oaks (*Quercus* spp.), beech (*Fagus sylvatica*) and chestnut (*Castanea sativa*) among others. Although some of these chronologies developed from living trees could serve as a basis for developing reference chronologies for dating historic timbers, many of them cover a short time period or have been obtained from forests located at high elevation, in sites that were not subjected to systematic logging activities (e.g. *Pinus uncinata* trees growing in the Pyrenees). So even when these chronologies span several centuries, they are not suitable for dating historic timbers.

Consequently, the lack of multi-century long reference chronologies covering historic source areas for construction timber hinders results in an inadequate assessment of cultural heritage built of wood. This is illustrated, for example, by the inability to date and confirm the Iberian origin of numerous wrecks of Spanish ships of the Age of Discovery (16th to 18th centuries) found along the shores and ocean beds across the world. The development of such reference chronologies for the Iberian Peninsula, and

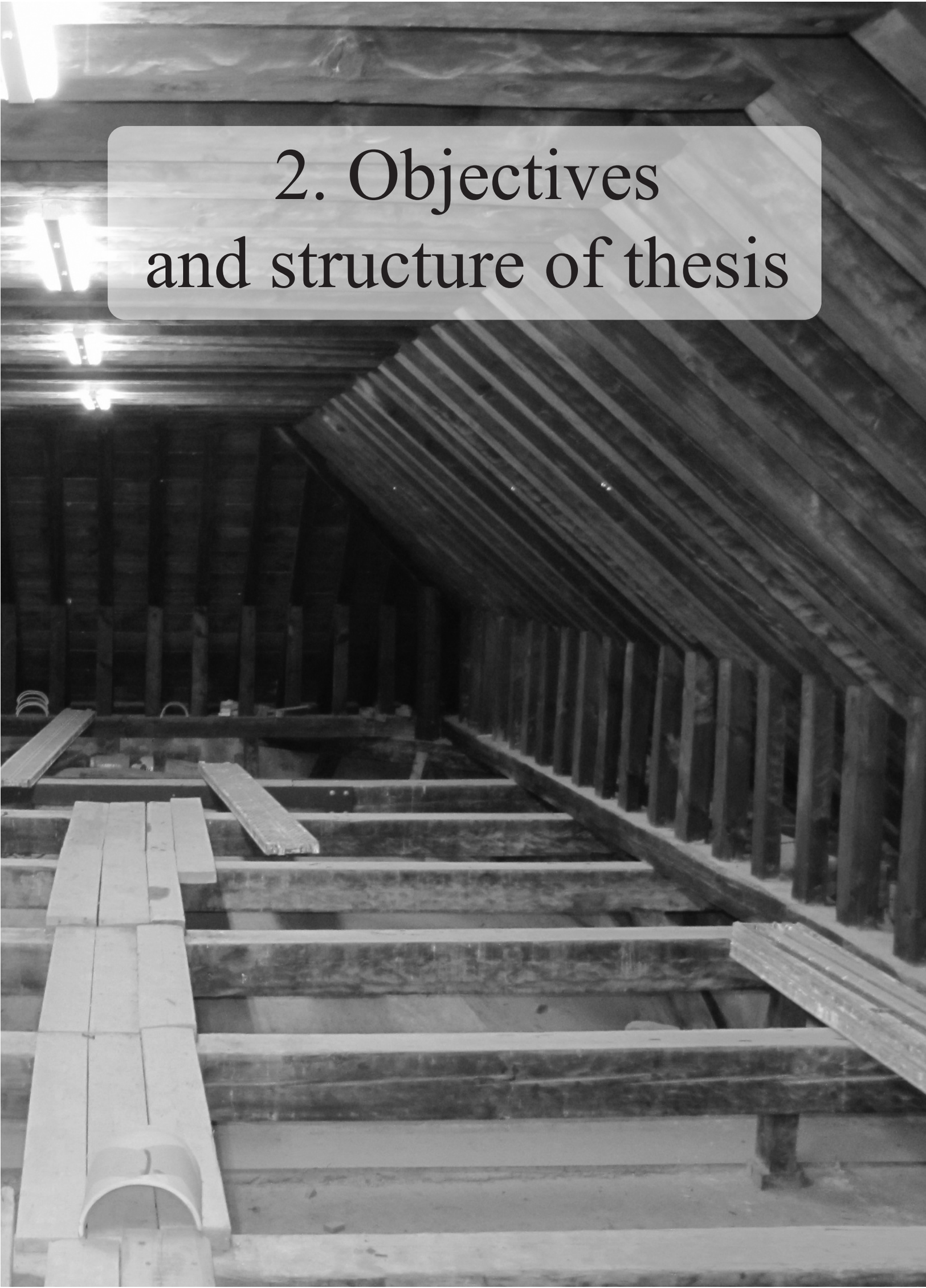
the systematic application of this scientific discipline in the study of historic buildings, archaeological sites, furniture and works of arts, are key and necessary steps to improve the study of our cultural heritage and make well-informed decisions for its preservation. This PhD thesis represents an important effort to develop and implement this multidisciplinary science in the Iberian Peninsula.

1.5. Background of this thesis

The research presented in this thesis has as background a two-year project entitled '*Filling in the blanks in European dendrochronology: building a multidisciplinary research network to assess Iberian wooden cultural heritage worldwide'* that was launched by the Cultural Heritage Agency of the Netherlands (RCE) in collaboration with the Ring Foundation, with Prof. Dr. Esther Jansma as main applicant, and myself as principal investigator. Funding came partly from the Netherlands Organisation for Scientific research (NWO, section Humanities, funding program 'Internationalization in the Humanities', project number 236-61-001), with matching from the main partners. The project run from September 2009 until Sept 2011 and gathered an international and multidisciplinary network of researchers specialised in the fields of forestry, archaeology, history and dendrochronology. This initial network had as core partners, beside the RCE and the Ring Foundation, the Agroforestry Sciences Department from the University of Huelva in Spain (with the participation of Dr. Reyes Alejano Monge), the Institute for the Study, Conservation and Restoration of Cultural Heritage of the Nicolaus Copernicus University in Poland and the Tree-Ring Laboratory at Cornell University in the United States (Prof. Dr. Tomasz Wazny), the Department of Botany from the University of Santiago de Compostela in Spain (Dr. Ignacio García González), the University of Wales, Trinity Saint David in Great Britain (Nigel Nayling), the *Centro de Ciencias Humanas y Sociales* from the National Research Council (CSIC) in Spain (Dr. Ana Crespo Solana) and the Arkeolan Foundation in Spain (Josué Susperregi).

Main goals of the project were to expand the initial research network within Iberia as well as overseas in order to promote dendroarchaeological studies in the Iberian Peninsula. The international interest of this project, which became informally known as the 'Iberian Heritage Project', was mostly sparked by the hundreds of shipwrecks of potential Iberian origin that cannot be assessed by dendrochronology due to the lack of a network of long-span tree-ring chronologies from different species for the Iberian Peninsula. This underwater archaeological heritage is highly relevant at national and international levels, as boats and ships of different periods were the vectors that allowed exploration, trade and cultural exchanges. The wood used for their construction represents a unique ethnographical, historic and environmental archive that can be studied by means of dendrochronology. Therefore, establishing contacts with different underwater archaeology centres in Spain, Portugal and abroad in order to inspect their collections became a crucial part of this project.

As principal investigator, I designed the project, prepared the research proposal with support and guidance from Esther Jansma, gathered the research network that supported the application, organised and participated in the sampling campaigns, and analysed all the samples, discussing the different results with the project partners and preparing the related articles with them. The articles included in this thesis are to a higher or lesser extent the result of the Iberian Heritage Project.



2. Objectives and structure of thesis

2. OBJECTIVES AND STRUCTURE OF THESIS

The main goals of this thesis are **to review, assess and validate the potential of dendroarchaeology in the Iberian Peninsula, defining strategies for its future development and implementation, and illustrating the importance of its application in the study of cultural heritage made of wood.**

To accomplish these main goals, five specific objectives were defined, which were divided into five sub-projects directed at exploring every aspect covered by dendroarchaeological research, from the development of multi-century long reference chronologies suitable for dating and provenancing, to the inference of wood-working techniques derived from the observation of tool marks in the wood, and going through the organisation of timber supply for construction, production of art pieces, shipbuilding as well as the transport and trade of timber. The outcome and specific results from these sub-projects were published (or will be shortly submitted for publication) in international scientific journals and are presented in Appendix 1:

Objective 1. Review of the current state and future prospects of dendroarchaeology in the Iberian Peninsula

- To review the current state of dendroarchaeology in the Iberian Peninsula in relation to the particular relevance and complexity of this territory and its material heritage for dendroarchaeological studies, making an inventory of the existing dendrochronological data, and proposing future research lines towards the assessment of Iberian heritage made of wood in Spain, Portugal and worldwide.

Objective 2. Development of chronologies from living trees

- To develop reference tree-ring chronologies of black pine (*Pinus nigra* subsp. salzmannii) along an altitudinal gradient in the Cazorla and Segura mountains and assess their suitability to date and provenance historic timbers from different elevations employed in roof structures.

Objective 3. Dendroarchaeological investigations of architectural heritage

- To perform dendrochronological investigations in roof structures from historic buildings made with wood from the Cazorla and Segura mountains in order to evaluate the dating potential of the newly developed black pine chronologies, and to study the tools and techniques applied to process the wood, and its transport from the forests to the construction sites.

Objective 4. Dendroarchaeological investigations of art-historic objects

- To perform dendrochronological research on selected art pieces from the Renaissance in Seville in order to shed light into the organization of wood supply, and to compare the local construction techniques with those of north European artistic centres.

Objective 5. Dendroarchaeological investigations of underwater archaeological heritage (shipwrecks).

- To inspect, sample and research shipwreck timbers and assemblages suspected or known to be from Iberian construction, in order to promote good practice in the investigation of these objects, and to illustrate the knowledge gain that can be achieved through appropriate sampling and investigation of ship-timber elements.

The selection of targets in the Andalusian region (Fig. 3) for *Objectives 2, 3* and *4* is justified for several reasons:

a) Black pines reaching 1,000 years of age still survive in the Sierras de Cazorla and Segura (Creus, 1998). For centuries, these mountains have supplied black pine timber for construction of buildings, ships, hydraulic works and artifacts (De Aranda y Antón, 1990; Córdoba de la Llave, 1990, 1993; Martínez Ruiz, 1999; Ruiz García, 2010). These living trees could provide an ultra-long reference chronology to date cultural heritage built with wood from those mountains. However, since such trees grow at almost 2,000 m a.s.l. and climatic conditions change along altitudinal gradients, it was necessary to assess whether tree-ring chronologies obtained from relict trees growing at high elevations could be used to date historic timbers from sites at more accessible lower elevations in the same mountains (research questions comprised in Objective 2).

b) The Andalusian region is almost entirely encompassed within the Guadalquivir river watershed. With more than 600 km of length from its source in the Cazorla and Segura mountains to its mouth by the Atlantic Ocean, this is one of five biggest rivers of the Iberian Peninsula. Since antiquity, this river and its tributaries have served as connecting waterways between the mountains that enclose the region (with the Cazorla and Segura mountains located in its eastern end) and villages and cities along the river such as Cordoba or Seville. The transport of wood down the river is documented since at least the Middle Ages (e.g. Córdoba de la Llave, 1990, 1993; Martínez Ruiz, 1999), but could have been taken place since Roman times (López Almansa, 1999). Therefore, Andalusia represents a key area for the study of supply and transport of local timber for construction purposes (subject tackled in Objective 3).

c) The rich history of trade and cultural exchanges that have taken place in the region since antiquity, together with the abundance of built and mobile heritage that has survived until today allow assessing the potential of dendroarchaeology applied to different objects of the cultural heritage. Subjects such as the import of timber and the organisation of wood procurement for different purposes in the city of Seville (most important Spanish trade hub

from the 13th to the 18th centuries; Serradilla Avery, 2007; Crespo Solana, 2011) can also be addressed in this region, adding a broader dimension to dendroarchaeological studies (questions raised in case studies 3 and 4).

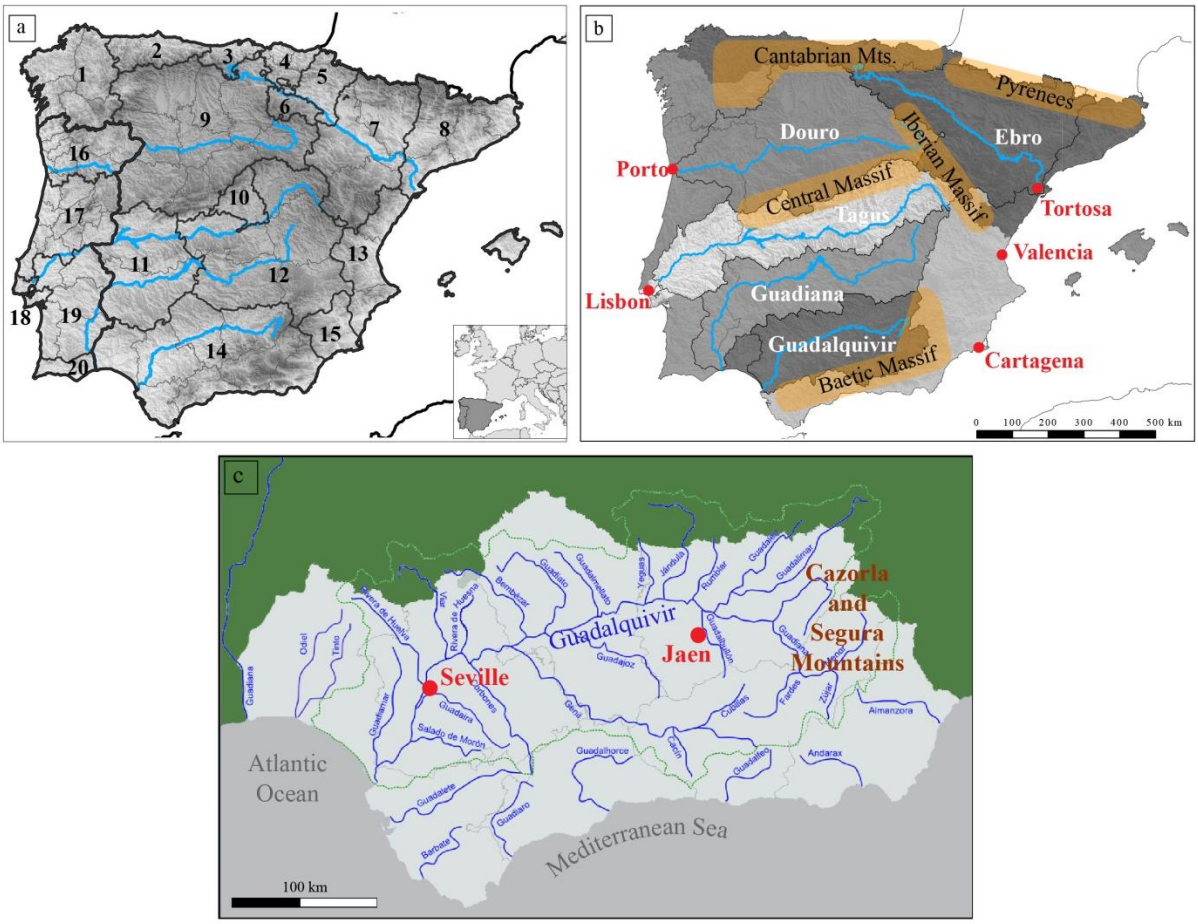


Figure 3. Location maps illustrating regions, rivers and mountains mentioned throughout the text: a) regions of peninsular Spain and Portugal according to current political division (thinner lines delineate provinces): 1, Galicia; 2, Asturias; 3, Cantabria; 4, Basque Country; 5, Navarra; 6, La Rioja; 7, Aragon; 8, Catalonia; 9, Castilla y Leon; 10, Madrid; 11, Extremadura; 12, Castilla La Mancha; 13,Valencian Community; 14, Andalusia; 15, Murcia; 16, Nord; 17, Centre; 18, Lisbon; 19, Alentejo; 20, Algarve; b) schematic position of the five main mountain ranges, and the five big rivers and their watersheds. Some cities mentioned in the text in relation to the transport of timber have been included; c) region of Andalusia enclosed within the green line. The light area represents the Guadalquivir watershed;

3. Material and Methods

3. MATERIAL AND METHODS

3.1. Documentary research

3.1.1. Dendrochronological data and metadata

To create an overview of chronologies with potential to serve as a base for dendroarchaeological studies (goal included in Objective 1), the existing dendrochronological data in the Iberian Peninsula had to be compiled. For this, the digital Bibliography of Dendrochronology, which is updated yearly by Grissino-Mayer and is hosted by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL (http://www.wsl.ch/dienstleistungen/produkte/glossare/dendro_bibliography/index_EN) was firstly consulted. To find relevant publications in this database the keywords 'Spain' and 'Portugal' were used in the 'Full-text search' field. Additionally, the publication lists of Spanish and Portuguese dendrochronologists were also checked, and relevant articles were downloaded from the specific journals. Furthermore, as the earliest dendrochronological works made in Spain were published in Spanish journals, conference proceedings, or as PhD theses, searches were also carried out on the Spanish database Dialnet, managed by the *Universidad de la Rioja* (http://dialnet.unirioja.es/). Only chronologies for which the time span and coordinates were provided in the publications were considered, excluding chronologies not reaching back further than 1950. In this way, chronologies that were developed in the context of studies related to physiological processes such as cambial activity or vessel development would be excluded. The final list of chronologies and their respective publications was included as supplementary material in ***Article 1*** (Table S2, p. 131-142).

The reference chronologies used in ***Article 2*** to test the teleconnection signal of Iberian and Mediterranean conifer chronologies with the black pine chronologies from Cazorla mountains developed for this article were downloaded from the International Tree-Ring Data Bank (ITRDB). This database is managed by the Paleoclimatology Team of the National Center for Environmental Information and the World Data Center for Paleoclimatology (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/ datasets/tree-ring).

3.1.2. Literature research

The historical information used in this thesis has been retrieved exclusively from secondary sources (published books and articles). Search engines from Google and websites such as Academia and ResearchGate were used to identify and locate relevant literature. Access to specialised scientific journals was obtained through the online resource *Catálogo de Revistas Electrónicas* from the University of Huelva (UHU), whereas hard copies of books and articles not linked to the digital network of the UHU were obtained by loan request to the library services of the UHU and the Agency of Cultural Heritage of the Netherlands (*Rijksdienst voor het Cultureel Erfgoed*, RCE).

3.2. Study areas, living trees and research objects

3.2.1. The Iberian Peninsula: geographical and bio-climatological description

The Iberian Peninsula, located on the verge of the Atlantic Ocean and the Mediterranean Sea in the south-western corner of Europe, represents a key spot from a climatological, ecological and historical perspective. Its geography is characterised by five main mountain ranges and a central plateau that reaches an average elevation of 600 m a.s.l.. Three of these mountain ranges spread along longitudinal gradients (the Cantabrian Mountains in the north, the Central Massif in the middle, and the Beticas in the south), whereas two of them follow a north-west south-east direction (the Pyrenees in the east and the Iberian Massif in the centre/east) (Fig. 3). These mountains divide the peninsula into several watersheds, five of which gather the water of the main Iberian rivers: Douro, Tagus, Guadiana and Guadalquivir rivers flow from east to west and drain into the Atlantic Ocean, whereas the Ebro flows from north-west to south-east to the Mediterranean Sea (Fig. 3).

The convergence of both Atlantic and Mediterranean climates creates two main biogeographical areas, commonly known as the Wet-(Atlantic) and the Dry-(Mediterranean) Iberia (Blanco *et al*., 1997). Average rainfall decreases from north to south and from west to east, reaching maximum values in mountain and coastal areas from the north-west where precipitation often reaches 3,000 mm/year, and dropping down to 200 mm/year in the driest areas of the southeast and the Ebro basin (see Fig. 1c in ***Article 1***, p. 96). Average temperature increases from north to south and decreases from the coast to the inner regions of the peninsula, January and August being the months with the lowest and highest average temperatures respectively (Fig. 1d in ***Article 1***, p. 96).

This combination of relief and geographic location upon climate, coupled with the role of the Mediterranean as a refuge during the Ice Ages, confers the Iberian Peninsula a remarkable diversity of plant species along altitudinal and latitudinal gradients (Galán *et al*., 2013). Several tree species are endemic to Iberia (e.g. *Acer granatensis*) or Iberia and North Africa (e.g. *Abies pinsapo, Quercus faginea, Q. canariensis* or *Tetraclinis articulata*). Many others have their south-western distribution limit in Spain and/or Portugal (e.g. *Pinus sylvestris, Abies alba, Quercus robur, Q. petraea, Fagus sylvatica, Pinus uncinata*) (Ruiz de la Torre, 2006). Therefore, these species are of great scientific interest due to their susceptibility to climatic changes (Benito Garzón *et al*., 2008). See Table 1 in ***Article 1*** (p. 183) for a description of types of forests and their geographic coverage.

3.2.2. The Andalusian region: a valuable source of cultural heritage

The Andalusian region is particularly rich in architectural heritage. Numerous buildings and architectural ensembles with a strong representative character of architecture styles from different periods (e.g. Islamic, Moorish, Gothic, Renaissance and Baroque) are still preserved in the region. Wood represents an important component of this architectural heritage, as it was an essential raw

material for the construction of religious temples, palaces, houses and other vernacular buildings (Córdoba de la Llave, 1990; Martínez Ruiz, 1999). Its use was not restricted to roof structures, ornamental ceilings, stairs, floors, doors or windows, but it was also used to make scaffolding, cranes and other structures required to lift building materials such as stone (Higueras Maldonado, 2009; Albendea Ruz, 2011).

The Cazorla and Segura mountains (Fig. 3), located in the eastern limit of the Andalusia region and included within the Cazorla, Segura and Las Villas Natural Park, have supplied construction timber for buildings and ships since at least the Middle Ages (e.g. Córdoba de la Llave, 1990; De Aranda y Antón, 1990; De la Cruz Aguilar, 1994; Araque Jiménez, 2007), especially from black pine (*Pinus nigra* Arnold subsp. *salzmannii* (Dunal) Franco). This species was highly appreciated for its good mechanical properties for construction purposes (Fernández-Golfín *et al*., 2001). Consequently, black pine from these mountains can be found nowadays in a great number of historic buildings in the south of Spain (e.g. Mendoza, 2008; Higueras Maldonado, 2009), and probably in shipwrecks all over the world (De Aranda y Antón, 1990; Castro, 2008).

3.2.3. Black pine (*Pinus nigra* subsp. *salzmannii*) from the Cazorla and Segura mountains

Black pines of the Cazorla mountains represent mostly relic forests growing close to the south-western distribution limit of this subspecies (Alejano and Martínez, 1996). They grow at elevations ranging from 1,000 to almost 2,000 m a.s.l. and, despite centuries of intensive logging in most areas of the mountain range, trees reaching 1,000 years of age had been reported at the highest elevations (Creus, 1998). Those trees are living archives of past climate, and they could also provide a much needed millennium-long tree-ring chronology for dating cultural heritage in the region. Such chronology could be in turn improved and extended retrospectively with local wood from historical sources. However, climate variability along this elevation gradient could trigger heterogeneous tree-growth responses that could hamper crossdating of historic timbers extracted from lower elevations and make dendrochronological dating remarkably difficult, as observed with other conifer species in central Europe (Wilson and Hopfmueller, 2001; Dittmar *et al*. 2012).

A well replicated long-span dataset of black pine covering the ca. 1,000 m elevation gradient in the Cazorla mountains was therefore needed. After obtaining the necessary permits from the direction of the *Parque Natural de Cazorla, Segura y las Villas*, four sites with a long logging history were selected at different elevations covering the whole altitudinal range of black pine in southeastern Spain: Linarejos (LIN, 1,079-1,177 m a.s.l.), Poyos de la Mesa (PMB, 1,500-1,619 m a.s.l.), Navanoguera (NAV, 1,582-1,702 m a.s.l.) and Cabañas (CBS, 1,755-1,953 m a.s.l.) (see Fig. 1c in ***Article 2***, p. 147). LIN, the site at the lowest altitude, represented a mixed forest of *P. nigra* and *P. pinaster* growing on a narrow valley. PMB, at mid-elevation, was located on a high-elevation plain descending towards a southern slope, whereas NAV, still a mid-elevation site but slightly higher than

PMB, represented an open valley with low smooth slopes located in the divide between the Atlantic and the Mediterranean aspects of the Cazorla mountains. Finally, CBS lay at the altitudinal limit of the black pine in the Cazorla and Segura mountains.

3.2.4. Historic buildings: Jaen Cathedral and the *Colegial del Salvador* church in Seville

Jaen Cathedral and the *Colegial del Salvador* church in Seville (Fig. 4) were selected for this thesis for two reasons (see Mendoza, 2008; Higueras Maldonado, 2009): i) according to historical sources, wood from the Cazorla and Segura mountains was employed for their construction, and ii) both buildings were erected at the site of previous mosques, hence timber reused from the mosques may be preserved in the roof structures. The great mosque in Jaen was one of the first ones in Andalusia to be replaced by a Christian temple (Higueras Maldonado, 2009). After the conquest of Jaen by the Christians in AD 1246, the great mosque was consecrated and dedicated to Christian cult until its demolition in AD 1362-1382. The construction of the current cathedral was initiated in AD 1551, with the completion of the sacristy in AD 1577. Subsequent phases followed in the 17th and 18th centuries, until the cathedral acquired its current shape. In contrast, the mosque at the site of the *Colegial del Salvador* church in Seville was used for Christian cult during more than four centuries, from 1248 until its demolition in AD 1679 (Mendoza, 2008). The construction of the church that has survived until today was carried out between AD 1679 and 1712.

Figure 4. Facades of Jaen cathedral (left) and the *Colegial del Salvador* church (right). Photos: M. Domínguez-Delmás (left) and S. van Daalen (right).

Dendroarchaeological research of these buildings would allow assessing the dating potential of the chronologies developed in ***Article 2***, as well as verifying the construction dates of the different parts of the buildings, and finding out if timbers from the old mosques were reused in the new structures. Furthermore, the research would inform about the organisation of timber supply, transport from the forests to the construction sites, and wood-working techniques applied in the different construction periods from the 16th to the 18th century. Permission for the research at Jaen cathedral was granted by Francisco Juan Martínez Rojas, dean-president of the *cabildo catedralicio*, and at *Colegial del Salvador* also by the *cabildo* through a request sent to Antonio Calvo and Raquel Liñán.

3.2.5. Art-historical objects: the *Evangelistas* altarpiece at Seville Cathedral

During the 14th and 15th centuries Seville became the main trade centre and harbour from south-western Europe. By the early 16th century it was also bustling with artistic activity. All this development carried along the expansion of the city, as well as an increasing demand for construction timber for buildings and ships. By the mid-16th century wood had become a scarce product in the vicinities of the city, as indicated by numerous documents at the Notarial Protocol Archive and the *Archivo de Indias* referring to the import of wood (Palomero Páramo, 1983; Bruquetas Galán, 2002; Otte Sander, 2008).

The construction of Seville Cathedral, initiated in the 15th century (Jiménez Martín, 2006), was followed by the decoration of its interior. The *Evangelistas* altarpiece is located at the chapel of the same name in the north side of Seville Cathedral. The altarpiece consists of nine panels, which had to be made of *borne* wood (Hernández Díaz, 1937), distributed in a bench or predella and two tiers of three blocks each (Fig. 5). This art piece was commissioned on May 27 of 1553 from the Dutch painter Hernando de Esturmio (originally called Ferdinand Storm), who completed the work in AD 1555 as indicated by his signature "HENANDVS STVRMIVS ZIRICZEENCIS FACIEBAT 1555" situated in the panel representing Saint Barbara and Saint Catherine (Magdaleno Granja *et al*., 2005).

Restoration works carried out by the *Instituto Andaluz de Patrimonio Histórico* offered the chance to undertake dendroarchaeological investigations of the panels, in order to verify the construction date of the altarpiece and to establish the origin of the wood employed. Furthermore, this opportunity would allow the study of the construction process of the panels for its comparison with that of north European art-production centres.

Figure 5. *Evangelistas* altarpiece at Seville Cathedral. Photo kindly provided by A. Jiménez.Martín.

3.2.6. Underwater archaeology: the *Arade 1* shipwreck

As part of the pre-doctoral work leading to this thesis, various underwater archaeology institutes and companies were contacted and visited in Spain (CASC, CAS, Archeonauta), Portugal (former IGESPAR/ DANS) and France (SEAS) (see Domínguez-Delmás, 2014).

Timbers from the *Arade 1* shipwreck were preserved in water tanks at the facilities of the former IGESPAR/DANS in Lisbon, Portugal (Fig. 6). This shipwreck was first discovered in 1970 at the mouth of the Arade River, in the south of Portugal, and after being reported missing in 1972, it was relocated again in 2001 by members of the DANS (Castro, 2006). In the course of five field missions between 2001 and 2005, the shipwreck was documented, dismantled and recovered. In 2005, dendrochronological analyses carried out on five fragments of timbers identified as deciduous oak (*Quercus* subg. *quercus*) resulted in the successful dating of two of them in the second half of the 16th century (Wazny, unpublished report). Additionally, 73% of 20 structural timbers were identified by Queiroz *et al*. (2005) as *Quercus faginea*, commonly known as Portuguese oak. This identification had been done based on an ongoing study carried out by Queiroz's group at the *Centro de Investigacão em Paleoecologia Humana* from the former IGESPAR, in Lisbon. The goal of that study was to identify anatomical characteristics that would allow the systematic differentiation between deciduous oak species among others. However, the research was abandoned before reaching significant and conclusive results (Queiroz, email comm. 24 June 2011).

Figure 6. Timbers from different shipwrecks conserved in water tanks at the facilities of the former IGESPAR/DANS (now CNANS) in Lisbon. Photo: M. Domínguez Delmás.

The good preservation of the numerous structural timbers from the *Arade 1* shipwreck stored at the DANS would allow dendrochronological research, and the re-examination of the identifications reported by Queiroz *et al*. (2005). The differentiation of *Quercus faginea* from other deciduous oaks present in the Iberian Peninsula and northern Europe, such as *Q. robur* and *Q. petraea* for example, has not yet been described based on wood anatomical features (Schweingruber, 1990), but the wood identifications provided by Queiroz *et al*. had mislead the archaeologists to the hypothesis that the *Arade 1* shipwreck corresponded to a 16th century ship built with local/regional timber (Loureiro and Alvés, 2008; Loureiro, 2011). For all these reasons, the *Arade 1* shipwreck was selected for additional and in-depth dendrochronological research.

3.3. Dendroarchaeological research

3.3.1. Selection and sampling of living trees for chronology building

The selection of living trees for ***Article 2*** was driven by the objective of developing high-quality long-span tree ring chronologies for dating and provenancing purposes. Therefore, at each site the oldest-looking trees were selected, which in black pine can be identified by the flattened crown and silvery bark. As old trees often have numerous missing rings, it is advisable to also sample younger-looking ones in order to obtain undisrupted tree-ring series in the recent centuries where the old trees may have missing rings (Fritts, 1976). All in all, 19 trees were selected at LIN (low elevation site), 20 and 21 trees respectively at PMB and NAV (mid-elevation sites), and 55 at CBS (high-elevation site).

Two to five samples were taken from each tree at approximately breast high (1.30 m) with 60 cm long Haglöf borers of 0.5 cm diameter, trying to avoid parts of the stem that presented obvious injuries or thick branches, in order to avoid distorted tree-ring patterns. Samples were stored and preserved in paper straws for the transport to the laboratory. For each tree, coordinates, elevation, diameter, height, apparent anomalies and injuries were recorded, as well as some environmental characteristics (soil appearance, slope, and exposition).

3.3.2. Species identification of (pre)historic wood

The species identification of (pre)historic wood is a very important step in dendroarchaeology for different reasons. Firstly, the species will determine the suitability of the wood for dendrochronological research, given that the selected timbers must be of a wood species that produces clearly distinct annual rings. Secondly, the identification of different species in specific parts of a shipwreck for example, or in a settlement, provides information about the supply of materials and the potential availability of certain species the vicinities of settlements (e.g. Martín Seijó and Piqué i Huerta, 2013). Last but not least, the determination of the wood species may provide the first clue towards the source area (Giachi *et al.*, 2003; Guibal and Pomey, 2003; Wicha *et al.*, 2003), as some species have restricted distribution areas (e.g. *Pinus nigra* in the Mediterranean basin, *Abies alba* in

central Europe and the Pyrenees, etc.). Therefore, the identification of wood species is a crucial step when researching (pre)historic timbers.

Sampling for species identification can be performed simultaneously to the inspection of timbers for dendrochronological research. A fragment of about 2-3 cm^3 of wood can be removed from all items inspected, regardless of their subsequent selection for dendrochronological dating. In the case of archaeological or historic timbers selected for tree-ring analysis, the identification can be performed on the same samples by cutting thin micro-slides from each section of the wood (transverse, tangential and radial). In the case of art pieces, thin micro-sections will be cut directly from the piece in the least conspicuous places (e.g. transverse edges of planks, radial back side, etc). The observation under a microscope of wood anatomical features in those sections will lead to the species identification.

Some species such as deciduous oaks and chestnut for example, are relatively easy to identify with the naked eye, as they possess very distinct macroanatomical features. Deciduous oaks show a ring-porous disposition of earlywood vessels, abrupt transition from earlywood to latewood, clearly visible multiseriate medullary rays and clearly distinguishable ring boundaries (Fig. 7). The wood anatomy of chestnut is similar to that of deciduous oaks (ring-porous, with clearly distinguishable ring boundaries, flame-like groups of pores in the latewood, uniseriate rays), but it differs in that it lacks multiseriate medullary rays (Schweingruber, 1990) (Fig. 7). Therefore, when these features are clearly visible in the wood, the identification can be done without removing a sample for this purpose.

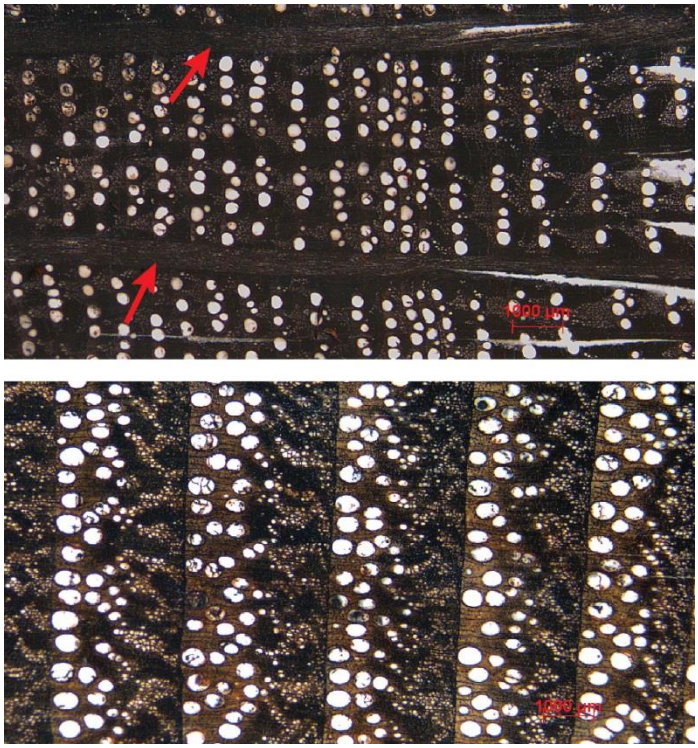


Figure 7. Macroscopic wood anatomy of oak (*Quercus* subg. *quercus*; above) and chestnut (*Castanea sativa*; blow) corresponding to ship timbers from the *Arade 1* shipwreck. Both species show in the transverse section clearly distinct ring boundaries, ring-porous disposition of earlywood vessels, sharp transition between eralywood and latewood and flame-like groups of pores in the latewood. However, oak has multiseriate medullary rays (indicated by the arrows), which are visible by the naked eye, whereas chestnut lacks this feature. Photos: M. Domínguez Delmás.

The wood identification of the samples taken for tree-ring analyses at Jaen Cathedral, *Colegial del Salvador* church and from the *Arade 1* shipwreck was done by cutting thin micro-slices by hand with razorblades, and observing them under a microscope. The wood anatomy guide by Schweingruber (1990) was used for the identification of the species. In the case of the *Evangelistas* altarpiece, the clear observation of the medullary rays in the back of the planks as well as in the transverse edges, together with the observation of the ring-porous disposition of earlywood vessels, allowed the identification of the wood as deciduous oak.

3.3.3. Suitability of historic samples for dendrochronological research

Provided a wood species suitable for dendrochronology (i.e. a species that produces distinct tree-rings with annual resolution), the suitability of the samples for tree-ring dating will be determined by the number of rings. Baillie (1982: 84) proposes 100 tree-rings as the minimum advisable to consider a sample suitable for dendrochronological dating, given that the probability to find outstanding statistical matches by chance becomes small with such length. García-González (2008, Fig. 2) however, demonstrated that Student's *t*-value becomes rather stable when the number of observations

(e.g. years of overlap between two compared series) reaches 70 to 80 or more. In practice, numerous studies have shown that shorter series can be reliably crossdated (e.g. Billamboz, 2008; Domínguez-Delmás *et al*., 2011), but this requires high expertise and also special conditions, such as e.g. the availability of numerous timbers from the same structure or construction phase presenting bark edge if possible, originating from the same area and cut in the same year or within a short period of time, sensitive tree-ring patterns, etc. Nevertheless, the successful dating of short series (40 to 60 rings) represents an exception, and attempts to crossdate them should be restricted to very specific conditions. Those timbers however, still provide information about the availability of timber resources in certain areas, or the specific selection of fast grown trees, landscape history, management practices, etc. (Beeckman, 2005), hence they should still be examined. For dendrochronological dating, the more rings in the sample, the better.

3.3.4. Inspection and sampling of timbers from buildings

Cutting dates of timber element from roof structures of historic buildings allow finding out or verifying their history, providing a timeline for different construction phases, later additions, renovations or repairs (e.g. Haneca and Debonne, 2012; Brun and Tegel, 2007). This information contributes greatly to the historic significance of a building, which can be crucial in the decision-making process towards future renovations and conservation strategies.

Therefore, the sampling strategy is defined by the research question. When the objective of the dendroarchaeological research is to date major construction phases, re-used timbers or timbers used

for repairs should be avoided. However, considering the objectives of ***Article 3***, during the inspection of the roof structures of Jaen Cathedral and the *Colegial del Salvador* church special attention was paid to timbers that may have been re-used from the former mosques. Keeping this in mind, individual roof timbers were thoroughly inspected in search for tool and assembly marks. Tool marks become clearly visible when placing a beam of light along the surface of the timber (see Fig. 4 in ***Article 3***, p. 177), and they provide valuable technological and ethnographical information about the processing of wood in different periods. Assembly marks indicate the building sequence of a structure, and may provide clues about later repairs or the re-use of timbers when the sequence of marks is broken or different numbering systems are found. After registering that information, those timber elements preserving sapwood (i.e. outermost part of the stem and branches of woody species where the sap is transported along the tree) and/or the bark edge (i.e. last growth-ring formed before the felling of the tree), and apparently containing a large number of tree-rings were selected. Hillam (2004) recommends to sample eight to 10 timbers per building phase, so that if some samples are broken or do not yield matches with the others, a mean curve may still be built with the rest. In major buildings such as big churches or cathedrals, it is wise to increase these numbers, as wood for the roofs may have been procured from different sources (De Vries, 1994).

Between five to 30 timber elements were sampled at each roof structure of the researched buildings. Five timbers were selected at the smaller 17th and 18th century's structures of Jaen cathedral, whereas 15 were sampled in the more complex roof above the sacristy (see Tables 2 and 4 in ***Article 3***). At *Colegial del Salvador*, 30 elements were sampled in the large nave, 19 in the southern pyramid, and 10 and 12 respectively in the eastern and northern ones. One or two cores were taken from the selected timber elements using a 1.2 cm thick dry-wood borer powered by electric drill. The samples were stored in envelopes where observations about the timber element and its marks were registered. The holes left by the drill were filled with cork plugs, which disguise the intervention while keeping a register of where the samples were taken. Cross-sections were manually sawn from protruding ends of ceiling timbers from the chapter room at Jaen Cathedral.

3.3.5. Inspection and non-destructive research of art pieces

The main premise when researching art pieces is keeping the intervention as non-intrusive as possible (e.g. Eckstein, 2005; Fraiture, 2009). This implies that the first step should be a careful selection of the elements that are going to be subjected to dendrochronological research. In the case of panel paintings, the panel can be made by one or more planks. The inspection will start by observing the back of the panel, where tool marks are visible in the planks under ranking light. Although sometimes the back of the panels are varnished or painted, often they are not, and remaining bits of sapwood can be identified in some parts of the planks. Sapwood was usually removed during the preparation of planks, as it is the most perishable part of the wood and contains substances that may attract insects. But sometimes, a few sapwood rings are preserved in the wood (see Fig. 4 in ***Article 4***, p. 198), offering the possibility

to estimate the felling date of the parental tree (see point 3.3.9). Planks with sapwood should be selected for dendrochronological research. The next step is the inspection of the transverse edges of the planks, in order to make a rough estimate of the number of tree-rings in each plank, as well as to observe the growth direction, and the way in which the plank was processed (radially, tangentially, etc.). Radial planks were obtained by splitting the timber along the longitudinal axis, whereas tangential planks were usually obtained by sawing the timber in sections parallel to the diameter line. Planks presenting irregular edges in the transverse end should be excluded from the research, as the preparation of the surface would have to be too intrusive to allow the optimal visualization of the tree-rings.

To make the tree-rings visible in the selected planks, a shallow 2-5 mm wide line must be cleaned at the back edge of the planks with very sharp scalpel knives or sand paper (see Fig. 3 in ***Article 4***, p. 196). The sequence of tree-rings is then photographed with a macro lens, using a scale to calibrate the measurements. Ring-widths are measured on a computer screen with specialised software (see point 3.3.7 on this section).

3.3.6. Inspection and sampling of timbers from shipwrecks

Dendrochronological studies of shipwreck timber elements from the structure and the cargo can help inferring the temporal and geographical context of the construction of the ship, as well as her life time (Guibal and Pomey, 2003; Daly, 2007; Bridge, 2011; Nayling and Susperregi, 2014; Haneca and Daly, 2014). Furthermore, tree-ring analyses and wood species identification can inform about the selection of trees and ancient forest management practices for the production of compass timber for shipbuilding. An adequate sampling strategy defined according to the research question to be answered will be the key for the success of the research. If the objective is finding out when the ship was built, sampling should focus on structural elements (keel, frames, hull planking) containing sapwood and/or large number of rings, avoiding those elements that lack sapwood rings or insufficient tree-rings for dendrochronological research, as well as those that could have been replaced or that appear to be made from reused wood. If in addition to the construction period one wants to gain information about the life time of the ship or the route she followed, repaired timbers must be sampled. Additionally, to obtain information about technological aspects of shipbuilding such as the predefined selection of trees and/or species for specific timber-elements, the methods of wood processing, etc., timbers that do not include sapwood or a sufficient number of rings for dendrochronological research should also be targeted.

Given our objective to find out the precise date and provenance of timbers used in the construction of the *Arade 1*, our first task while inspecting the timbers was to identify groups of species (tropical wood, evergreen oaks, deciduous oaks, others). Then, the number of rings in the timbers was estimated by rough counting, as samples for dendrochronological research must have a sufficient number of tree-

rings to allow statistically sound results (preferably more than 80). Finally, to obtain the felling dates of the parent trees (or to be able to estimate them), priority was given to timbers presenting sapwood, or even better, bark edge. In the absence of samples with bark edge, sampling several timbers with sapwood may help narrowing the estimated felling-date range of the trees to within a few years. In such case, exceptionally, some timbers with few rings (less than 50 for example) but retaining sapwood, can also be considered for dendrochronological research. In addition, it is desirable to sample as many suitable timbers as possible, preferably from structural elements that are likely to belong to the original ship-structure, in different parts of the ship (for example the keel, floor timbers, futtocks and planks). This way, the chances of establishing relative dates between (presumably) original timbers increase, and object-chronologies can be constructed when the wood originated from the same area. These object-chronologies are easier to date than tree-ring series from single samples, as they contain a stronger environmental signal (Fritts, 1976; Hillam, 1979).

Taking into account all these aspects the sides of the timbers were examined in search for sapwood, and the transverse sections at the ends of planks and framing elements, where the tree-rings and the medullary rays are usually visible. A total of 42 timbers (all planking and framing elements) were selected, including six elements (two planks and four frames) previously researched for wood identification by Queiroz *et al.* (2005). Cross-sections (2-4 cm thick) were manually sawn from the timbers selected for dendrochronological analysis. For wood identification, fragments of c. 3 cm^3 were removed from the timbers that were not selected for dendrochronological research and that needed microscopic verification. All the samples were stored in sealed plastic bags with water to prevent them from drying during their transport to the laboratory.

3.3.7. Preparation of samples and acquisition of tree-ring data

The cores obtained from the living trees were mounted and glued onto wooden supports with the tracheids positioned vertically, in order to have the transverse section positioned horizontally. After drying overnight at room temperature, the transverse section of the cores was prepared with a Stanley knife. This procedure allows observing the anatomical structure of the wood (i.e. tree-ring boundaries, earlywood and latewood) with a binocular (x10). Chalk powder was applied on the prepared surfaces to enhance the contrast of the ring boundaries and other anatomical features. The same procedure was followed to prepare the surface of the cores obtained in the historic buildings, with the exception that the thickness of these samples (12 mm) allows handling them for the preparation without gluing them onto wooden supports. The waterlogged samples from the *Arade 1* shipwreck were prepared with razorblades by paring two lines along the transverse surface from the inner to the outermost ring. Chalk was also applied to the cleaned surface to facilitate the observation of the tree-ring boundaries.

Ring widths were observed through a binocular microscope Leica M-50 and measured to the nearest 0.01 mm from the inner to the outermost ring, with a TimeTable measuring device (VIAS, University of Vienna), coupled with the software PAST4 v.4.3.1021 (B. Knibbe, SCIEM).

In the case of the Evangelistas altarpiece, 600-800 grit sandpaper were used to prepare the surface of the selected planks. Tree-ring sequences were photographed along overlapping segments using a Nikon camera with macro objective. The images were calibrated at a maximum resolution of 120 pixel/mm. CooRecorder (Larsson, 2011a) was used to measure ring-widths as series of coordinates, and CDendro v. 7.4 (Larsson, 2011b) to convert the coordinates to millimetres.

3.3.8. Crossdating of tree-ring series

The process of synchronising tree-ring series between them or with reference chronologies is known as *crossdating* (Fritts, 1976), and it represents the key-concept of dendrochronology. Crossdating is done by comparing the high-frequency (i.e. year-to-year) variation between tree-ring series, shifting one year at the time, until a matching position is found where the tree-ring patterns of both series are synchronous (Fig. 8). This process may result in the absolute dating of the investigated tree-ring series when they synchronise with reference chronologies absolutely anchored in time, or in a relative dating when they crossdate only with other floating series. Crossdated floating series can also be averaged into floating chronologies and are continuously compared with newly acquired data from different regions until they are eventually dated.

Statistical tests are used to suggest possible crossdating positions (Wigley *et al*., 1987):

- Correlation coefficient (*r*): Pearson product-moment correlation coefficient measures the linear relationship or correlation between two variables (i.e. ring-width series). This coefficient may range between -1 and 1, and it is very sensitive to the length of the series, resulting in higher values with shorter series (see Fig. 2 in García-González, 2008).

- Student's *t*-test: to reduce the dependence on the length of the series, Baillie and Pilcher **(1973**) introduced the use of Student's *t*-test to assess the statistical significance or strength of the match between tree-ring series. This *t* is defined as follows:

$$t = \frac{r\sqrt{(n-2)}}{\sqrt{(1-r^2)}}$$

  Where *r* is the correlation coefficient and *n* the sample size (i.e. number of overlapping years between the two series). The result is a more robust parameter than r alone when comparing series of different lengths, which allows identifying a true match from random ones. Therefore the *t*-value is broadly used in dendroarchaeological studies. The method proposed by Baillie and Pilcher (1973) also normalizes the compared series by applying a five-year

moving average and fitting them to a lognormal distribution before calculating the correlation coefficient. The normalization of the data is necessary for the *t*-value to represent a valid measure of the probability of *r* having occurred by chance. Hollstein (1980) also adapted the Student's *t*-test for dendrochronological analysis by applying a lognormal distribution to the series before calculating the correlation coefficient. Grissino-Mayer *et al*. (2010) also stress the need to remove the autocorrelation present in the tree-ring series, which is caused by the influence of environmental conditions from preceding years in current year's growth, and may mask the high-frequency variability needed for crossdating. In practice, the normalization of the data is typically performed in the background of software packages for dendrochronology that include the tBP (*t*-value calculated with the transformation of data proposed by Baillie and Pilcher) and the tHO (*t*-value calculated after normalising the data with the method proposed by Hollstein). The standardization and removal of autocorrelation can also be done in separate programs such as ARSTAN (Cook, 1985), where the standardization method and autocorrelation order can be defined by the user depending on the low-frequency trends that need to be removed. If the autocorrelation is not removed, *t*-scores may result higher than they would with the residual (i.e. non autocorrelated) series, hence dendroarchaeologists should acquire the ability to identify highly significant 'fake' matches and disregard them.

Although the statistical goodness of the crossdating will depend on the similarity of the undated series compared against the reference chronologies, in general, *t*-values below 3.5 should be disregarded, as the chances of random matches providing such score are high (Baillie, 1982: 84). For overlaps around 100 rings or more, values between 3.5 and 6 could be indicative of a match and should be examined visually, whereas values higher than 6 most likely represent the correct crossdated position between two series (Sass-Klaasen *et al*., 2008: 101). Again, one must keep in mind that highly significant scores can still occur by chance for random positions (Baillie, 1982: 85; Grissino-Mayer *et al*., 2010), hence they should not be accepted right away as correct matches. A visual verification of the synchronization at the potential matching position must always be made before reaching a final decision.

- Percentage of parallel variation (%PV), also known as *Gleichläufigkeit* (Gl) (Eckstein and Bauch, 1969). This is a non-parametric value that indicates the percentage of times that the year-to-year values of two tree-ring series increase and decrease synchronously along the overlapping period. The fact that it is non-parametric means that there is no measure of the magnitude of the year-to-year variation in ring widths; therefore, basically, this percentage provides an empirical representation of the goodness of the visual match between the compared series. Values higher than 60% for very long overlaps (e.g. more than 150-200 years) may reflect statistically significant matches, but for overlaps of around 100 years, the

percentage should be higher (preferably over 65%), as it has been found that values of 60% would easily result from random matches (Baillie and Pilcher, 1973). This Gl should always be used accompanied by its statistical significance (disregarding all non-significant matches) and in combination with the *t*-value.

Different software packages designed for dendrochronological research (PAST, TSAP, DENDRO, etc.) implement these statistical tests to facilitate crossdating. However, as Daly (2007) pointed out, the resulting *t*-values may vary considerably from one program to the other, probably due to different transformations of the data being carried out in the background (Daly, 2007: 14-15). To overcome this issue, *t*-values provided by the same program should be used consistently. This way results from different investigations will be comparable.

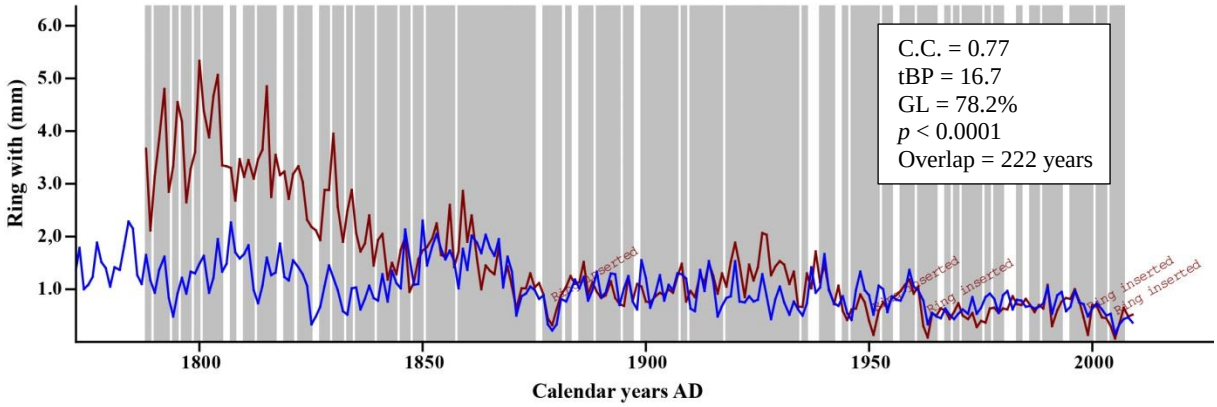


Figure 8. Visual and statistical crossdating between the tree-ring series of a living tree (brown) and the mean curve of the crossdated trees from the same site (blue). The samples from this tree were missing five rings. The identification of the missing rings has been done working with the raw (non-standardized) series. The grey area represents the parallel variation (Gl) between the series.

All the samples from living trees and historic timbers investigated in this PhD thesis were crossdated considering the *t*-value according to Baillie and Pilcher (1973) (tBP) and the percentage of parallel variation (Gl) with its associated significance level, as calculated by the software PAST4 v.4.3.1021 (SCIEM, Vienna). The same approach was used in all cases: firstly, tree-ring series (TRS) from the same tree or cross-section were statistically and visually compared to verify the quality of the measurements and identify potentially absent rings. Once in agreement, these TRS were averaged into one series per tree or cross-section. Then, TRS from the same object (forest, building phases, panel paintings, shipwreck) were internally crossdated to try and identify i) timbers that may originate from the same tree, and ii) timbers derived from trees that grew in the same area. Timbers obtained from the same tree will usually produce high statistical scores. For example, Hillam (2004) suggests that *t*-

values above 10 will usually occur for two samples extracted from the same tree, but in practice this will depend on the internal variability of the tree. Slow-grown trees often show lower internal variability than fast-grown ones, hence *t*-scores lower than 10 can be expected for samples from the later. In general, Mom *et al*. (2010) propose that samples from the same tree will be more similar than samples from different trees, and that the way the timbers were processed should be taken into account, under the assumption that it would have maximised the efficiency of use of lumber wood. Therefore, to conclude that two or more timbers were probably obtained from the same tree, it is important to observe the type of timber product (e.g. half stems, quarters of a stem, radial/tangential planks, etc.) in addition to the tree ring patterns of the samples. Tree-ring series from samples suspected to belong to the same tree were averaged and treated in further analyses as one series. Groups of matching series representing individual trees were standardised with ARSTAN (Cook, 1985) using different methods depending on the growth trends present in the samples (see the Material and Methods section of each article for a specific description). The standardised TRS were averaged with a robust mean into 'floating' (i.e. not yet absolutely dated) standardised object chronologies. Finally, these floating chronologies and the loose TRS remaining were crossdated against absolutely dated master chronologies. As standard procedure, *t*BP values lower than 3.5 have been disregarded, as well as *t*BP values associated to non-significant Gl's, or to overlaps shorter than 40 rings.

3.3.9. Undated samples, absolute dates and estimated felling dates

Given a single sample from an historic timber of a wood species suitable for dendrochronological research and with enough tree rings to allow a reliable match, there are several reasons for which the research might not result in a date:

- reference chronologies of that species are not available for the area where the tree grew;
- the span of the available chronologies does not reach or overlap with the time period in which the tree grew;
- the tree-growth reflected in the investigated sample is strongly influenced by factors other than climate (i.e. continuous favourable growth conditions, such as enough water availability, result in 'complacent' growth patterns; regular pruning or strong defoliations due to insect attack result in disturbed patterns; trees that grow suppressed for decades show growth depressions that contain little climatic signal; etc.).

In all those cases, the sample will remain undated. However, when the dendrochronological research is successful and provides a date, three cases may occur (Baillie, 1982):

a) The last measured ring in the sample is the last one formed right under the bark before the tree was cut (bark edge). The date obtained for that ring will indicate the year, and even the season, in

which the tree was felled. If that ring is fully formed (i.e. it contains fully formed latewood) it can be established that the tree was cut between the late summer of that year (months of September/October) and the end of the winter (months of February/March of the following year), whereas if on earlywood cells are present in that ring, the felling date will be established in the spring or early summer (approximately April to June) of that year.

b) The last measured ring is a sapwood ring or it is identified as the heartwood/sapwood border. Given that species such as oak and pine produce a limited number of sapwood rings, it is possible to estimate the number of missing sapwood rings in wood from areas where sapwood estimates are available. Although the number of sapwood rings in oaks may vary considerably within the tree and between the trees of a specific site, a general decrease of sapwood rings has been observed from west to east in Europe (Haneca *et al*., 2009). Therefore, once the date and estimated provenance are established for a sample or group of coeval samples retaining partial sapwood, Bayesian statistics can be applied in OxCal (Bronk Ramsey, 2009) to estimate the felling date range of the timbers within a defined confidence interval (Millard, 2002; Miles, 2006; Tyers, 2008; see Material and Methods section in ***Article 4*** for details). In the case of pine species, the number of sapwood rings in the trees follows a different distribution than in oaks. Gjerdrum (2003) defined a formula to describe the number of heartwood rings in *Pinus sylvestris* from Scandinavia, which can be used in turn to estimate the sapwood rings of Scots pines when the pith of the tree is present in the sample and the sapwood is only partially preserved. However, no such formula has yet been defined for *Pinus nigra* in the Mediterranean basin. Therefore, when carrying out the sampling in historic buildings, the careful inspection of the timbers in search for the bark edge is crucial to establish if the last ring present in pine samples is the bark edge.

c) The last measured ring is a heartwood ring. In this case, it is not possible to know how many rings are missing till the sapwood; hence only a *terminus post quem* date (date after which the tree was felled) can be provided. The 'earliest possible felling date' can be estimated by adding to the date of the last measured ring the minimum number of sapwood rings that would correspond to the 95% confidence interval (Haneca *et al*., 2009).

When the dendrochronological analyses provides an exact felling date or an accurate estimation thereof (cases 'a' and 'b'), one must take into account that this date might not strictly correspond with the construction date of the structure or artefact under investigation. The wood could have been re-used, or it could be a repair, or there could be a time span between the felling of the tree and the use of the timber depending on the drying process, storage time, transport, etc. (Miles, 1997). Therefore, it is crucial to investigate a large number of samples per structure, adapting the sampling strategy to the research questions to be answered.

3.3.10. Dendroprovenancing

Once a sample from a (pre)historic timber has been dated, the basic principle of dendroprovenancing is that, provided a well-developed network of tree-ring chronologies, those producing the most outstanding statistical matches will represent the area where the wood originated from (Daly, 2007; Eckstein and Wrobel, 2007). This implies that the same statistical tests employed to date the samples are the ones used to assess the provenance. However, as Bridge (2011) pointed out, this method has various limitations. The similarity between tree-ring series is not a linear function exclusively dependent on the geographical distance, as environmental site conditions may differ importantly in short distances. For example, *Abies alba* shows strong teleconnections over large areas in central Europe (Büntgen *et al*., 2011), which are favourable for dating historic timbers, but will hamper dendroprovenancing. In contrast, strong elevation changes along short distances may induce differences in climatic factors such as temperature and precipitation, which could hamper crossdating of trees from different elevations, but provide excellent conditions for provenancing with high resolution (Wilson and Hopfmueller, 2001; Dittmar *et al*. 2012).

Taking these limitations into account, the dendroprovenancing method proposed by Daly (2007) was followed, by which site chronologies representing local growth conditions (including those developed in ***Article 2***) were employed to assess the provenance of the historic timbers investigated in ***Articles 3, 4 and 5***.

4. Discussion of main results

4. DISCUSSION OF MAIN RESULTS

4.1. Forest history and the development of long-span tree-ring chronologies in the Iberian Peninsula

As outlined in ***Article 1*** of this thesis, the deforestation of the Iberian Peninsula began with the arrival and settlement of Romans in the 3rd century BC, and continued almost until the 20th century. In addition to the exploitation of woodlands for local supply of construction timber, tools, furniture, firewood, and wood-derived products such as tar and resin for caulking of ships, the Romans also supplied their navies with wood from the south of Portugal and the south and east of Spain (e.g. Devi-Vareta, 1985: 51-52 and references therein). Similarly, Muslims saw the woodlands in *Al-Andalus* as a potential source of timber assortments for their homeland, and during the Middle Ages, wood from the south of Portugal and the east of Spain was exported towards the north of Africa and the eastern Mediterranean (Martínez Ruiz, 1999: 72). The export of timber from Portugal towards the north of Europe is also reported in AD 1194, when a Portuguese ship was expected to arrive in Bruges, in current Belgium, with a cargo that included timber (Oliveira Marques, 1959). However, the frequency of this direction of trade is unknown and could have occurred in seldom, specific occasions. Although the extent and relevance of these timber exports is difficult to quantify, it is certain that combined with the local demand for timber, wars and farming, they must have contributed to deforestation in Iberia until the 13th century. During the Early Modern Period, a growing population, extensive sheep farming and the expansion of Iberian empires further led to the reduction of woodlands (Gil, 2009 and references therein). More recently, during the 19th and 20th centuries, unfortunate policies such as the ecclesiastical confiscations, and the development of railways led to the scarce forest cover (barely 5.2% of the territory; ***Article 1*** of this thesis) present nowadays in the Iberian Peninsula.

This history of deforestation has direct consequences for the implementation of dendroarchaeological studies in the Iberian Peninsula, as old forests are scarce in the territory. As reported in ***Article 1***, just 30.5% of the existing broadleaf and conifer tree-ring chronologies in the Iberian Peninsula reach back beyond AD 1800 (see Fig. 6, p. 108 and Table S2, p. 131 in ***Article 1***). From those, only 47 chronologies reach back further than AD 1600, corresponding to the species *Abies alba* (2 chronologies), *Pinus nigra* (8), *P. sylvestris* (6), *P. uncinata* (27), *Quercus faginea* (3) and *Q. robur* (1). The oldest living trees in the Peninsula are both, *Pinus uncinata* growing above 2,100 m a.s.l. in the Pyrenees (e.g. Andreu-Hayles *et al*., 2011; Büntgen *et al*., 2008), and *Pinus nigra* from the Cazorla and Segura mountains growing between 1,755 and 1,953 m a.s.l. (e.g. Creus, 1998; ***Article 2*** in this thesis). In these areas, living trees surpassing 700 years of age have been found, providing reference chronologies anchored in time that span from the present to the 14th century with good replication.

However, chronologies developed from trees growing at such high elevations may have two limitations for dating and provenancing purposes:

- they might be representative of sites that were not subjected to logging activities in the past (i.e. they do not represent source areas interesting for dendroarchaeological studies)

- they may not serve to date timbers from trees grown at lower elevations, as climatic factors driving the high-frequency variation necessary for crossdating can change along elevation gradients inducing different responses in tree growth at different altitudes (see for example studies in the south of Germany by Wilson and Hopfmueller (2001) and Dittmar *et al*. (2012)).

Long-span chronologies of *Pinus uncinata* from the upper parts of the Pyrenees are a good example of the first limitation pointed out. However, *Pinus nigra* in the Cazorla and Segura mountains, which grow in more accessible areas below 2,000 m a.s.l., have a long history of timber exploitation that goes back to at least the late 10th century (e.g. De Aranda y Anton, 1990; De la Cruz Aguilar, 1994; Martínez Ruiz, 1999: 72). In the 1980s, Richter and others included three sites of *P. nigra* from the Cazorla and Segura mountains in their study about the dendrochronological potential of several pine species in Spain (Richter and Rodríguez Trobajo, 1985; Richter and Eckstein, 1986; Richter and Rodríguez Trobajo, 1986; Richter, 1988; Richter and Eckstein, 1990; Richter *et al*., 1991). In that study, the retrospective extension of chronologies with historic timbers was attempted for the first time in this country, targeting buildings in the province of Teruel, east of Spain. The successful dating of samples from different buildings allowed the retrospective extension of *Pinus sylvestris* chronologies from nearby areas back to AD 1068 (Richter, 1986). The dendroarchaeological potential of the *Pinus nigra* from the Cazorla and Segura mountains, however, was yet to be assessed, especially in regard to the second limitation aforementioned, subject that was addressed in ***Article 2*** of this thesis.

Results showed that the length of the chronologies obtained in these mountains seems to reflect the intensity of historic logging activities in these mountains, with the longest chronology (888 years in total) obtained at the upper site (CBS, 1,755-1,953 m a.s.l.), and spanning well replicated the period AD 1331-2010, and the shortest one (369 years) obtained at the lower, more accessible site (LIN, 1,079-1,177 m a.s.l.), and spanning with good quality the short interval AD 1840-2009 (see Fig. 2 in ***Article 2***, p. 152). The two chronologies at intermediate elevations (PMB, 1,500-1,619 and NAV, 1,582-1,702) provided high statistical quality for intervals of variable length (1544-2009 and 1698-2009 respectively), achieving a total length of 510 and 491 years. Furthermore, in spite of presenting a common pattern, the black pine chronologies developed in ***Article 2*** revealed significant differences in the climate-growth relationships along the 1,000 m elevation gradient, and through time (see Figs. 3 to 6 in Article, p. 153, 155 and 156). Such differences imply that the chronology from the upper part of the mountains reaching back to the 14th century may not be suitable to date individual timbers, or low-replicated object chronologies, from historic structures made of wood from lower elevations.

This was assessed researching roof structures of Jaen cathedral and the *Colegial del Salvador* church in Seville (***Article 3*** of this thesis), both built between the 16th and the 18th century with pine from the Cazorla and Segura mountains (Mendoza, 2008; Higueras Maldonado, 2009). Dating results obtained for the 17th and 18th century construction phases of Jaen cathedral led to the conclusion that the wood was obtained from mid-elevation sites with southern aspect, proving that the chronologies developed in ***Article 2*** retain elevation-specific signals (see Table 3 in ***Article 3***, p. 182). The timber elements that remained undated in both buildings could have originated from lower elevations, but the relative young age of the trees sampled at the low-elevation site hinders the possibility to verify this hypothesis, as the LIN chronology does not cover the construction periods corresponding to the different phases of both buildings. Likewise, the relatively limited time-span of the developed chronologies does not allow an assessment of whether the examined roof structures contain reused timbers from the previous mosques.

Altogether, the results obtained by Richter and Eckstein (1986, 1990), Richter *et al*. (1991) and in *Articles 2 and 3* of this thesis demonstrate that strategies directed to achieve long-span chronologies for dating and provenancing wooden cultural heritage in the Iberian Peninsula, must begin with the sampling of old living trees in the source areas, e.g. areas that supplied timber for construction of buildings, ships, and the production of art and furniture among others. In those areas, sites should be selected at different elevations and aspects, reflecting also variations across latitudinal and longitudinal gradients. Next, to improve the replication of the earlier centuries and extend the chronologies back in time, sampling of roof structures from historic buildings is recommended. In this case, i.e. when the research of roof structures aims at prolonging reference chronologies, the selection of buildings should be preceded by historical research, in order to acquire as much information *a priori* as possible in regard to the dates of the building phases and the origin of the historic wood (Richter and Rodríguez Trobajo, 1985). This will maximize the efforts towards the development of the chronologies while verifying the documented history of the buildings.

4.2. The challenge of dendroprovenancing

Together with assigning absolute dates to historic timbers, establishing the provenance of the wood is one of the main goals of dendroarchaeology. For this, several approaches can be followed. Traditionally, matching tree-ring series from the structure or object under investigation are averaged into a mean curve that is then compared with reference chronologies (preferably independent site chronologies (Daly, 2007)), representing well defined bigger or smaller geographical area. This approach has been illustrated in this thesis with the research of roof structures from Jaen cathedral (***Article 3***), the *Evangelistas* altarpiece (***Article 4***), and the *Arade 1* shipwreck (***Article 5***). In these cases, the researched elements represented dendrochronologically homogeneous groups (i.e. tree-ring series from individual timbers showed very high internal correlation), hence mean curves could be

made and compared with local site chronologies. The origin of the wood from the 17th and 18th century roofs of Jaen cathedral was established in this manner as west-aspect mid-elevation sites of the Cazorla and Segura mountains. Such a high-resolution result could only be achieved through the previous development of four reference chronologies of black pines growing at different elevations (***Article 2*** in this thesis). If the only available chronology had been the one developed at the highest elevation (CBS), the date from the 17th century timbers of the cathedral may have been overlooked, due to the low statistical correlation values with this chronology (see Table 3 in ***Article 3***, p. 182), and the provenance of the timbers from the 18th century structure could have mistakenly been placed in the upper part of the mountains, with the consequent misleading interpretation regarding historic logging activities in those mountains.

In the case of the *Evangelistas* altarpiece (***Article 4***), the area of origin of the oak planks was identified as the southwest of Sweden, more specifically in the historic region of Halland (see Fig. 8 in ***Article 4***, p. 202), whereas the oak and chestnut ship timbers investigated from the *Arade 1* shipwreck (***Article 5***) could be sourced to the Pays-de-Loire region, west of France, most likely in the area around Fontevraud (see Figs. 9 and 11 in *Article 5*, p. 232). In both cases, local site chronologies made of historic/archaeological timbers where employed as reference material for provenancing. As discussed in ***Article 4***, the limitation of using such reference chronologies is that the site where the timbers were found may not correspond to the location where the wood originated from (see also Domínguez-Delmás *et al*., 2014). In these cases, documentary sources had provided information about the procurement areas of the timbers included in the reference chronologies, which where local nearby forests in both cases (Lavier, pers. comm.; Bråthen, 1982). When historical information is not available, special attention should be paid to the regional and local geography, and the possibility that timber was transported by rivers from inland to coastal areas or by sea aboard ships should be taken into account. These cases have been documented not only in the north of Europe (e.g. oak from inland Polish forests was transported down the Vistula river to Gdansk (Wazny, 2005 and references therein), but also in the Iberian Peninsula. For example, in medieval times, wood floated down the Ebro and the Jucar to Tortosa and Valencia respectively was afterwards transported by sea aboard ships to the current provinces of Murcia and Almería (Lombard, 1980), and to the arsenal of Cartagena in the 18th century (Gil Olcina, 2006). In the north of Spain, transport of timber from the Basque Country (in the east) to the royal shipyard in Ferrol (in the west) also occurred in the 18th century (De la Fuente, 2006)), and from the Basque Country to Portugal for the same purpose in earlier centuries (Devi-Vareta, 1985, 1986 and references therein).

When timbers from a structure under investigation do not represent a single homogeneous group, their tree-ring series must be compared individually with reference chronologies. Such a lack of cross-correlations between contemporaneous timbers could occur when the wood originates from e.g. Atlantic maritime climates, where tree growth-patterns tend to be complacent due to the lack of factors

limiting their growth (Fritts, 1976). Another cause could be that the wood was procured from different geographical sources, as illustrated e.g. by Bridge (2011) with the Mary Rose shipwreck timbers. De Vries (1994) also reported high diversity of timbers (in terms of tree-ring patters) in late medieval churches and cathedrals in the Netherlands, attributing such mixture to the purchase of wood in major wood markets where timber would have arrived from different procurement areas. Research of the roof structures of the *Colegial del Salvador* church (***Article 3***) encountered this challenge. Given that documentary sources place the provenance of the wood in the Cazorla and Segura mountains, it is likely that the source areas lie further to the north of the sites from where chronologies were developed in ***Article 2***, or that this newly developed chronologies do not cover the period of interest of those samples (e.g. the low-elevation chronology, LIN, barely reaches back to AD 1840, so 18th century timbers originating from this site would remain undated). Last but not least, the possible occurrence of wood from different, non-overlapping periods (i.e. reused timbers from the previous mosque or bought second hand from other buildings) should not be excluded as a reason for the lack of matches between timbers from those roofs.

In the north of Spain, although not tested in this thesis with a case study, provenancing timbers from oak species growing in the Cantabrian Mountains looks *a priori* promising (***Article 1***). In the region of Galicia, northwest of Spain, oaks growing on low-elevation (200-300 m a.s.l.) coastal sites present distinct growth patterns that clearly separate from those growing at higher-elevation (475-700 m a.s.l.) inland sites (García-González, 2008). In the central part of the Cantabrian Mountains (regions of Asturias and Cantabria), Rozas (2006) studied climate-growth relationships of beech and oak stands and found highly significant correlations between chronologies of the same species located at similar elevations, with 52 to 64% of the tree-growth variance being explained by regional climate. Further to the east, in the Basque Country, the development of several long-span chronologies of oak by Susperregi (2007) recently led to the dating and provenancing of a floating chronology of hull-planks from the Newport ship (Nayling and Susperregi, 2014), although the authors stress the need to develop more reference chronologies in the region in order to improve the resolution of the source area. These promising results contrast with those from studies in England, Belgium and the eastern Baltic, where the year-to-year growth of oak species in coastal areas presents complex relationships with environmental factors, which hamper the definition of provenance areas (Bridge, 2012 and references therein).

The successful results achieved for Jaen cathedral (***Article 3***) and in ***Articles 4*** and ***5*** illustrate the potential of dendroprovenancing historic wood from different areas, i.e. local wood from the Cazorla and Segura mountains, wood imported to Iberia from northern Europe, and wood from shipwrecks found in Iberian coasts, corresponding to ships that may have been built elsewhere. Failure to date and provenance the numerous timbers sampled at *Colegial del Salvador* church (***Article 3***) illustrates part of the challenge of dendroprovenancing in the Iberian Peninsula. Regardless of the method employed,

given that the same parameters used for tree-ring dating are used to establish the provenance of wood (i.e. correlation coefficient and Student's *t*-value), both dating and provenancing wood from the Iberian Peninsula face similar limitations. Until a dense grid of long-span tree-ring chronologies for different species is developed in source areas, numerous historic timbers will have to remain undated and their provenance will be unknown. Strong teleconnections (i.e. long-distance synchronisation between forests of the same species) found between pine stands growing at similar elevations in different mountain ranges (e.g. Richter *et al*., 1991; Fig. 7 in ***Article 2*** this thesis, p. 158), are an advantage for dating purposes but may pose a challenge to define the exact procurement area. In such cases, watersheds could be considered in initial research hypotheses as major provenance units (***Article 1*** this thesis), given that transport over land across mountain ranges from one watershed to another is very unlikely (Rodríguez Trobajo, 2008). In coastal locations however, secondary hypotheses should consider the transport of timber over sea from the mouth of a major river to other sites. This is documented not only in Spanish coasts for different historic periods, but also in Portugal, as previously indicated. The greatest challenge in Portugal will be the development of tree-ring chronologies from living trees, due to the heavy depletion of woodlands since the late Middle Ages and the current lack of long-lived forests (see *Article 1* in this thesis and references therein). Other lines of research involving isotope ratios could be pursued to complement dendrochronological information and help defining source areas where provenancing by tree-ring methods encounters limitations (see for example Reynolds *et al*., 2005; Kagawa and Leavitt, 2012; Rich *et al*., 2012, 2015).

4.3. Historical transport of wood in Iberian rivers

The finding of oak wooden pegs and willow (*Salix* sp.) twigs in timbers from the roofs of the *Colegial del Salvador* church in Seville (see Fig. 8 in ***Article 3***, p. 180) represents material evidence of the transport of logs in rafts, proving that this practice was also carried out in Andalusian rivers. To the best of our knowledge, and according to Gil Olcina (2006: 59), the transport of wood in rafts was carried out in the Ebro and its Pyrenean tributaries, maybe in the Tagus, and in some Basque rivers such as the Bidasoa, whereas the transport of wood as loose logs from the upper part of the mountains down to the valleys, and also to coastal areas, was common practice in the Turia, Cabriel-Jucar, Segura, Guadalquivir and their tributaries (Navarro Reverter, 1872; Gil Olcina, 2006). Flotation of timbers acquired a high degree of specialisation, particularly during the mid-19th and first half of the 20th century in the Cazorla and Segura mountains, where thousands of railroad sleepers were processed from black pines growing high up in the mountains and transported through elaborate water channels down to the valley (Araque Jiménez, 1996, 2007; Tresaco Calvo, 1968). However, the Guadalquivir being a large river, it seems logical that in former centuries wood was assembled into rafts at some point along the valley, as suggested by Córdoba de la Llave (1995: 104) for late-medieval times. Since the timbers from the *Colegial del Salvador* remain undated, it is not yet possible

to assign an exact temporal frame to this practice in Andalusia, but considering that the roofs of the *Colegial del Salvador* church were built between AD 1703 and 1709 (Mendoza, 2008), it is reasonable to assume that those timbers must date close to those years, or earlier, if the wood was reused from another structure. Moreover, as they remain undated, their provenance is also unknown, hence they could have originated from forests in the south of the region and have reached the Guadalquivir through some tributary where timbers were assembled into rafts.

Furthermore, this finding suggests that the same system employed to prepare the rafts in the Ebro river was used to prepare these rafts in Andalusia. In the Ebro, raftsmen used willow shoots cut in May as cords. To make them more flexible they used oak stakes to fasten the end bits of the willow shoots into holes that were made in the logs with a borer (see Pallaruelo, 2008: 128-129). The oak wooden pegs and willow twigs found in the timbers of the *Colegial del Salvador* church would be a leftover of this process, indicating that there must have been transfer of knowledge between the raftsmen of the Ebro and the Guadalquivir rivers. Another, less likely option, is that these holes with oak pegs and willow twigs are leftovers from stakes and cords used to tie the logs as illustrated in Eissing and Dittmar (2011: 141, Fig. 4) for rivers in the south of Germany. In Belgium, rafting joints found in oak rafters and collar beams from a medieval building consisted on holes piercing the timbers, where cords or twigs would be used to assemble the raft (Haneca and Debonne, 2012, Fig. 9). This system has also been found in the Netherlands (Van Daalen, pers. comm.) and is totally different from the one found in the *Colegial del Salvador* timbers.

4.4. Assembly marks, tools and wood-working techniques

When dendrochronology is combined with the observation of assembly marks and tool marks, as well as with the register of the timber products obtained (squared beams, quarters of a beam, etc.), valuable ethnographic information about the processing of the wood can be placed in specific periods of time (Crone and Barber, 1981).

Carpenter's marks observed in several timbers of the sacristy roof at Jaen cathedral (see Fig 5 in ***Article 3***, p. 178) seem to correspond to assembly marks, suggesting that the roof structure could have been pre-designed and assembled on the ground before lifting up the individual elements to their final position in the roof. This method was commonly used for example in Britain, the north of France, Belgium, Germany, the Netherlands, etc., since the late Middle Ages (e.g. De Vries, 1994; Hoffsummer, 2002; Coomans, 2011; Haneca and Debonne, 2012). However, only two of the numerals found at the sacristy roof agree with the sequence of those timber elements, hindering the clear interpretation of the structure. Interestingly, the rest of the roofs researched (17th and 18th century structures at Jaen cathedral, and the 18th century roofs from *Colegial del Salvador* church) lack assembly marks. This, together with the standard sizes of half- and quarter-sawn timbers suggests that

a change in wood-working techniques occurred towards a standardization in the production of timber elements. For this hypothesis to be verified, however, more buildings in the Andalusian region should be thoroughly investigated, and observations should be cross-checked with historical sources about the construction of the buildings, the architects involved, and their trajectory and influences.

Such a change in wood-working techniques also seems to have taken place in Atlantic Iberia and the north of Europe during the 16th century in panel making and shipbuilding, with an increase of the use of the saw to produce planks (Fraiture, 2009: 105; Domínguez-Delmás, 2013: 1090). Tool marks observed in the planks from the *Evangelistas* altarpiece revealed that they had been obtained by cleaving (see Figs. 4 and 6 in ***Article 4***, pp. 198 and 200), resulting in radial or almost radial planks. This indicates that the planks were prepared at some workshop where the saw was not yet introduced. However, the inspected planks from the *Arade 1* shipwreck were tangential (***Article 5***), indicating that they had been obtained by sawing at a shipyard where the practice of splitting the oaks to obtain thin radial planks had already been abandoned. Furthermore, the presence of sapwood in numerous planks from the altarpiece proves that the specifications of the guilds, which required the sapwood to be completely removed (Bruquetas Galán, 2002; Beeckman, 2005; Haneca *et al*., 2005), were not strictly followed. This raises questions about the motives for such infringement of the production rules. An explanation could be the use of a blunt tool to remove it, although a more likely one could be the need to stick to certain width of the planks that was not met by the heartwood.

4.5. The impact of timber trade in Iberian dendroarchaeology

As reviewed in ***Article 1*** and demonstrated in ***Article 4***, the relevance of the import of timber to Spain and Portugal from the 15th century onwards cannot be overlooked, as it can have a strong impact in Iberian dendroarchaeology.

The earliest references about the import of timber to Portugal date from AD 1254, when documentary sources report the arrival in Porto of wood from La Rochelle and other places in France (Devi-Vareta, 1985 and references therein). From the late 13th century onwards, Baltic wood arrived occasionally in Lisbon, becoming a regular import product during the 15th century (Oliveira Marques, 1959). This trade was facilitated by the Hanseatic League, a confederation of German merchants that obtained privileges in the Baltic and Scandinavian countries to trade their raw materials, cereals and minerals in western Europe in exchange for rich commodities and manufactured products (Brand, 2007). However, in the second half of the 15th century, the League's trade-monopoly was challenged and eventually broken by Dutch and Flemish merchants, who had gained the support of Hanseatic towns in the south eastern Baltic to trade their goods. Consequently, timber products were imported to the Iberian Peninsula mostly by Hanseatic traders and merchants from the Low Countries, hence the

recurrent reference to 'Flemish oak' and 'Flemish pine' in documentary sources (Bruquetas Galán, 2002; Otte Sander, 2008).

This trade of timber from the north of Europe into the Iberian Peninsula is documented both in foreign registers (e.g. Bogucka, 1978; Zunde, 1999) as well as in Spanish and Portuguese archives (Palomero Páramo, 1983; Devi-Vareta, 1986; De Aranda y Antón, 1990; Bruquetas Galán, 2002; Otte Sander, 2008), especially in relation to shipbuilding and the acquisition of materials for art pieces. The Danish Sound Toll Registers, now digitised and made openly available through the Sound Toll Registers Online (SRO) database (http://www.soundtoll.nl/index.php/en/ over-het-project/str-online last accessed on 30 July 2015) are a valuable source of information about traffic and traded goods from the Baltic towards western Europe in the period AD 1497-1857. Entries recorded in the registers include among others the departure harbour, the harbour of destination (from the mid-1660s onwards) and the composition of the cargo. Timber products exported from the Baltic included among others oak boards (*barkholt, bord, brædder, inholt, splitholt*) and barrel staves (*fadholt, klapholt, store stænger*) of different types and sizes, as well as different types of ship timber-elements such as masts (*master, skibs*), planks (*skibsholt, skibsplanker, skips-bord, skudeplanker*, etc.), compass timber (*krumholt*) and even wooden nails (*nagler*) (http://dietrich.soundtoll.nl/public/cargoes.php last accessed on 1st August 2015). As the SRO indicate, the terms of some timber products seem to have changed through time towards more descriptive or specific names, which could be the result of the diversification of the products or the source areas. Archival sources also reflect changes in some timber products through time, as reflected for example in Gdansk export registers, where oak boards known as wainscots differed in sizes from the early 15th to the second half of the 16th century (Wazny, 2005 and references therein). Wainscots were high quality oak boards (Eckstein and Wrobel, 2007), usually obtained by splitting slow-grown branchless oak stems into radial boards. At specialised workshops they were split or sawn into thin planks, resulting in timber products of different dimensions as time moves on from the 15th to the 17th century (see the evolution of timber processing for panel making in Fraiture, 2009, Figs. 7, 9 and 10). These wainscots were highly appreciated for panel painting, wall panelling and shipbuilding, hence they were exported from the south-eastern Baltic to most of western Europe (Germany, Denmark, The Low Countries, France, Great Britain and the Iberian Peninsula) (Wazny, 2005).

Dendroarchaeological research on the altarpiece of the *Evangelistas* chapel in Seville cathedral (***Article 4*** in this thesis), has linked the wainscots with the timber assortment known as *borne* in the Iberian Peninsula. In Spain and Portugal, the term *borne* appears in numerous commission contracts for altarpieces from the late 15th to the early 17th century (see some examples in Gañán Medina, 1999: 114-115) and in documents related to shipbuilding. For example, in the north of Spain, written sources from AD 1522 report about the use of *borne* for hull-planking in clinker-built ships constructed in the Cantabrian town of San Vicente de la Barquera (Casado Soto, 2003: 175). The

panels for the *Evangelistas* altarpiece had to be made of *borne* wood, according to the commission contract (Hernández Díaz, 1937). The research has provided an accurate description of the characteristics of this wood, which are very similar to those reported for 16th century oak wainscots in the north of Europe (see ***Article 4*** in this thesis). This confirms that high quality oak boards imported from northern Europe were known as *borne* in the Iberian Peninsula, as pointed out by Bruquetas Galán (2002). More importantly, this investigation has revealed that the *borne* wood employed in the *Evangelistas* altarpiece originated from the southwest of Sweden. This find also demonstrates that the provenance of such timber products was not restricted to the south-eastern Baltic.

Whereas the Baltic trade and its impact in western economies has broadly been studied by historians in different countries, trade of products from western Sweden, Norway and north of Russia, i.e. not passing through the Sound straight, is by comparison relatively underrepresented. Some historians have considered this non-Baltic trade in their studies (e.g. Dow, 1969; De Vries and Van der Woude, 1997; Veluwenkamp, 2000), including information about the trade of timber from those areas towards e.g. the Netherlands and Scotland. Dendrochronological research has also provided evidence of the trade of timber from Scandinavia to the Netherlands (Sass-Klaassen *et al*., 2008; Domínguez-Delmás et. al., 2011) and Scotland (Crone and Faucett, 1998; Crone and Mills, 2012). Therefore, if non-Baltic timber was available in the north western markets, it is very likely that it also arrived to the Iberian Peninsula.

Besides the import of timber from the north and northeast of Europe to the Iberian Peninsula, there was also import of timber from the New World. For example, in Seville so-called *cedro de Indias* arrived already in the second half of the 16th century (Bruquetas Galán, 2002 and references therein). Not to be confused with the conifers *Cedrus atlantica* or *Cedrus libani*, this *cedro de Indias* was some species of *Cedrela*. Highly appreciated for its excellent qualities for carving, it was commonly used by Europeans in the Caribbean basin to build ships and other structures, and in Sevilla for altarpieces (sculptures and panels).

As a result of this timber trade from the north of Europe and the Americas into Spain and Portugal, the presence of non-Iberian wood should be expected in objects from the cultural heritage built with wood, particularly in works of art and shipwrecks of ships built in Iberian shipyards. In such cases, international collaboration between dendrochronologists will be crucial to identify the date and provenance of the wood. In Europe, dendrochronologists have developed extensive datasets for the main source areas in the south-eastern Baltic, Scandinavia, Germany and France (Čufar, 2007 and references therein), hence the chances to date and provenance the imported timber used in Spanish and Portuguese constructions and objects are higher than when the wood employed had a local origin. However, one should bear in mind that finding foreign wood in a shipwreck or an artefact found in the Iberian Peninsula does not imply that the object in question originates from elsewhere. In the case of

shipwrecks, the non-Iberian wood could have been applied during repairs in some foreign harbour, but the lack of long-span reference chronologies for tropical species such as *Cedrela odorata* hampers the possibility to establish the date and provenance of the wood. Similarly, the impossibility to date timbers with foreign reference chronologies does not necessarily mean that the wood has a local, i.e. Iberian, origin. In this case historical research should be pursued to add another piece to the puzzle, and aid unravelling the history of the researched object.

4.6. The relevance of providing accurate wood identifications and reliable dendrochronological dates

4.6.1. Accurate wood identifications

An important step in the assessment of cultural heritage made of wood is the identification of the wood species employed in structures, objects or as firewood in different time periods. The research carried out on the *Arade 1* shipwreck (***Article 5*** this thesis), including the re-examination of wood samples previously identified as *Quercus faginea* and *Q. suber* by Queiroz *et al*. (2005), clearly illustrates the relevance of providing accurate wood identifications (even when this means leaving the identification in the subgenus level).

The identifications delivered by Queiroz *et al*. (2005) misled the archaeologists into believing that the ship had been built mostly with local/regional wood, as both *Q. suber* (cork oak) and *Q. faginea* (commonly known as Portuguese oak) are a very abundant species in Portugal. However, whereas the group of deciduous oaks can be identified by the naked eye (Morgan, 1975), there is as of yet no method to distinguish one species from another by wood-anatomical features (Schweingruber, 1990). An attempt to differentiate *Q. robur* from *Q. petraea* was made in the late 1990s by Feuillat *et al*. (1997), who concluded that for trees of a cambial age between 60 and 120 years old, rings c. 2 mm wide in *Q. robur* would present more than two rows of earlywood vessels and a percentage of latewood less than 60% of the total ring-width, whereas in *Q. petraea* such wide rings would present less rows of earlywood vessels and a percentage of latewood higher than 70%. This observation proved valid for an 80% of the samples from living trees. Recently, Hros and Vavrcik (2014) carried out a similar study comparing intra tree-ring anatomical variables of trees from *Q. robur* and *Q. petraea* growing at the same site in Czech Republic, and similarly to Feuillat *et al*. (1997) concluded that for the mean values of vessel area analysed *Q. robur* showed higher values than *Q. petraea*, suggesting that those features are strongly determined by the genetics of the species. In the light of these results, it seems that a method to distinguish those two species has been achieved in those areas. However, in the Iberian Peninsula, the group of deciduous oaks (*Quercus* subg. *quercus*) is represented not only by *Q. robur* and *Q. petraea*, but also by the species *Q. pubescens, Q. faginea, Q. canariensis* and *Q. pyrenaica* (Amaral Franco, 1990) and their various hybrid taxa, which have again

very similar wood anatomical features that do not allow their separation. Three of these species (*Q. faginea*, *Q. canariensis* and *Q. pyrenaica*) are endemic to the Iberian Peninsula and their presence outside this territory is very limited (Akkemic and Yaman, 2012). Results presented in ***Article 5*** demonstrate, not only that there was no justification to identify the wood species from the *Arade 1* shipwreck timbers as *Q. suber* and *Q. faginea*, but also that the timber originated from the Pays-de-Loire region in the west of France, an area out of reach from the natural distribution of those species. Finding a method to distinguish all these oak species from each other based on their wood anatomy would be very helpful in dendroarchaeological studies, especially for the interpretation of archaeological sites such as shipwrecks. However, as long as there is no method to distinguish them, the most accurate identification that can be provided is 'deciduous/marcescent oaks' (*Quercus* subg. *quercus*).

Another example of the consequences of providing erroneous wood identifications is found in reports related to restoration works of altarpieces. Due to a misleading definition in the *Diccionario de la Real Academia Española*, which describes the *roble borne* as '*melojo*' (i.e. *Quercus pyrenaica*) (http://lema.rae.es/drae/, last accessed on 30 July 2015), art-historians carrying out restoration works on the altarpiece from *Mariscal Diego Caballero* chapel at Seville cathedral, concluded that the wood referred to as *borne* in the commission contract must have been *Quercus pyrenaica* (Villanueva Romero *et al*., 2007: 126). This led them to assume that the wood required for the altarpiece had been procured from some local area within the Peninsula, obviating the real provenance of the wood outside the peninsula, and the merchant network involved in the import of this timber product to Seville (Otte Sander, 2008: 184). It is unclear where this misleading definition of the term *borne* comes from, but as described by Bruquetas Galán (2002) and demonstrated in ***Article 4*** of this thesis, the term *borne* was used in Spain during the 16th and early 17th century to define a specific timber product, i.e. radial oak boards imported to Spain and Portugal from northern Europe. Restorers and (art)historians making use of this definition from the *Diccionario de la Real Academia Española* and obviating these results, would fail to realise that they are dealing with historical evidence of such import of timber. ***Article 4*** also illustrates how provenancing by means of dendrochronology can provide precious information to improve our understanding of the wood supply in former times.

4.6.2. Reliable dendrochronological dates

The fact that wood species used for dendrochronological dating produce one tree-ring per year makes dendrochronology the most accurate method to date wood. This implies that there can only be one temporal position for each tree-ring series (Baillie, 1982: 263). To find the right position, i.e. the exact calendar date when a series is crossdated with reference chronologies anchored in time, or a relative date when compared with floating chronologies, dendrochronology relies on statistical parameters and visual agreement (Baillie, 1982 and references therein) (see point 3.3.8. in Material and Methods).

A good selection of samples will enhance the chances of dating success (see e.g. Morgan (1975), Hillam (2004), or ***Article 5*** in this thesis, p. 220, for guidelines). However, even when suitable samples with an acceptable number of tree rings (more than 80) are selected, the research may still not result in the dating of the wood. There could be different reasons for this (see point 3.3.9 in the Material and Methods sections), but regardless of the cause, the samples should remain undated, and the resulting floating tree-ring series should be systematically compared with each newly developed dataset.

This approach has been followed in this thesis, with the result that all except two timbers from the *Colegial del Salvador* church (***Article 3***), four planks from the *Evangelistas* altarpiece (***Article 4***) and one timber from *Arade 1* shipwreck (***Article 5***) have remained undated. Dendroarchaeology being a discipline under development in the Iberian Peninsula, numerous tree-ring series from archaeological and (art)historic timbers derived from local woodlands will inevitably have to remain undated until the reference data network acquires a widespread temporal and geographical coverage.

4.7. Interpretation of dendrochronological results

Given that dendroarchaeology is limited to elements made of wood, the dates found for historic and ancient timbers will strictly correspond to the tree-ring sequence they contain, hence they may not represent the date in which the structure or artefact was made. As described by Baillie (1982: 54-55) the last tree ring formed before the cutting of the tree may not be present in the investigated sample, and even when it is, the wood could have been reused from a previous structure, or seasoned for several months prior to its use, stockpiled for a couple of years, or it could represent a later repair. Whereas seasoning was common practice for planks used for panelling, some studies suggest that wood for buildings was cut and used as needed (Hillam, 2004: 14 and references therein). In major buildings, however, the provision of materials could induce a lapse of time between the felling of the trees and the use of the timber, in which the wood would be stockpiled. This seems to have been the case during the construction of the roofs of Jaen cathedral (***Article 3***). Complete sapwood was found in numerous timbers of the researched structures. Felling dates between three to nine years earlier than the documented construction dates of the roofs suggest that wood was stockpiled to be worked afterwards as it was required.

When no information is available about the construction date of the investigated object or structure, a sampling strategy adapted to each particular case, together with a proper selection of timbers, can often help inferring the construction time. This has been illustrated in this thesis by the research of the *Arade 1* shipwreck (***Article 5***). The careful selection of structural timbers distributed in different parts of the ship and containing complete or partial sapwood, allowed establishing the felling of the oak trees between the spring/summer of 1579 and the spring/summer of AD 1583. Since all the timbers represented a dendrochronologicaly homogeneous group with the same provenance, it seemed

reasonable to assume that the ship was built in or shortly after AD 1583, as converting oak trunks into planks and framing elements was easier done in fresh wood than in long-seasoned, dried out trunks (Darrah, 1982).

In contrast, when the bark edge is absent in all the samples, sapwood estimates can be used (when available for the species under investigation and the area of origin of the wood) to infer the felling dates of the parental trees (see Table 1 in Haneca *et al*., 2009 for available sapwood estimates for oak in different geographical areas of Europe). This is typically the case of works of art, where sapwood was partially or totally removed during the wood-working process, as it is very susceptible to insect attack and decay (Bruquetas Galán, 2002). Through the research of the *Evangelistas* altarpiece (*Article 4* in this thesis) it has been demonstrated that the use of Bayesian statistics as proposed by Millard (2002) constitutes a powerful tool to infer the felling date range of parental trees in the absence of bark edge (see also Miles, 2006). Tyers (2008) proposed a systematic way to report absolute dendrochronological dates and estimated felling dates obtained by Bayesian analysis, which has been implemented in ***Article 4***. The estimated felling date interval for the trees used to make the panels of the *Evangelistas* altarpiece ranged between a couple of months to four years before the altarpiece was commissioned in AD 1553, revealing a seasoning time shorter than what has been reported for 16th and 17th panels in northern Europe (e.g. Klein, 1996).

However, the implementation of sapwood estimates in general require the availability of a pre-existing dataset of sapwood observations for a specific species and geographical area, in order to define a sapwood model. When the observed number of sapwood rings from a dataset conforms to a lognormal distribution, as it is the case for sapwood of oaks in central, northern and eastern Europe (Haneca *et al*. 2009 and references therein), probability ranges can be estimated with different degrees of confidence (Millard, 2002). In pines however, the number of sapwood rings has been found to fit a linear model, being highly related to tree age and silviculture, and independent on environmental factors and position along the stem (Gjerdrum, 2003). In the Iberian Peninsula, a sapwood model for deciduous and marcescent oak species is yet to be defined, and the 'pine heartwood age rule' proposed by Gjedrum (2003) must still be tested for pine species. Therefore, lacking a sapwood model for pines in Andalusia, the observation of presence/absence of bark edge in the timbers from the roof structures investigated in ***Article 3*** of this thesis became crucial for the interpretation of results. For the timbers in which no bark edge was observed during the sampling, the estimated felling date was expressed as 'after' the year of the last measured ring.

4.8. Preservation of samples, data and metadata

The preservation and curation of dendrochronological samples, as well as the data and meta-data derived from them, has for decades been a point of concern for archaeologists and

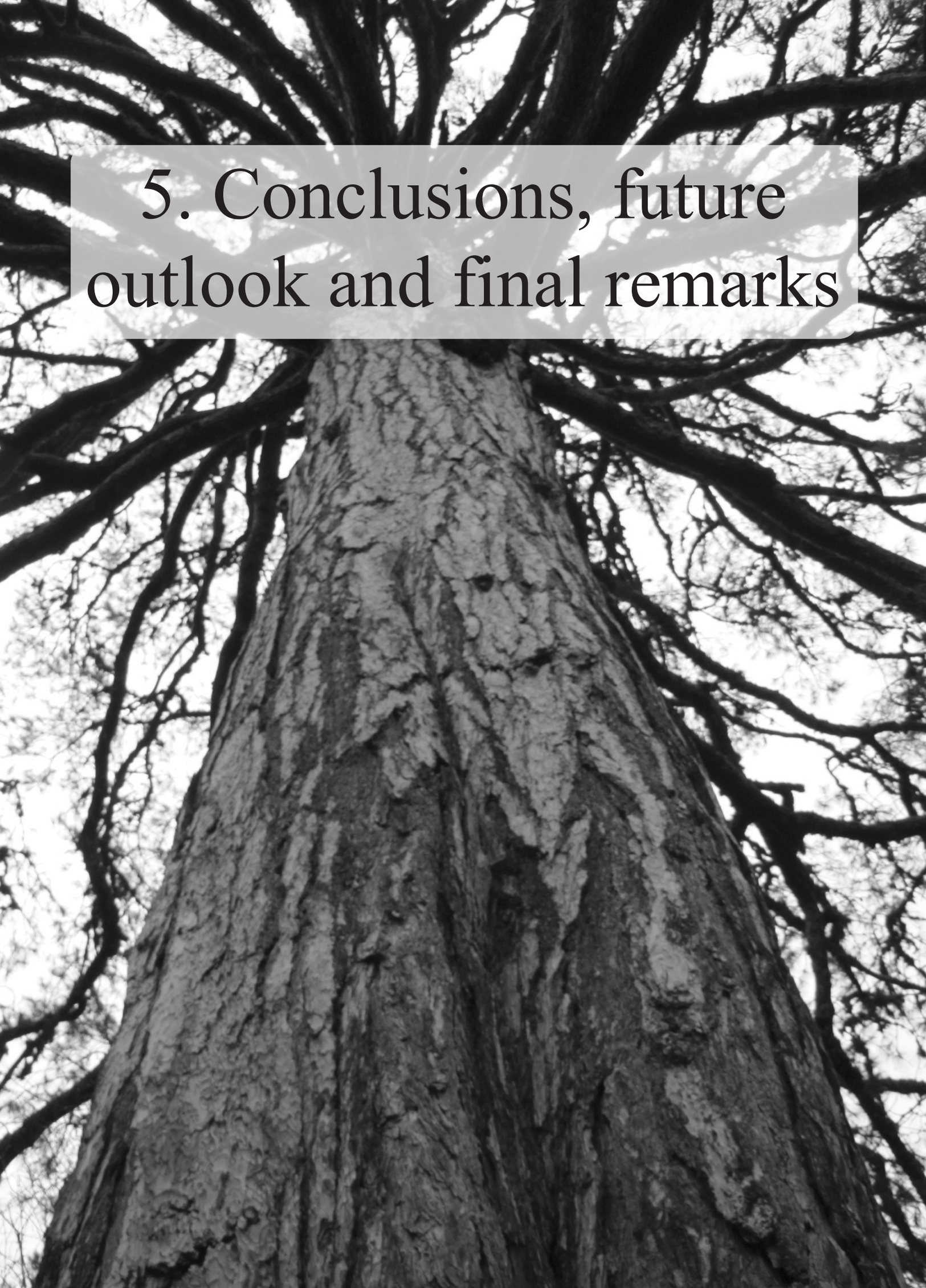
dendrochronologists in different parts of the world (e.g. Baillie, 2002: 70; Creasman, 2011 and references therein). Samples collected from living trees, historic buildings, archaeological sites and ancient natural environments represent the primary source of tree-ring data and an open window to the past. The environments and structures where they were collected may disappear or undergo major changes in the future (Fig. 9). Therefore, the samples may remain the sole material evidence of past environmental conditions, human-environment interactions, cultural encounters or technological choices. Their proper conservation and curation would allow scientists to re-examine them if necessary, and to use them for analyses that were not initially contemplated (Baillie, 2002).

Although cores extracted from living trees and dry-wood samples from historic timbers may suffer the attack of xylophages if not conserved in proper conditions, waterlogged wood is especially susceptible to degradation by fungi, bacteria and microbes (Huisman and Klaassen, 2009). Charcoal is also susceptible to decay in high relative-humidity environments (Creasman, 2011). A series of guidelines exist for the preservation and curation of wood specimens of different nature (e.g. Jones, 2010; Creasman, 2011, 2012). However, more often than not, research institutes, museums, universities and private laboratories where dendrochronological research is being carried out lack specific facilities to provide adequate conditions for long-term preservation of wood specimens (e.g. storage space, rooms with humidity and temperature control, etc.), or the funds to commission the conservation from specialised institutes or professionals. Redressing this situation should be a top priority for holders of collections of dendrochronological samples, and funding agencies should be aware of the importance of providing funds for such purposes, so that scientists can include the preservation and conservation of samples, data and metadata in future proposals as part of the research process.

Figure 9. Roof timbers removed from an historic building in Andalusia, ready to be disposed. Photo: M. Domínguez Delmás.

Research on works of arts, which is nowadays based on digital pictures, deserves the same consideration as dendrochronology of living trees or historic and archaeological wood. Given that such pieces are seldom available for dendrochronological research and permission for re-examination may not be granted a second time (Baillie, 2002), the photographs of the tree-ring series obtained during the first examination represent the only register for future verification. Therefore, they should be uploaded to permanent digital repositories. Likewise, the storage of tree-ring data and metadata (including individual tree-ring series) in digital repositories is equally important, to ensure the preservation of the data for the future and to allow large-scale research on different subjects such as climate change, historic timber trade, etc. Efforts towards the creation of digital repositories for dendrochronological data resulted in the 1970s in the development of the International Tree-Ring Databank (Grissino-Mayer and Fritts, 1997 and references therein). Since then, other repositories have been created (see an overview in Creasman, 2011: 104), among which the *Digital Collaboratory for Cultural Dendrochronology*, DCCD (Jansma *et al*., 2012) was specially designed to host dendrochronological data, metadata, measurement files, photographs, articles and reports derived from research on historic and archaeological sites and objects.

The samples collected within the scope of this PhD project are stored at different facilities. Samples from the living trees (***Article 2***) and historic buildings (***Article 3***) are currently stored at the facilities of the *Rijksdienst voor het Cultureel Erfgoed* (Cultural Heritage Agency of the Netherlands) in Amersfoort, the Netherlands. The photographs from the researched planks of the *Evangelistas* altarpiece (***Article 4***) are stored in digital format at the *Instituto Nacional de Investigaciones Agrarias* in Madrid (Spain). Samples from the *Arade 1* shipwreck (***Article 5***) were sent back to the facilities of the DANS (now CNANS) in Lisbon, where they were washed/waterlogged, wrapped in polyethylene film and kept inside a 'blackout' box in a cool place (Johao Coelho, conservator and restorer of the Portuguese *Divisão de Salvaguarda do Património Arqueitectónico e Arqueológico*, email comm.). The data and metadata will be uploaded into the DCCD, as this is the most suitable repository to store dendroarchaeological data.



5. Conclusions, future outlook and final remarks

5. CONCLUSIONS, FUTURE OUTLOOK AND FINAL REMARKS

5.1. Conclusions and future outlook

Dendroarchaeology and the development of reference chronologies in the Iberian Peninsula

- *Dendroarchaeology has a great potential in the Iberian Peninsula* to provide exact felling dates, determine the provenance of historic wood, inform about the use, transport and processing of wood in past centuries, and provide evidence for historic timber trade. This has been reviewed in ***Article 1*** and empirically demonstrated in ***Articles 3, 4*** and ***5*** of this thesis.

- *The black pine (*Pinus nigra *subsp.* salzmannii*) chronologies developed in the Cazorla and Segura mountains are suitable for dating and provenancing historic wood extracted from those sites (**Articles 2 and 3**).* Furthermore, strong teleconnections found between the developed chronologies and other conifer species in Iberia, particularly those of black pine located at mid-elevation sites with similar aspect, are an advantage for dendrochronological dating of historic samples, as connecting chronologies could provide replications for eventual dates of historic tree-ring series. However, the differences found in climate-growth relationships along the elevation gradient may hamper crossdating of historic timbers from low-elevations with the chronology from the upper part of the mountains. Chronologies at mid-elevation sites can serve as bridges to overcome this obstacle.

- *To achieve a reference tree-ring dataset for dating and provenancing cultural heritage made of wood in the Iberian Peninsula, further strategies for tree-ring data compilation should be directed in the first instance at living-trees in key source areas (**Articles 1 and 2**).* Forest of areas formerly exploited for timber production should be selected along elevation, latitudinal and longitudinal gradients, covering the wide spectrum of climatic and ecological conditions.

- *Timbers from historic buildings offer the best prospects to improve the quality of the chronologies from living trees in older centuries and to prolong them back in time (**Articles 1 and 3**).* The lack of old-grown forest stands in many regions of Spain and most of Portugal will require targeting recent buildings (19th century) in those areas. It is strongly advised to carry out historical research preceding the selection of buildings, in order to gain *a priori* knowledge about the construction history and the provenance of the wood, and maximise in this way the efforts towards the extension of the chronologies.

Dendroprovenancing

- *The Iberian Peninsula is an excellent territory to apply and test provenancing methods with high spatial resolution (**Articles 1, 2 and 3**).* Provided a dense grid of reference tree-ring chronologies for different species becomes available, provenancing historic wood with high resolution by dendrochronological means seems very plausible, given the strong variability of environmental conditions along latitudinal, longitudinal and elevation transects throughout the territory.

- *Teleconnections over large distances between forests located in different watersheds should not hinder identifying the provenance of the wood (**Articles 1, 2 and 3**).* Watersheds should be considered in departing hypothesis as the most potential provenance units, although in the case of shipyards and major buildings in coastal cities or cities located by main navigable rivers, the possibility that timber was imported by sea from different watersheds should also be taken into account.

Historical rafting in Andalusian rivers

- *Evidence for the use of rafts in Andalusian rivers has been found in the Colegial del Salvador church (**Article 3**).* This finding suggests that the same system used in the Ebro to prepare rafts was employed in Andalusia, indicating that a transfer of knowledge occurred between people from those watersheds. Such ancestral practice deserves to be studied from an academic and geographically global perspective, as it was not restricted to the Spanish territory, and it is of great ethnographic interest.

Wood-working techniques

- *Changes in constructive and wood-working techniques seem to have occurred between the 16th and the 17th in Andalusian roof structures (**Article 3**).* This subject should be approached from a multidisciplinary perspective, considering also the influence that immigrant craftsmen had in the development of new solutions for the construction of wooden roofs. Dendrochronology has the potential to contribute to such studies providing an exact temporal and geographical framework.

- *The oak planks for the* Evangelistas *altarpiece were obtained at a workshop where wood was processed by cleaving (**Article 4**), whereas the planks from the* Arade 1 *shipwreck had been made at a shipyard where the saw was already used to prepare planks (**Article 5**).* Comparative multidisciplinary studies at European level could shed some light into the exact moment of the shift of wood-working techniques in different regions and the causes that triggered it.

The import of wood into Spain and Portugal

- *Empirical evidence has been provided for the characteristics of the timber product known as 'borne' used to make the Evangelistas altarpiece in Seville (**Article 4**).* The term *borne* seems to refer to the timber product known as wainscot in the north of Europe, and its occurrence in Spanish and Portuguese documentary sources has a similar timeframe than the wainscots in north European markets (15th to early 17th century).

- *The absolute dating of the planks from the Evangelistas altarpiece further allowed determining the provenance of this borne wood in the southwest of Sweden (**Article 4**).* This is the first time that oak from that region is reported in panel paintings in Western Europe, demonstrating that this high quality product was not only exported from the eastern Baltic, but also from the southwest of Sweden. Further research on works of art made of *borne* in Spain and Portugal should shed light on the frequency and magnitude of the trade of this product in the Iberian Peninsula. Efforts towards the combined study of documentary sources and comparative dendroarchaeological investigations of *borne*, Baltic and Scandinavian wainscots in different countries should be pursued.

- *The import of timber from northern Europe and the Americas to Spain and Portugal will have a strong impact on dendroarchaeological studies involving cultural heritage from the 14th to the 18th century, particularly in the research involving works of art and shipwrecks, but also buildings in coastal and fluvial navigable locations (**Articles 1, 4 and 5**).* These investigations should be carried out with an open mind, taking into account that those objects and structures may have been partly or fully made with imported wood. In the specific case of shipwrecks found on Spanish and Portuguese coasts, the premise to address the research should be that the ship may have been built anywhere.

- *The research of objects made with wood from northern, central and eastern Europe will profit from the existence of a dense tree-ring network in those areas (**Articles 4 and 5**).* Therefore, the chances to get those samples dated are *a priori* higher than when dealing with local, Iberian wood. Reference chronologies from selected American species need to be developed to allow dating and provenancing wood imported from the Caribbean basin. International collaboration between dendrochronologists is paramount for the success of research involving imported wood.

Wood identifications and dendrochronological dates

- *The identification of wood species is a very important step in dendroarchaeological studies as demonstrated in **Article 5***. Until methods are found to discern between the deciduous/marcescent

oak species present in the Iberian Peninsula, the determination of this group based on wood anatomical features should be restricted to the subgenus level (*Quercus* subg. *quercus*).

- *Dendroarchaeology being a developing discipline in the Iberian Peninsula, numerous samples of local timber will invariably have to remain undated until a local tree ring network becomes available in Spain and Portugal (**Article 3**)*. Reporting potential or provisional dates, as well as different possible dates for a single tree-ring series should be avoided, as such practices contradict the basic foundation of tree-ring science and deeply harm its reputation.

- *Sapwood models for Iberian oak and pine species should be developed to allow inferring felling dates from exact dendrochronological dates when the bark edge is absent in the samples (**Article 3**)*. Sapwood information compiled from living trees should serve to this purpose.

Preservation of samples, data and metadata

- *The conservation of samples and photographs of tree-ring series, as well as their related data and meta-data, must be integrated in the research process*. This will not only prevent the loss of data, but in combination with datasets from other countries, will also allow tackling large research subjects such as European-scale timber trade, and it may provide source material for future research projects or analyses not yet envisaged.

5.2. Final remarks

As illustrated in this PhD thesis, the applications of dendrochronology within the Humanities are very diverse and can provide a great amount of information. Professionals working in fields related to material cultural heritage, such as archaeologists, art- and architectural-historians, restorers and conservators among others, must be informed about the potential of this science to provide not only absolute dates, but also evidence about the provenance of the wood, ancient forestry practices, transport and trade of timber, ways to process the wood, etc. The replacement of original timbers from historic buildings without previously conducting dendroarchaeological research still is a common practice in different parts of the peninsula and represents an irreparable loss of valuable environmental, historic, and ethnographic data. Equally, the non-inclusion of dendroarchaeological research at early stages during restoration of pieces of art or furniture deprives historians and art-historians from gathering all available information to produce well informed conclusions about the pieces being investigated. Fortunately, this trend is changing.

Campaigns of awareness such as the one undertaken during this PhD thesis, provide good results in the short and medium term. But for dendroarchaeology to be fully established in the Iberian territory,

i.e. for it to be applied systematically in the study of cultural heritage made of wood, long-term structural strategies must be adopted. National and regional research institutes, as well as universities, should provide the platform to include this scientific discipline in their groups and working towards its inclusion in research and academic programs. Only then will dendroarchaeology reach the full potential and high standards that have already been acquired in northern, central and eastern Europe.

CONCLUSIONES, PERSPECTIVAS FUTURAS Y COMENTARIOS FINALES

Conclusiones y perspectivas futuras

Dendroarqueología y el desarrollo de cronologías de referencia en la Península Ibérica

- *La dendroarqueología tiene un gran potencial en la Península Ibérica* para proporcionar fechas exactas de corta, determinar la procedencia de la madera histórica, informar sobre el uso, transporte y procesado de la madera en siglos pasados y aportar evidencias del comercio histórico de este material. Esto ha sido revisado en el ***Artículo 1*** de esta tesis y empíricamente demostrado en los ***Artículos 3, 4 y 5***.

- *Las cronologías de pino salgareño (*Pinus nigra *subsp.* salzmannii*) desarrolladas en las montañas de Cazorla y Segura son aptas para establecer la datación y procedencia de la madera histórica extraída de esas zonas (**Artículo 2 y 3**).* Además, las teleconexiones encontradas entre las cronologías desarrolladas y otras especies de coníferas en España (especialmente las de pino salgareño de cotas intermedias y orientaciones similares), representan una ventaja para la datación dendrocronológica de muestras históricas, ya que la conexión entre cronologías podría proporcionar replicaciones de las fechas encontradas, contribuyendo así a validar la datación de las piezas. Sin embargo, las diferencias encontradas en las relaciones clima-crecimiento de cada cronología a lo largo del gradiente altitudinal, pueden obstaculizar la datación de maderas históricas obtenidas de cotas inferiores con la cronología de la parte superior de las montañas. Cronologías de cotas intermedias pueden servir para salvar dicho obstáculo.

- *Para conseguir un conjunto de cronologías de referencia que sirvan para datar y establecer la procedencia de madera del patrimonio cultural en la Península Ibérica, estrategias futuras deben dirigirse en primera instancia al muestreo de árboles vivos en zonas históricas de abastecimiento de madera (**Artículo 1 y 2**).* En dichas zonas, los lugares de muestreo deben situarse a lo largo de gradientes altitudinales, latitudinales y longitudinales, cubriendo el amplio espectro de condiciones climáticas y ecológicas de las zonas explotadas para la producción de madera en siglos pasados.

- *Las maderas de edificios históricos ofrecen las mejores perspectivas para mejorar la calidad de las cronologías de los árboles vivos en siglos pasados y para prolongarlas en el tiempo (**Artículos 1 y 3**).* La escasez de bosques antiguos en muchas regiones de España y la mayor parte de Portugal requerirá en determinadas zonas la selección de edificios relativamente recientes (siglo XIX). Antes de realizar dicha selección, es recomendable llevar a cabo la investigación histórica de los inmuebles, con el fin de informarse *a priori* sobre la historia de su construcción y la procedencia

de la madera y, de esta manera, maximizar los esfuerzos hacia la extensión retrospectiva de las cronologías.

Dendroprocedencia

- *La Península Ibérica es un territorio excelente para testar y aplicar métodos de determinación de procedencia con alta resolución espacial (**Artículos 1, 2 y 3**)*. La gran variabilidad de condiciones ambientales a lo largo de gradientes altitudinales, latitudinales y longitudinales facilitará la determinación de la procedencia de madera histórica con alta resolución.

- *Teleconexiones entre bosques ubicados en diferentes cuencas hidrográficas no deben obstaculizar la identificación de la procedencia de la madera (Artículos 1, 2 y 3)*. Las cuencas hidrográficas donde se sitúan los edificios históricos por ejemplo, deben ser consideradas en hipótesis de partida como áreas probables de procedencia, aunque en el caso de los astilleros y de grandes edificios de ciudades costeras o ciudades situadas a lo largo de los principales ríos navegables, la posibilidad de que la madera fuese importada por mar desde otras cuencas hidrográficas también debe tenerse en cuenta.

Flotación de madera en almadías en ríos andaluces

- *El transporte de madera en almadías se realizaba en los ríos andaluces, tal y como han demostrado las pruebas encontradas en la iglesia Colegial del Salvador (**Artículo 3**)*. Dichas pruebas sugieren además que el sistema empleado en Andalucía para preparar las almadías era el mismo que el utilizado en el Ebro, lo que indica que hubo transferencia de conocimiento entre personas de ambas cuencas hidrográficas. Esta práctica ancestral merece ser estudiada desde una perspectiva académica y global a nivel geográfico, ya que no se limita al territorio español y es de gran interés etnográfico.

Técnicas de procesado de la madera

- *Cambios en técnicas constructivas y de procesado de madera para la fabricación de cubiertas de edificios andaluces parecen haber ocurrido entre los siglos XVI y XVII (**Artículo 3**)*. Este tema debe ser abordado desde una perspectiva multidisciplinar, considerando también la influencia que artesanos inmigrantes tuvieron en el desarrollo de nuevas soluciones para la construcción de estructuras de cubierta de madera. La dendrocronología tiene el potencial de contribuir a este tipo de estudios proporcionando un marco temporal y geográfico.

- *Las tablas de roble para el retablo de los Evangelistas se fabricaron en un taller donde la madera todavía se partía al hilo (Artículo 4), mientras que la tablazón del pecio Arade 1 se hizo en algún astillero en el que ya se usaba la sierra para procesar la madera (Artículo 5).* Estudios comparativos interdisciplinares a nivel europeo podrían arrojar algo de luz sobre el momento exacto del cambio de técnicas de procesado de madera en diferentes zonas geográficas y las causas que lo desencadenaron.

Importación de madera a España y Portugal

- *Se ha proporcionado una descripción empírica de las características del producto de madera conocido como 'borne', utilizado para hacer el retablo de los Evangelistas de la catedral de Sevilla (**Artículo 4**).* El término 'borne' parece referirse al producto de madera conocido como *wainscot* en el norte de Europa, y su incidencia en fuentes documentales de España y Portugal cubre un periodo similar al de los *wainscots* en los mercados del norte de Europa (del siglo XV a mediados del XVII).

- *La datación absoluta de los tablones del retablo de los Evangelistas permitió además establecer el suroeste de Suecia como zona de procedencia de esta madera en el suroeste de Suecia (**Artículo 4**).* Esta es la primera vez que se reporta roble de esa región en soportes para pintura fabricados en el oeste de Europa, lo que demuestra que este producto de alta calidad no sólo se exportó desde el sureste Báltico, sino también desde el suroeste de Suecia. Investigaciones futuras de obras de arte hechas con borne en España y Portugal arrojarán luz sobre la frecuencia y magnitud del comercio de este producto en la Península Ibérica. Dichas investigaciones deberían combinarse con el estudio de fuentes documentales e investigaciones dendroarqueológicas paralelas de obras de arte hechas con madera báltica en diferentes países.

- *La importación de madera del norte de Europa y las Américas a España y Portugal, tendrá un gran impacto en estudios dendroarqueológicos de objetos y estructuras del patrimonio cultural comprendidos entre los siglos XV al XVIII, sobre todo en lo que respecta a la investigación de obras de arte y de pecios, así como de edificios en zonas litorales o al pie de ríos navegables (**Artículos 1, 4 y 5**).* Estas investigaciones deben llevarse a cabo con una mente abierta, teniendo en cuenta que los objetos y las estructuras pueden estar hechos parcial o totalmente con madera importada. En el caso específico de los pecios, la premisa para abordar la investigación debe ser que la embarcación pudo haber sido construida en cualquier parte.

- *La investigación de los objetos fabricados con madera procedente del norte, centro y este de Europa se beneficiará de la existencia de una densa red de cronologías de referencia en esas zonas (**Artículos 4 y 5**)*. Por lo tanto, las posibilidades de obtener dataciones para esas muestras son *a priori* más altas que cuando se trata de madera local ibérica. La colaboración internacional entre dendrocronólogos es crucial para el éxito de este tipo de investigaciones.

Identificaciones de madera y dataciones dendrocronológicas

- *La identificación de especie por medio de la madera es un paso muy importante en los estudios dendroarqueológicos, tal y como ha demostrado el **Artículo 5***. Hasta que no se desarrolle un método para discernir entre las distintas especies de roble caducifolio/marcescente presentes en la Península Ibérica, la determinación de este grupo basada en las características anatómicas de la madera debe restringirse al nivel de subgénero (*Quercus* subg. *quercus*).

- *Siendo la dendroarqueología una disciplina en desarrollo en la Península Ibérica, es inevitable que numerosas muestras de madera local queden sin datar hasta que haya disponible en España y Portugal una densa red de cronologías de referencia* (***Artículo 3***). El reportar dataciones posibles o provisionales, así como diferentes dataciones potenciales para una muestra o conjunto de muestras, debe evitarse a toda costa, ya que tales prácticas contradicen el fundamento básico de la dendrocronología y dañan profundamente su reputación.

- *El desarrollo de modelos de predicción de albura para especies de roble y pino ibéricos es necesario para poder inferir fechas de tala a partir de dataciones dendrocronológicas exactas cuando el borde de la corteza está ausente en las muestras (**Artículo 3**)*. La compilación de datos de albura a partir de árboles vivos pude servir para este propósito.

Conservación de muestras, datos dendrocronológicos y metadatos

- *La conservación de muestras y fotografías (en caso de obras de arte), así como los datos dendrocronológicos y metadatos relacionados, debe integrarse en el proceso de investigación*. Esto no sólo puede prevenir la pérdida de datos, sino que en combinación con datos de otros países, también permitirá investigar cuestiones de mayor envergadura como el comercio de madera a nivel europeo, y proporcionará material de partida para futuros proyectos de investigación o análisis que todavía no se han concevido.

Comentarios finales

Como ha puesto de manifiesto esta tesis doctoral, las aplicaciones de la dendrocronología en las Humanidades son muy diversas y pueden proporcionar una gran cantidad de información. Los profesionales que trabajan en ámbitos relacionados con el patrimonio cultural material, tales como arqueólogos, historiadores del arte, arquitectos, restauradores y conservadores entre otros, deben ser informados sobre el potencial de esta ciencia para proporcionar no sólo dataciones absolutas, sino también evidencias sobre la procedencia de la madera, las prácticas forestales ancestrales, el transporte y el comercio de madera, formas de procesar la madera, etc. La sustitución de maderas originales de edificios históricos sin realizar previamente la investigación dendroarqueológica sigue siendo una práctica común en diferentes partes de la península y representa una pérdida irreparable de valiosos datos ambientales, históricos y etnográficos. Igualmente, la no inclusión de la investigación dendroarqueológica en etapas tempranas durante la restauración de obras de arte o muebles priva a los historiadores y los historiadores del arte a partir de la recopilación de toda la información disponible para producir conclusiones bien informadas sobre las piezas están investigando. Afortunadamente, esta tendencia está cambiando.

Campañas de sensibilización como la llevada a cabo durante esta tesis doctoral, proporcionan buenos resultados a corto y medio plazo. Sin embargo, para establecer la dendroarqueología plenamente en el territorio ibérico, es decir, para que sea aplicada de forma sistemática en el estudio del patrimonio cultural de madera, deben adoptarse estrategias estructurales a largo plazo. Los institutos de investigación nacionales y regionales, así como las universidades, deben proporcionar la plataforma para incluir esta disciplina científica en sus grupos y trabajar hacia su inclusión en programas académicos y de investigación. Sólo entonces alcanzará la dendroarqueología en España y Portugal el pleno potencial y alto estándar de calidad que ya ha adquirido en la mayor parte del centro, norte y este de Europa.

6. References

6. REFERENCES

Akkemic, Ü, Yaman, B., 2012. *Wood Anatomy of Eastern Mediterranean Species*, Kessel Publishing House, Remagen-Oberwinter.

Albendea Ruz, M.E., 2011. La Carpintería de lo Blanco de la Casa de Pilatos de Sevilla. Tesis doctoral Universidad de Sevilla, Sevilla. URL: http://fondosdigitales.us.es/tesis/tesis/1566/la-carpinteria-de-lo-blanco-de-la-casa-de-pilatos-de-sevilla/#description

Alejano, R., Martínez, E., 1996. Distribución de *Pinus nigra* Arn. ssp. *salzmannii* en las Sierras Béticas. *Ecologia* **10**, 231–241.

Amaral Franco, J., 1990. Quercus. In G. López, (ed.) *Flora Ibérica*, vol. II. Real Jardín Botánico de Madrid, Servicio de Publicaciones del CSIC, 15-36, Madrid.

Andreu-Hayles, L., Planells, O., Gutiérrez, E., Muntan, E., Helle, G., Anchukaitis, K. J., Schleser, G. H., 2011. Long tree-ring chronologies reveal 20th century increases in water-use efficiency but no enhancement of tree growth at five Iberian pine forests. *Global Change Biology* **17**(6), 2095-2112, doi: 10.1111/j.1365-2486.2010.02373.x

Araque Jiménez, E., 1996. Escritos forestales sobre las sierras de Cazorla y Segura. Diputación Provincial de Jaén, Jaén.

Araque Jiménez, E., 2007. Conducciones fluviales de madera desde las Sierras de Segura y Cazorla (1849-1949). *Cuad Geogr* **40**, 81-105.

Baillie, M.G.L., 1982. Tree-Ring Dating and Archaeology, University of Chicago Press, Chicago.

Baillie, M.G.L., 2002. Future of Dendrochronology with Respect to Archaeology. *Dendrochronologia* **20**(1-2), 69-85.

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

Beeckman, H., 2005. The impact of forest management on wood quality. The case of medieval oak, in: Van de Velde, C., Beeckman, H., Van Acker, J., Verhaeghe, F. (Eds.), Constructing wooden images: proceedings of the symposium on the organization of labour and working practices of late gothic carved altarpieces in the Low Countries. VUB Press, Brussels, pp. 93–113.

Benito Garzón, M., Sánchez de Dios, R., Sainz Ollero, H., 2008. Effects of climate change on the distributions of Iberian forest. Appl Veg Sci 11, 169–178.

Billamboz, A., 2003. Tree rings and wetland occupation in southwest Germany between 2000 and 500 BC: dendroarchaeology beyond dating in tribute to F.H. Schweingruber. Tree-Ring Res 59(1), 37-49.

Billamboz, A., 2008. Dealing with heteroconnections and short tree-ring series at different levels of dating in the dendrochronology of the Southwest German pile-dwellings. Dendrochronologia 26(3), 145-155.

Blanco, E., Casado, M.A., Costa, M., Escribano, R., García Antón, M., Génova, M., Gómez Manzaneque, A., Gómez Manzaneque, F., Moreno, J.C., Morla, C., Regato, P., Sainz Ollero, H., 1997. Los bosques ibéricos, Editorial Planeta, Barcelona.

Bogucka, M., 1978. Le commerce de Gdanks avec la Péninsule Ibérique à la charnière du XVIe et du XVIIe siècle, in De Rosa *et al*. (eds), *Studi in memoria di Federico Melis*, Napels, pp. 289-307.

Brand, H., 2007. Baltic connections: Changing Patterns in Seaborne Trade (c. 1450-1800), URL: http://www.balticconnections.net/index.cfm?article=baltic+sea+trade.

Bridge, M., 2011. Resource Exploitation and Wood Mobility in Northern European Oak: dendroprovenancing of individual timbers from the Mary Rose (1510/11–1545), *International Journal of Nautical Archaeology* **40(**2), 417–423. doi: 10.1111/j.1095-9270.2010.00309.x

Bridge, M., 2012. Locating the origins of wood resources: a review of dendroprovenancing, *Journal of Archaeological Science* **39**, 2828-2834. doi: 10.1016/j.jas.2012.04.028

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–60.

Brun, O., Tegel, W., 2007. Premiers résultats des analyses dendrochronologiques relatives aux boulins de construction de la cathédrale de Reims. *Bulletin de la Société Archéologique Champenoise* 98e annee, n° 4 octobre-décembre 2005, Reims, 84-93.

Bruquetas Galán, R., 2002. Técnicas y materiales de la pintura española en los Siglos de Oro. Fundación de Apoyo a la Historia del Arte Hispano, Madrid.

Bråthen, A., 1982. Dendrokronologisk serie från västra Sverige 831–1975. Rapport RAÄ 1.

Büntgen, U., Brázdil, R., Heussner, K.U., Hofmann, J., Kontic, R., Kyncl, T., Pfister, C., Chromá, K., Tegel, W., 2011. Combined dendro-documentary evidence of Central European hydroclimatic springtime extremes over the last millennium, *Quaternary Science Reviews* **30,** 3947-3959.

Büntgen, U., Frank, D., Grudd, H., Esper, J., 2008. Long-term summer temperature variations in the Pyrenees, *Climate Dynamics* **31**(6), 615-631.

Casado Soto, J.L., 2003. El Cantábrico y las galeras hispanas de la Edad Media a la Moderna. Itsas Memoria 4, 537-552.

Castro, F. Vieira de, 2006. The Arade 1 shipwreck. A small ship at the mouth of the Arade river, Portugal, in Blue,L., Hocker, F., Englert, A. (Eds.), Connected by the sea,Proceedings of the tenth International symposium on boat and ship archaeology, Roskilde, pp. 300-305.

Castro, F. Vieira de, 2008. A Group for the Study of Iberian Seafaring, in Castro, F.Vieira de, Custer, K. (Eds.), Edge of Empire, proceedings of the symposium Edge of Empire,Caleidoscopio, Casal do Cambra, pp. 7-22.

Coomans, T., 2011. How tree-ring dating can provide historical contexts to buildings "without history". In: Fraiture, P. (Ed.), *Tree-Rings, Art and Archaeology*, proceedings, Brussels, Collection *Scientia Artis* **7**, 225-238.

Córdoba de la Llave, R., 1990. *La industria Medieval de Córdoba*. Caja provincial de Ahorros de Córdoba, Córdoba.

Córdoba de la Llave, R., 1993. Molinos y batanes de la Córdoba medieval. *Revista de la sección de Geografía e Historia* **9**, 31-56.

Córdoba de la Llave, R., 1995. Comunicaciones, transportes y albergues en el reino de Córdoba a fines de la Edad Media. *Historia, Instituciones y Documentos* **22**, 87-118.

Creasman, P.P., 2011. Basic Principles and Methods of Dendrochronological Specimen Curation. *Tree-Ring Research* **67**(2), 103-115.

Creasman, P.P., 2012. Long-term Preservation of Dendroarchaeological Specimens: Problems and Practical Solutions. *Conservation and Management of Archaeological Sites* **14**(1-2), 349-358.

Crespo Solana, A., 2011. Dutch Merchant Networks and the trade with Hispanic Port Cities in the Atlantic (1648-1778), in Hausberger, B., Böttcher, N. (eds.), *Redes y negocios globales en el mundo ibérico, siglos XVI-XIX*, Iberoamericana, Madrid, pp. 107-144.

Creus, J., 1998. A propósito de los árboles más viejos de la Península, los *Pinus nigra* Arn. ssp. *salzmannii* (Dunal) Franco de Puertollano-Cabañas, sierra de Cazorla, Jaén. *Montes* **54**, 68-76.

Crone, A., Barber, J., 1981. Analytical techniques for the investigation of non-artefactual wood from prehistoric and medieval sites. Proc Soc Antiq Scot 111, 510–515.

Crone, B.A., Fawcett, R., 1998. Dendrochronology, documents and the timber trade: new evidence for the building history of Stirling Castle, Scotland. Med Archaeol XLII, 68–87.

Crone, B. A., Mills, C.M., 2012. Timber in Scottish buildings, 1450 - 1800; a dendrochronological perspective, *Proc Soc Antiq Scot* 142, 329-69.

Cook, E.R., 1985. A time series analysis approach to tree-ring standardization. Ph.D. dissertation, University of Arizona, Tucson.

Čufar, K., 2007. Dendrochronology and past human activity – A review of advances since 2000. Tree-Ring Res 63(1), 47-60.

Daly, A., 2007, The Karschau Ship, Schleswig-Holstein: Dendrochronological Results and Timber Provenance, *IJNA* **36**(1), 155-166.

Darrah, R., 1982, Working unseasoned oak, in McGrail, S. (ed.), *Woodworking Techniques before 1500*, 219–28. BAR International Series, Oxford.

De Aranda y Antón, G., 1990. *Los Bosques Flotantes: historia de un roble del siglo XVIII*. Colección Técnica, Ministerio de Agricultura, Pesca y Alimentación, ICONA, Madrid.

De la Cruz Aguilar, J., 1994. *La destrucción de los Montes*. Universidad Complutense de Madrid, Madrid.

De la Fuente, P., 2006. El Triunfante: tecnología y ciencia en la España de la ilustración. Historia de un navío hundido en el golfo de Rosas, Museo Marítimo de Barcelona, Barcelona.

De Vries D. J., 1994. Bouwen in de late Middeleeuwen. Stedelijke architectuur in het voormalige Over- en Nedersticht, PhD Dissertation, University of Leiden, Leiden.

De Vries, J., Van der Woude, A.M., 1997. The first modern economy. Success, failure, and perseverance of the Dutch Economy, 1500–1815, Cambridge University Press, Cambridge.

Devi-Vareta, N., 1985. Para uma geografía histórica da floresta portuguesa: as matas medievais e a "coutada velha" do Rei. *Revista da Faculdade de Letras-Geografia* vol. I, 47-67.

Devi-Vareta, N., 1986. Para uma geografia histórica da floresta portuguesa: do decínio das matas medievais à política florestal do renascimiento (séc. XV e XVI). *Revista da Faculdade de Letras-Geografia*, vol. I, 5-37.

Dittmar, C., Eissing, T., Rothe, A., 2012. Elevation-specific tree-ring chronologies of Norway spruce and Silver fir in Southern Germany, *Dendrochronologia*, doi: 10.1016/j.dendro.2011.01.013

Domínguez Delmás, M., 2004. Estudio dendrocronológico del *Quercus pyrenaica* Willd. en las sierras Galaico-Leonesas de Ancares y Courel. Unpublished MSc. Thesis University of Lleida, Lleida.

Domínguez-Delmás, M., 2014. Avances de la dendrocronología al servicio de la arqueología subacuática española: ¿qué información podemos extraer de la madera de los pecios?, in: Nieto Prieto, X., Ramírez Pernía, a., Recio Sánchez, P. (Coords. Eds.), Actas I Congreso Arqueología Náutica y Subacuática española. MECD, pp. 1080-1094.

Domínguez-Delmás, M., Benders J.F., Kortekaas G.L.G.A., 2011. Timber supply in Groningen (north-east Netherlands) during the early Modern period (16^{th}-17^{th} centuries). In: Fraiture, P. (Ed.), *Tree-Rings, Art and Archaeology*, proceedings, Brussels, Collection *Scientia Artis* 7, 151-173.

Domínguez-Delmás, M., Driessen, M., García-González, I., Van Helmond, N., Visser, R., Jansma, E., 2014. Long-distance oak supply in mid-2nd century AD revealed: the case of a Roman harbour (Voorburg-Arentsburg) in the Netherlands. *J Archaeol Sci* **41**, 642-654.

Dow, J., 1969. Scottish trade with Sweden 1512–80. Scot Hist Rev 48, 64–79.

Eckstein, D., 2005. Wood science and art history – interdisciplinary research illustrated from a dendrochronological point of view, in: Van de Velde, C., Beeckman, H., Van Acker, J., Verhaeghe, F. (Eds.), *Constructing wooden images: proceedings of the symposium on the organization of labour and working practices of late gothic carved altarpieces in the Low Countries*. VUB Press, Brussels, pp. 93–113.

Eckstein, D., Bauch, J., 1969. Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit. Forstwissenschaftliches Centralblatt 88, 230–250.

Eckstein, D., Wrobel, S., 2007. Dendrochronological proof of origin of historic timber- retrospect and perspectives, in: Haneca, K., Beeckman, H., Gärtner, H., Helle, G., Schleser, G. (Eds.), TRACE - Tree Rings in Archaeology, Climatology and Ecology, Vol. 5, pp. 8–20.

Eissing, T., Dittmar, C., 2011. Timber transport ad dendro-provenancing in Thuringia and Bavaria. In: Fraiture, P. (Ed.), *Tree-Rings, Art and Archaeology*, proceedings, Brussels, Collection *Scientia Artis* **7**, 137-149.

Fernández-Golfín, J.I., Díez, M.R., Baonza, M.V., Gutiérrez, A., Hermoso, E., Conde, M., Vanden., V., 2001. Caracterización de la calidad y propiedades de la madera de Pino laricio (*Pinus nigra* Arn. ssp. *salzmannii*). Invest Agrar Sist Recur For **10**(2), 311-331.

Feuillat, F., Dupouey, J.L., Sciama, D., Keller, R., 1997, A new attempt at discrimination between *Quercus petraea* and *Quercus robur* based on wood anatomy, *Canadian Journal of Forest Research* 27: 343-351.

Fraiture, P., 2009. Contribution of dendrochronology to understanding of wood procurement sources for panel paintings in the former Southern Netherlands from 1450 AD to 1650 AD, *Dendrochronologia* **27**, 95-111.

Fritts, H.C., 1976. Tree rings and climate, Academic Press, London.

Galán, P., Gamarra, R., García-Viñas, J.I., Alvarez, S. 2013. Sobre árboles ibéricos. URL: http://www.arbolesibericos.es

Gañán Medina, C., 1999. Técnicas y evolución de la imaginería policroma en Sevilla. Universidad de Sevilla, Sevilla.

García-González, I., 2008. Comparison of different distance measures for cluster analysis of tree-ring series. Tree-Ring Res. 64(1), 27–37.

Giachi, G., Lazzeri, S., Mariotti Lippi, M., Macchioni, N., Paci, S., 2003, The wood of "C" and "F" Roman ships found in the ancient harbour of Pisa (Tuscany, Italy): the utilization of different timbers and the probable geographical area which supplied them. *Journal of Cultural Heritage* 4: 269-283.

Gil, L. 2009. Una desmedida devoción por los matorrales (o por qué estabilizar el paisaje humanizado). Conferencia magistral 5º Congreso Forestal Español. Avila. URL: http://www.secforestales.org/buscador/pdf/5CFE02-003.pdf

Gil Olcina, A., 2006. Importancia y desaparición de un uso tradicional del agua: la flotación de maderas. *Ería* **69**, 57-74.

Gjerdrum, P., 2003. Heartwood in relation to age and growth rate in Pinus sylvestris L. in Scandinavia. *Forestry* **76**(4), 413-424.

Grissino-Mayer, H.D., Fritts, H.C., 1997. The International Tree-Ring Data Bank: an enhanced global database serving the global scientific community. *The Holocene* **7**(2), 235-238.

Grissino-Mayer, H.D., Sheppard, P.R., Cleaveland, M.K., Cherubini, P., Ratcliff, P., Topham, J., 2010. Adverse implications of misdating in dendrochronology: Addressing the re-dating of the ''Messiah'' violin. *Dendrochronologia* **28,** 149–159.

Guibal, F. and Pomey, P., 2003, Timber Supply and Ancient Naval Architecture, in C. Beltrame (ed.), *Boats, Ships and Shipyards Proceedings of the Ninth International Symposium on Boat and Ship Archaeology*, 12/2000 Venice, pp. 35-48.

Haneca, K., Wazny, T., Van Acker, J., Beeckman, H., 2005. Provenancing Baltic timber from art historical objects: success and limitations. *Journal of Archaeological Science* **32**, 261-271.

Haneca, K., Čufar, K., Beeckman, H., 2009. Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe, *Journal of Archaeological Science* **36**(1), 1–11.

Haneca, K., Debonne, V., 2012. Precise tree-ring dating of building activities despite the absence of bark: A case-study on medieval church roofs in Damme, Belgium, *Dendrochronologia* **30**, 23-34.

Haneca, K., Daly, A., 2014. Tree-Rings, Timbers and Trees: a dendrochronological survey of the 14th-century cog, Doel 1. *International Journal of Nautical Archaeology* **43(**1), 87–102.

Hernández Díaz, 1937. Arte Hispalense en los siglos XV y XVI. Documentos para la historia del arte vol. IX, 41–49.

Higueras Maldonado, J., 2009. La catedral de Jaén. Su construcción renacentista (s. XVII-XVIII), Universidad de Jaén, Jaén.

Hillam, J., 1979. Tree-rings and archaeology: some problems explained. *Journal of Archaeological Science* **6**, 271-278.

Hillam, J., 2004. Dendrochronology–Guidelines on producing and interpreting dendrochronological dates. English Heritage, London, URL: http://www.english-heritage.org.uk/content/ publications/ docs/dendrochronology.pdf

Hoffsummer, P., 2002. Les charpentes du XIe au XIXe siècle, typologie et évolution en France du Nord et en Belgique coll. " Cahiers du Patrimoine ", n°62, Monum, Editions du Patrimoine, Paris.

Hollstein, E., 1980. Mitteleuropäische Eichenchronologie. Verlag Phillipp von Zabern, Mainz am Rhein.

Hroś, M., Vavríck, H., 2014. Comparison of earlywood vessel variables in the wood of Quercusrobur L. and Quercus petraea (Mattuschka) Liebl. growingat the same site. *Dendrochronologia* **32,** 284–289

Huisman, D.J., Klaassen, R.K.W.M., 2009. Wood, in: Huisman, D.J. (Ed.), *Degradation of archaeological remains,* Sdu Uitgevers b.v., Den Haag.

Jansma, E., Van Lanen, R.J, Brewer, P.W., Kramer, R, 2012. The DCCD: a digital data infrastructure for tree-ring research. *Dendrochronologia* **30** (4), 249-251.

Jiménez Martín, A., 2006. Las fechas de las reformas. Selección crítica de fuentes documentales para la cronología del edificio medieval, in: Jiménez Martín, A. et al., La catedral gótica de Sevilla. Fundación y fábrica de la obra nueva. Universidad de Sevilla, Collección de Divulgación Científica 7, Sevilla, pp. 15–113.

Jones, D. M., (Ed.), 2010. Waterlogged Wood: Guidelines on the Recording, Sampling, Conservation and Curation of Waterlogged Wood. English Heritage Publishing, Belgium.

Kagawa, A., Leavitt, S.W., 2010. Stable carbon isotopes of tree rings as a tool to pinpoint the geographic origin of timber. *Journal of Wood Science* 56, 175-183.

Kaplan, J.O., Krumhardt, K.M., Zimmerman, N., 2009. The prehistoric and preindustrial deforestation of Europe, *Quaternary Science Review* **28**, 3016–3034.

Klein, P., 1996. Dendrochronological findings in panels of the Campin group. In: Foister, S., Nash, S. (Eds.), Robert Campin. New Directions in Scholarship. National Gallery in Collaboration with Brepols Publishers, London, Turnhout (Belgium), 77-86.

Larsson, L.A., 2011a. Cybis CooRecorder - Image Coordinate Recording program, URL: www.cybis.se.

Larsson, L.A., 2011b. CDendro - Cybis dendro dating program, URL: www.cybis.se.

Lombard, M., 1980. *Espaces et réseaux du haut moyen âge*. Mouton, Paris.

López Almansa, J.C., 1999. Aprovechamientos forestales y evolución de la vegetación en el macizo del Segura. Cuadernos de la S.E.C.F. 8, 67-74.

Loureiro, V., 2011. L'Épave Arade 1: l'influence des chantiers régionaux sur la tradition de construction navale ibéro-atlantique, Unpublished doctoral dissertation, Université de Paris I – Panthéon Sorbonne.

Loureiro, V., Alves, J.G., 2008. The Arade 1 Shipwreck: Preliminary Results of the 2004 and 2005 Field Seasons, *IJNA* **37**(2), 273-282.

Magdaleno Granja, R., Pérez Cano, Mª V., Gutiérrez Carrasquilla, E., García de Casasola Gómez, M., Martín García, L., Sameño Puerto, M., 2005. Retablo de los Evangelistas de la Catedral de

Sevilla. Investigación e intervención. PH Boletín del Instituto Andaluz del Patrimonio Histórico 53, 84-106.

Martín Seijó, M., Piqué i Huerta, R., 2013. New data about wood use in the northwest of the Iberian peninsula, in Damblon, F. (Ed.), Proceedings of the Fourth International meeting of Anthracology, BAR International Series 2486, pp. 143-154.

Martínez Ruiz, E., 1999. Los montes en la cultura islámica. Los bosques de al-Andalus del siglo VIII al XIII, in: Marín Pageo, F., Domingo Santos, J., Calzado Carretero, A. (eds.), Los montes y su historia: una perspectiva política, económica y social. Collectanea 27, 151-185.

Mendoza, F., 2008. La Iglesia del Salvador de Sevilla. Biografía de una Colegiata, Sevilla.

Miles, D.H., 1997. The interpretation, presentation and use of tree-ring dates.Vernacular Architecture **28**, 40–56.

Miles, D.H., 2006. Refinements in the interpretation of tree-ring dates for oak building timbers in England and Wales. Vernacular Architect. 37, 84-96.

Millard, A., 2002. A Bayesian approach to sapwood estimates and felling dates in dendrochronology. Archaeometry 44 (1), 137-43.

Mom, V., Schultze, J., Wrobel, S., Eckstein, S., 2010. Allocating archaeological wood samples to a common source tree and its use for analysing wooden settlement structures, in Frischer, B., Webb Crawford, J. (Eds.), *Making History Interactive*. Proceedings of the 37th International Conference, Williamsburg, Virginia, United States of America, March 22-26 (BAR International Series S2079), 234-239.

Morgan, R.A., 1975. The selection and sampling of timber from archaeological sites for identification and tree-ring analysis. *Journal of Archaeological Science* 2(3): 221-230.

Navarro Reverter, J., 1872. Transportes fluviales. Revista Forestal ,Económica y Agrícola, vol. V, 86-93, 113-124. URL: http://www.revistamontes.net/Buscador.aspx?id=1708

Nayling, N., Susperregi, J., 2014. Iberian dendrochronology and the Newport Medieval Ship, *International Journal of Nautical Archaeology* **43**(2), 279–291. DOI: 10.1111/1095-9270.12052.

Oliveira Marques, A. H. de, 1959. A Hansa e Portugal na Idade Media. PhD thesis, Presença, Lisboa.

Otte Sander, E., 2008. Sevilla, siglo XVI: Materiales para su historia económica: herederos de Enrique Otte Sander. Centro de Estudios Andaluces.

Pallaruelo, S., 2008. *Navateros*, Prames, Zaragoza.

Palomero Páramo, J.M., 1983. El retablo sevillano del Renacimiento: análisis y evolución (1560–1629). Diputación Provincial de Sevilla.

Queiroz, P. F., Oliveira, H., and Pereira, T., 2005, Identificação de um conjunto de madeiras provenientes da estrutura do navio Arade 1, *Trabalhos do CIPA* 91. Lisbon.

Reynolds, A.C., Betancourt, J.L., Quade, J., Patchett, P.J., Dean, J.S., Stein, J., 2005. $^{87}Sr/^{86}Sr$ sourcing of Ponderosa pine used in Anasazi Great House construction at Chaco Canyon, NM. *J Archaeol Sci* **32**, 1061–1075.

Rich, S.A., Manning, S.W., Degryse, P.,Vanhaecke, F., Van Lerberghe, K., 2012. Tree-ring and strontium isotope signatures of Cedrus brevifolia in Cyprus. *J Anal At Spectrom* **27**, 796–806.

Rich, S.A., Manning, S.W., Degryse, P., Vanhaecke, F., Van Lerberghe, K., 2015. Provenancing East Mediterranean cedar wood with the $^{87}Sr/^{86}Sr$ strontium isotope ratio. *Archaeol Anthropol Sci*, DOI 10.1007/s12520-015-0242-7.

Richter, K., 1986. Dendrocronología aplicada en la provincia de Teruel.Primer avance 1985/86. Kalathos 5-6, 199-210.

Richter, K., 1988. Dendrochronologische und Dendroklimatologische Untersuchungen an Kiefern (*Pinus sp*.). PhD thesis University of Hamburg.

Richter, K., Eckstein, D., 1986. Estudio dendrocronológico en España. Dendrochronologia 4, 59-71.

Richter, K., Eckstein, D., 1990. A proxy summer rainfall record for southeast Spain derived from living and historic pine trees. *Dendrochronologia* 8, 67-82.

Richter, K., Rodríguez Trobajo, E., 1985. Dendrocronología en España. Montes 5, 12-20.

Richter, K., Rodríguez Trobajo, E., 1986. El Banco de datos dendrocronológicos para la Península Ibérica. Koiné 1, 66-77.

Richter, K., Eckstein, D., Holmes, R.L., 1991. The dendrochronological signal of pine trees (*Pinus* spp.) in Spain, *Tree Ring Bull* 51, 1–13.

Rodríguez Trobajo, E., 2008. Procedencia y uso de la madera de pino silvestre y pino laricio en edificios históricos de Castilla y Andalucia. Arqueología de la Arquitectura 5, 33-53.

Rozas, V., 2006. Caracterización y análisis de la señal climática en cronologías de *Fagus sylvatica* L. y *Quercus robur* L. en la región central de la Cornisa Cantábrica. *Invest Agrar: Sist Recur For* **15**(2), 182-196.

Ruiz de la Torre, J., 2006. Flora Mayor. Organismo Autónomo de Parques, Dirección General para la Biodiversidad, Madrid.

Ruiz García, V., 2010. *De Segura a Trafalgar*. El Olivo de Papel, Jaén.

Sass-Klaassen, U., Vernimmen, T., Baittinger, C., 2008. Dendrochronological dating and provenancing of timber used as foundation piles under historic buildings in The Netherlands. International Biodeterioration & Biodegradation 61, 96–105.

Serradilla Avery, D.M., 2007. Seville: between the Atlantic and the Mediterranean, 1248–1492. Pre-Columbus commercial routes from and to Seville. Master of Philosophy, University of St. Andrews.

Susperregi, J., 2007. Oak dendrochronology at the Basque Country, in: Haneca, K., Verheyden, A., Beekman, H., Gärtner, H., Helle, G., Schleser, G. (Eds.), TRACE - Tree Rings in Archaeology, Climatology and Ecology, Vol. 5: Proceedings of the DENDROSYMPOSIUM 2006, April 20th – 22nd 2006, Tervuren, Belgium. Schriften des Forschungszentrums Jülich, Reihe Umwelt Vol. 74, p. 35 - 42.

Schweingruber, F.H., 1990, *Anatomy of European woods*. Haupt Verlag, Bern, Stuttgart.

Schweingruber, F.H., 1996. Tree rings and environment dendroecology, Paul Haupt Verlag, Berne.

Tegel, W., Elburg, R., Hakelberg, D., Stäuble, H., Büntgen, U., 2012. Early Neolithic Water Wells Reveal the World's Oldest Wood Architecture. PLoSONE 7(12), e51374. DOI: 10.1371/journal.pone.0051374

Tresaco Calvo, J., 1968. Flotaciones de traviesas por ríos de Andalucía. *Montes* **141**, 261-267.

Tyers, C., 2008. Bayesian interpretation of tree-ring dates in practice. Vernacular Architect. 39, 91-106.

Veluwenkamp, J.W., 2000. *Archangel. Nederlandse ondernemers in Rusland 1550-1785*. Balans, Amsterdam..

Villanueva Romero, E., Magdaleno Granja, R., Rey Pérez, J., Fernández Medina, M.I., 2007. Retablo de La Purificación de la Virgen. Catedral de Sevilla. Criterios, *PH Boletín del Instituto Andaluz del Patrimonio Histórico* **64**, 122-145.

Wazny, T., 2005. The origin, assortments and transport of Baltic timber: historic-dendrochronological evidence, in: Van de Velde, C., Beeckman, H., Van Acker, J., Verhaeghe, F. (Eds.), Constructing Wooden Images: proceedings of the symposium on the organization of labour and working practices of late gothic carved altarpieces in the Low Countries, Brussels 25-26 October 2002. VUB Press, Brussels, pp. 115-126.

Wicha, S., Guibal, F. and Medail, F., 2003, Archaeobotanical characterization of three ancient Mediterranean shipwrecks. In Fouache E. (ed.), *The Mediterranean world environment and history*, Elsevier, pp. 233-237.

Wigley, T.M.L., Jones, P.D., Briffa, K.R., 1987. Cross-dating methods in dendrochronology, *Journal of Archaeological Science* **14**, 51-64.

Williams, M., 2006. Deforesting the Earth. From Prehistory to Global Crisis: An abridgement, University Chicago Press, Chicago.

Wilson, R.J.S., Hopfmueller, M., 2001. Dendrochronological investigations of Norway spruce along an elevational transect in the Bavarian Forest, Germany. *Dendrochronologia* **19**(1), 67-7.

Zunde, M., 1999. Timber export from old Riga and its impact on dendrochronological dating in Europe. Dendrochronologia 16–17, 119–130.

Appendix 1

APPENDIX 1. PUBLICATIONS INCLUDED IN THIS THESIS

Article 1. Domínguez-Delmás, M., Alejano-Monge, R., Van Daalen, S., Rodríguez-Trobajo, E., Susperregi, J., García-González, I., Wazny, T., Jansma, E., 2015., Tree rings, forest history and cultural heritage: current state and future prospects of dendroarchaeology in the Iberian Peninsula. *Journal of Archaeological Science* **57**, 180–196.

Article 2. Domínguez-Delmás, M., Alejano-Monge, R, Wazny, T., García-González, I., 2013. Radial growth variations of black pine along an elevation gradient in the Cazorla Mountains (South of Spain) and their relevance for historical and environmental studies. *European Journal of Forest Research* **132(4)**, 635-652.

Article 3. Domínguez-Delmás, M., Alejano-Monge, R., Wazny, T.,*en prep*. Dendroarchaeological research on roof structures from architectural heritage in Andalusia (Spain): case studies of the Jaen catedral and the *Colegial del Salvador* church in Seville.

Article 4. Rodríguez-Trobajo, E., **Domínguez-Delmás, M.,** 2015. Swedish oak, planks and panels: dendroarchaeological investigations on the 16th century *Evangelistas* altarpiece at Seville Cathedral (Spain). *Journal of Archaeological Science* **54**, 148–161.

Article 5. Domínguez-Delmás, M., Nayling, N., Wazny, T., Loureiro, V., Lavier, C., 2013. Dendrochronological dating and provenancing of timbers from the *Arade 1* wreck, Portugal. *International Journal of Nautical Archaeology* **42(1)**, 118-136. 92

ARTICLE 1

Tree rings, forest history and cultural heritage: current state and future prospects of dendroarchaeology in the Iberian Peninsula.

Domínguez-Delmás, M., Alejano-Monge, R., Van Daalen, S., Rodríguez-Trobajo, E., Susperregi, J., García-González, I., Wazny, T., Jansma, E., 2015.

Journal of Archaeological Science 57, 180–196.

Pollarded oaks in the province of Gipuzkoa, Basque Country. This used to be common practice to obtain compass timber for shipbuilding (photo: M. Domínguez Delmás).

TREE RINGS, FOREST HISTORY AND CULTURAL HERITAGE: CURRENT STATE AND FUTURE PROSPECTS OF DENDROARCHAEOLOGY IN THE IBERIAN PENINSULA

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Abstract

We review the current state of dendroarchaeology in the Iberian Peninsula and discuss its potential, outlining the particular relevance and complexity of this territory and its material heritage for dendroarchaeological studies. Whereas dendrochronology is used throughout the rest of Europe to answer questions about cultural heritage, the application of dendroarchaeology in the Iberian Peninsula has been remarkably underrepresented in comparison to dendroecology and dendroclimatology. Existing tree-ring chronologies in this territory have a widespread geographical coverage, but are often too short to allow dendroarchaeological studies, resulting in inadequate assessments of material heritage made of wood in and originating from the Iberian Peninsula. However, different studies have demonstrated that dendroarchaeology has a great potential in the area. This review illustrates the rich variety of Iberian material heritage from different periods and cultures covering over 8,000 years that could profit from dendrochronological research. Future research possibilities in relation to the available Iberian heritage in Spain, Portugal and worldwide are proposed.

Keywords

Dendrochronology; Archaeology; Shipbuilding; Art history; Ancient wood; Timber trade; Spain; Portugal

1. INTRODUCTION

Dendrochronology deals with the annual growth variations in the wood, which are mainly caused by the climatic and ecological conditions prevailing at the site where trees grow (Fritts, 1976), but can also be partly man-induced (Beeckman, 2005; Bleicher, 2014 and references therein; Schweingruber, 1996). Therefore, tree-ring patterns are series of annual records of the natural and historical environment of trees.

Several works overview the broad applications of this science within archaeology, art-history and architectural history, i.e. disciplines dealing with cultural heritage (e.g. Billamboz, 2014; Bridge, 2012; Čufar, 2007; Eckstein and Wrobel, 2007; Haneca et al., 2009). The direct application of *dendroarchaeology* is the establishment of the date and provenance of wood employed in historical and prehistorical objects and structures. Once the tree rings in the wood are anchored in time, the geographical provenance of the wood can be identified with different degrees of spatial resolution (Bridge, 2012), and information about the fabrication period of e.g. a panel painting, a ship, or a building can be inferred. Beyond construction dates, information about tree selection, type of forests, transport and trade of timber, tools, and ways to process the wood can be retrieved for well-defined temporal frames (e.g. Billamboz, 2003; Tegel, 2012). Additionally, in the lack of absolute dendrochronological dates, the relative crossdating of tree-ring series from numerous timbers of the same structure allows identifying construction phases, as well as defining the occupation timeline of ancient settlements, or inferring information about the organisation of wood supply (Billamboz, 2008; Bleicher, 2014). In summary, dendroarchaeology opens a window to the interactions between humans and their natural environment in specific periods of time.

Dendrochronological dating and provenancing requires reference or master chronologies for the specific tree species being researched, covering the time-span of interest and the area where the wood originated. In the last decades, European dendrochronologists have compiled numerous absolutely dated tree-ring chronologies from living trees, historic buildings, archaeological sites (both terrestrial and maritime), pieces of art and furniture, and palaeo-vegetation remains that represent local and/or region-specific tree growth of broadleaved and conifer species (e.g. Baillie, 1982; Becker and Delorme, 1978; Hollstein, 1980; Jansma, 1995; Jansma et al., 2004; Kuniholm, 1996; Leuschner and Delorme, 1988; Sass-Klaassen and Hanraets, 2006; Spurk et al., 1998; Wazny, 1990). The tree-ring data network currently available for central, south-eastern and northern Europe allows researchers not only to date timbers of different species and periods and accurately determine their provenance (e.g. Domínguez-Delmás et al., 2014; Fraiture, 2009; Sass-Klaassen et al., 2008), but also to address broader questions, such as European-scale timber trade (e.g. Crone and Mills, 2012; Wazny, 2005) or the influence of climate change on past societies (e.g. Büntgen et al., 2011). The recent development of a tree-ring repository for dendro-historical/-archaeological data in Europe (Digital Collaboratory for Cultural Dendrochronology, DCCD; Jansma et al., 2012; Jansma, 2013) further stimulates those lines of broad-scale interdisciplinary research.

In the Iberian Peninsula, the application of dendroarchaeology has been remarkably underrepresented in comparison to disciplines dealing with ecological and climatological questions, in spite of the abundance of historical wood from different periods. Sources of historical timber can be found all over the Iberian territory in archaeological sites from terrestrial and maritime contexts, in roof structures,

ceilings, doors and windows from buildings, and in furniture, paintings and sculptures in public and private art collections in different countries. Additionally, wood from Iberian forests used to build ships survives in wrecks worldwide. This material could be used to develop long-span tree-ring chronologies for the Iberian territory, which in turn would allow assessing the date and geographical provenance of more cultural heritage.

In the following, we first outline the relevance and complexity of the Iberian territory and its material cultural heritage for dendroarchaeological studies, offering a glimpse into the different cultures and the forest history of the territory. Then, we present the current state of dendroarchaeology in the peninsula, and review the efforts undertaken so far to establish this discipline in the area. Finally, we propose research lines and strategies towards the future implementation of dendroarchaeology in the study of Iberian cultural heritage.

2. GEOGRAPHICAL AND BIO-CLIMATOLOGICAL PECULIARITIES OF THE IBERIAN PENINSULA

The Iberian Peninsula, located on the verge of the Atlantic Ocean and the Mediterranean Sea in the south-western corner of Europe (Fig. 1a), represents a key spot from a climatological, ecological and historical perspective. The peculiarities of its relief, with five main mountain ranges and a central plateau reaching an average altitude of 600 m a.s.l., strongly determine its biogeographical zonation (Blanco et al., 1997). Three of these mountain ranges spread along longitudinal gradients (the Cantabrian Mountains in the north, the Central Massif in the middle, and the Beticas in the south), whereas two of them follow a north-west south-east direction (the Pyrenees in the east and the Iberian Massif in the centre/east) (Fig. 1b). These mountains divide the peninsula into several watersheds, five of which gather the water of the main Iberian rivers: Douro, Tagus, Guadiana and Guadalquivir rivers flow from east to west and drain into the Atlantic Ocean, whereas the Ebro flows from north-west to south-east to the Mediterranean Sea (Fig. 1b).

This combination of relief and geographic location upon climate, coupled with the role of the Mediterranean as a refuge during the Ice Ages, confers on the Iberian Peninsula a remarkable diversity of plant species along altitudinal and latitudinal gradients (Galán et al., 2013). Average rainfall decreases from north to south and from west to east, reaching maximum values in mountain and coastal areas from the north-west where precipitation often reaches 3,000 mm/year, and dropping down to 200 mm/year in the driest areas of the southeast and the Ebro basin (Fig. 1c). Average temperature increases from north to south and decreases from the coast to the inner regions of the peninsula, January and August being the months with the lowest and highest average temperatures respectively (Fig. 1d). The convergence of both Atlantic and Mediterranean climates creates two main biogeographical areas, commonly known as the Wet-(Atlantic) and the Dry-(Mediterranean) Iberia (Blanco et al., 1997).

Several tree species are endemic to Iberia (e.g. *Acer granatensis*) or Iberia and North Africa (e.g. *Abies pinsapo*, *Quercus faginea*, *Quercus canariensis* or *Tetraclinis articulata*). Many others have their south-western distribution limit in Spain and/or Portugal (e.g. *Pinus sylvestris*, *Abies alba*, *Quercus robur*, *Quercus petraea*, *Fagus sylvatica*, *Pinus uncinata*) (Ruiz de la Torre, 2006). Therefore, these species are of great scientific interest due to their susceptibility to climatic changes (Benito Garzón et al., 2008).

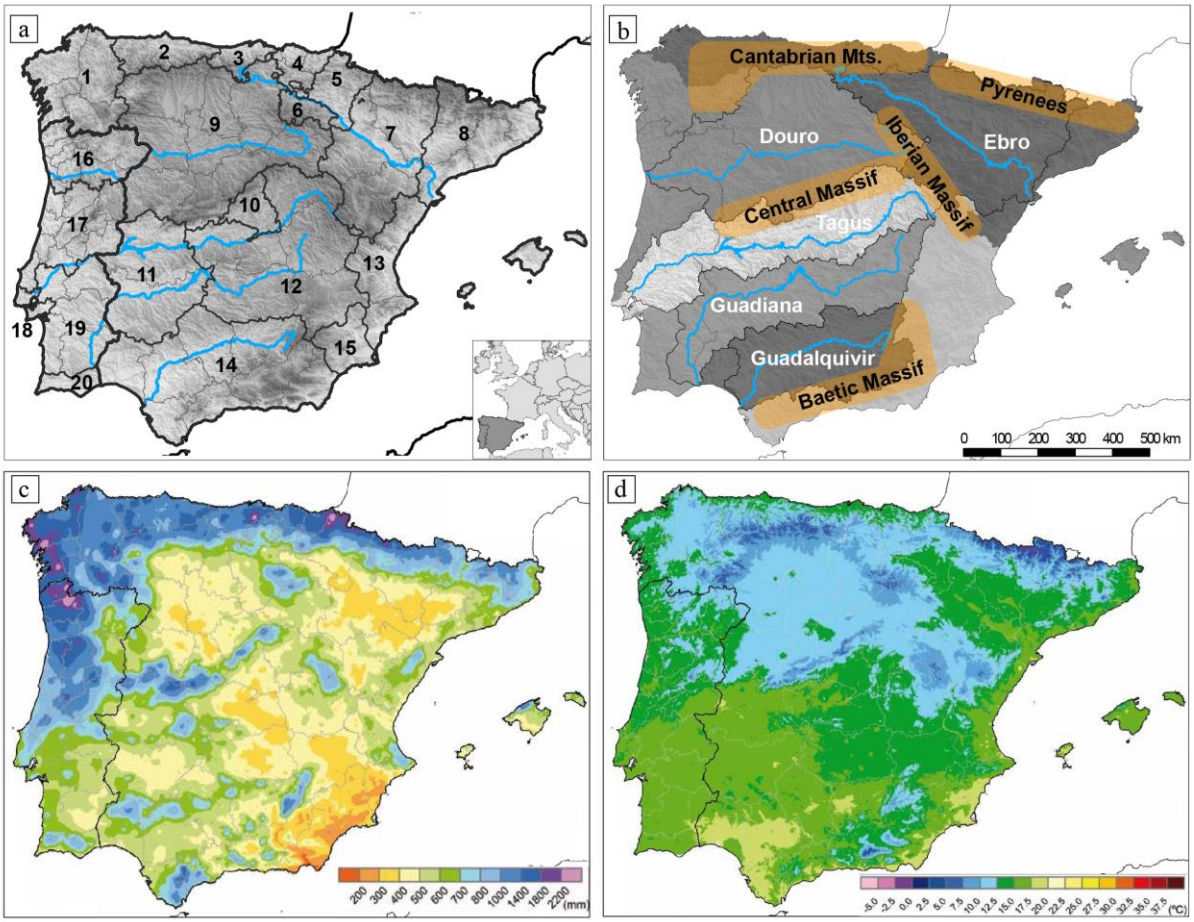

Figure 1. Geographical and climatological maps. a) Location map and Spanish and Portuguese regions according to current political division (thinner lines delineate provinces): 1, Galicia; 2, Asturias; 3, Cantabria; 4, Basque Country; 5, Navarra; 6, La Rioja; 7, Aragon; 8, Catalonia; 9, Castilla y Leon; 10, Madrid; 11, Extremadura; 12, Castilla La Mancha; 13,Valencian Community; 14, Andalusia; 15, Murcia; 16, Nord; 17, Centre; 18, Lisbon; 19, Alentejo; 20, Algarve; b) schematic position of the five main mountain ranges, and the five big rivers and their watersheds; c) average total annual precipitation period 1971-2000; d) annual average mean temperatures period 1971-2000 (source maps b and c: AEMET, 2011: http://www.aemet.es/documentos/es/conocermas/publicaciones/Atlas-climatologico/Atlas.pdf).

According to the Third Spanish National Forest Inventory (MAGRAMA, 2013) the total forested surface in Spain amounts to 18,265,394 ha (36.2% of the territory), from which 19.3% are open woodlands, 4.5% mixed forests, 35.7% conifer forests, 34.9% broadleaf forests and 5.7% plantations of fast-grown species (Table 1). Main native tree species are *Quercus* (both deciduous and semi-deciduous oaks, and also their evergreen relatives *Quercus suber* and *Quercus ilex*), *Pinus* (seven species are adapted to the ecological conditions of Iberia and the Spanish islands) and *F. sylvatica* (MAGRAMA, 2013). Other genera such as *Abies, Acer, Fraxinus, Juniperus, Sorbus* and *Betula* are also present in Iberia, but cover smaller areas. In Portugal, according to the 6th Portuguese National Forest Inventory (ICNF, 2013), the total forested surface amounts to 3,145,000 ha (34% of the territory), from which 43% are broadleaved forests, 31% conifer forests, and 26% forestry plantations of *Eucalyptus* (Table 1). The main species in the country is the planted *Eucalyptus*, mostly *E. globulus*, followed by the two native species *Q. suber* and *Pinus pinaster*. Other important species are *Pinus pinea*, *Castanea sativa*, *Q. ilex* and *Ceratonia siliqua*.

Table 1. Forested surface and forest types in Spain (adapted from SECF, 2011, data from 3rd IFN, 2009) and Portugal (adapted from ICNF, 2013. IFN6)

Forest types Spain	Surface (1000 ha)	Total%
Open woodlands and/or silvopastoral use	**3,521**	**19.3**
Dehesas *Quercus ilex., Q. suber, Q. pyrenaica, Q. faginea*	2,117	11.6
Scarse and scattered trees	1,404	7.7
Mixed forests	**823**	**4.5**
Conifer forests	**6,515**	**35.7**
Pinus halepensis	1,926	10.5
Pinus pinaster	1,373	7.5
Pinus sylvestris	1,184	6.5
Pinus nigra	625	3.4
Mixed pines	432	2.4
Juniperus spp.	391	2.1
Pinus pinea	390	2.1
Pinus uncinata	97	0.5
Pinus canariensis	78	0.4
Abies spp.	20	0.1
Broadleaved forests	**6,369**	**34.9**
Quercus ilex	2,792	15.3
Quercus pyrenaica	1,034	5.7
Fagus sylvatica	486	2.7
Quercus robur or petraea	459	2.5
Quercus faginea	334	1.8
Quercus suber	301	1.6
Riparian forests (*Fraxinus* spp., *Salix* spp., *Populus* spp.)	252	1.4
Castanea sativa	228	1.2
Mixed broadleaved Mediterranean species	219	1.2
Broadleaved Atlantic species (including *Acer, Betula* and others)	176	1.0
Other broadleaved Mediterranean species	55	0.3
Laurisilva (Canary islands forest)	32	0.2
Fastwood plantations	**1,037**	**5.7**
Eucalyptus spp.	633	3.5
Fast-growth Conifers	295	1.6
Populus spp.	97	0.5
Fast-growth broadleaved species	12	0.1
Total Spain	**18,265**	**100**
Forest types Portugal	**Surface (1000 ha)**	**Total%**
Conifer forests	**962**	**31**
Pinus pinaster	714	23
Pinus pinea	175	6
Other conifer sp.	73	2
Broadleaf forests	**1,371**	**43**
Quercus suber	736	23
Quercus ilex	331	11
Other Quercus	67	2
Ceratonia siliqua	11	<1
Castanea sativa	41	1
Acacia spp.	5	<1
Other broadleaved spp.	177	6
Fastwood plantations	**811**	**26**
Eucalyptus spp.	811	26
Total Portugal	**3,145**	**100**

3. IBERIAN CIVILIZATIONS AND FOREST HISTORY

The exploitation of timber resources and the clearing of woodlands in different parts of the world has been increasing from prehistory onwards proportionally with human population (Kaplan et al., 2009; Williams, 2006). The Iberian Peninsula is no exception. Its forest history is intrinsically linked to the

different cultures that populated it since ancient times, as well as to their degree of development, their cultural exchanges and the socio-political events that took place in each period (Bauer, 1980). All these factors determined the impact of each culture on the woodlands and the material heritage that can be found today.

3.1 Prehistory until ca. 3000 BC

Tribes of hunter-gatherers lived in caves and, by the 5th millennium BC, also in settlements located in valleys and in forests near water (Hernando, 1999; see Carvalho, 2010 and Ibáñez et al., 2008 for an overview of Neolithic sites found in Portugal and Spain respectively). Wood was used as fuel for heating and cooking, to produce ceramics, make tools, and to construct dwellings and other structures (e.g. Bernabeu Aubán et al., 2003; Tarrús, 2008). Human impact on the woodlands was still low.

3.2 Prehistory from ca. 3000 until 500 BC

Agriculture and animal husbandry spread. Mining and metallurgy developed throughout Iberia (e.g. Nocete et al., 2011; Rovira, 2002) with the consequent increase in the demand for firewood and charcoal. Increasing human disturbances became a main cause of vegetation changes (Carrión et al., 2001; Gil, 2009). Bronze Age cultures (e.g. *Los Millares* and *El Argar* in southern Iberia, Chapman, 1991) developed and exchanged. By the Iron Age (ca. 7th century BC), a complex mixture of cultures with different degrees of technological development occupied the peninsula (a comprehensive summary of their geographical and temporal spread is presented by Almagro-Gorbea and Ruiz Zapatero, 1992).

In the southwest, metallurgy (copper and silver) and agriculture from the *Tartessian* culture became noteworthy (Ruiz and Fernández, 1986). The Phoenicians, who had settled in Cadiz and Lisbon at the turn of the 1st millennium BC, and later on the Greeks (8th century BC), traded Tartessian silver across the Mediterranean (Chamorro, 1987). With the spread of Phoenician, Greek and, around the 6th century BC, Carthaginian colonies along the Mediterranean Iberian coast, a change towards a more urban economy took place, with the consequent increase in demand for natural resources. Wood became the most important resource for fuel to supply metallurgy, and for construction. As construction material, timber was also employed in ships, the most remarkable finds from this time being two Phoenician ships uncovered in Mazarrón, Murcia (Negueruela et al., 1995; Negueruela, 2000).

3.3 Ancient history (ca. 500 BC – AD 500)

During the transition from the Iron Age to the Roman period, wood became an even more important commodity, as it was also used for tools, furniture and personal objects. This has been evidenced by archaeological finds from the 4th to 1st century BC, e.g. at the site *Tossal de les Basses* in Alicante (Carrión and Rosser, 2010).

The arrival of the Romans in Iberia in 218 BC during the second Punic war against the Carthaginians was followed by two centuries of wars that culminated with the conquest of the whole peninsula. The accounts of Roman geographers such as Strabo provide an idea of the state of the forests in the last two centuries BC. For example, he wrote that “people in the mountains eat acorns for two thirds of the year” (Schulten, 1952), which could indicate that agriculture was underdeveloped in mountainous

areas. However, this situation rapidly changed, as the Roman economy in Iberia was set upon an agricultural commercial system based on the production of oil, wine and cereals. Farmland quickly took over the woodlands and firewood for ovens became a highly demanded product to produce amphorae for olive oil (Gil, 2009 and references therein).

Wood therefore was required for industry, but also for mining, heating, woodworking and, especially along the coast, for shipbuilding (Bauer, 1980). The latter was addressed among others by the Greek biographer Plutarch (c. AD 45-120) in his work *Moralia* (VVV, V, III, 676), where he described the use of pine wood for shipbuilding, and the importance of tar and resin for caulking the ships (Gil, 2008 and references therein).Waterwheels made of wood have been found in the Roman mines of Tharsis (in Huelva, Spain), where tar and resin for torches were also used (Domergue, 1990). All these uses, together with the urban development of cities (Rodriguez Neila, 1999) led to a considerable reduction of Iberian forests in Roman times.

3.4 Middle Ages (ca. AD 500 – 1450)

At the beginning of the 5th century AD, the Visigoths, an alliance of Alans, Sueves and Vandals from central Europe, entered Iberia through the Pyrenees. By the end of the 6th century AD, they had taken control of the whole peninsula except for a coastal fringe in the southeast (Collins, 2004). The harsh violence of their initial advance though Iberian territories was followed by a period of stabilization, characterised by a new increase of agriculture (cereals, vines, vegetables, fruits), hunting and fishing (Gil, 2009 and references therein).

In AD 711 an army of Arabs and Berbers from the north of Africa ventured into the Iberian Peninsula and established Islamic rule in barely a decade, with only the north resisting their advance and remaining Christian (Collins, 2004). The *Reconquista*, Christian war to regain the lost territories, lasted for almost eight centuries. Amidst this war, the Portuguese kingdom consolidated during the 12th century.

During the Middle Ages, the Muslims maintained an economy based on agriculture. They improved land use by recovering and expanding irrigation systems that also had been used in Roman times (De Aranda y Antón, 1999; Gil, 2009). Deforestation, which was slow in the first centuries of Islamic rule, increased rapidly during the 13th and 14th centuries as the Reconquista moved south (Martínez Ruiz, 1999). War took a high toll on the woodlands, especially along the frontier between Christian and Muslim territories, which was constantly changing from the 8th to the 15th centuries. Fire, commonly used as a tool for shifting cultivation, became a strategic military weapon, and entire forests were burned to prevent the enemies from taking shelter or organising ambushes (Sánchez Albornoz, 1956).

As the advance of the Christians progressed, the reconquered territories, depleted from forests, were dedicated primarily to sheep farming, but also to agriculture and beekeeping. In AD 1273, King Alfonso X of Castile founded the *Mesta*, a medieval guild of transhumant shepherds that quickly grew in wealth and power with the production of merino wool. By the 15th century, wool, honey and wax had become the main export products of the Castilian kingdom, with two thirds of the lands devoted to raising sheep (Gil, 2009 and references therein).

In the north of Portugal, forest exploitation of broadleaves was intense during the Middle Ages, and even resulted in wood exportation. After the 13th century though, wood became a more scarce

resource in this area. On the contrary, more southern areas with Mediterranean climate and under Islamic occupation provided abundant wood that was mainly used for shipbuilding (e.g. pine forests in Alentejo and Algarve), or for other products such as charcoal (Devy-Vareta, 1985).

The destruction of woodlands during these centuries triggered the enactment of privileges and laws (so-called *Fueros* and *Pragmáticas*) to protect forests, and to regulate their exploitation for firewood and other uses (e.g. *Fuero de Molina* dating from AD 1150, *Fuero de Salamanca* from AD 1210; the *Pragmáticas* from AD 1355, 1447, 1496, etc.). In some cases, the *Fueros* granted some localities exclusive rights to exploit the forests for shipbuilding (e.g. the privileges given to Guetaria, in the current Basque Country, by King Alfonso X already in the 13th century) (De Aranda y Antón, 1999). However, these laws were not sufficient to constrain the needs of a growing population, a powerful Mesta, and the ambitions of the monarchs. The pressure on the woodlands during the late Middle Ages was only a prelude of the deforestation that was to come in the following centuries (Martínez Ruiz, 1999).

3.5 Early Modern Period (AD 1450 – 1850)

The conquest of Granada by the Catholic Kings in AD 1492 put an end to centuries of Islamic rule in the south of Iberia, and Columbus' first voyage to the Americas in the same year marked the beginning of a new era. This feat, however, could not have been realised without the technological improvements in navigation and shipbuilding that took place during the years (or decades) preceding Columbus' trip. Therefore the transition to the Early Modern Period is generally accepted to have taken place throughout the second half of the 15th century.

The Age of Discovery, the Renaissance in the arts, architecture and technology and the globalization of trade became trademarks of this period (Williams, 2006). Iberian kingdoms built their empires overseas supported by their fleets. Their booming economies, also sustained by their merchant and fishing fleets, required timber. As a result, the supply of wood for shipbuilding became a priority (Bauer, 1980). More *Pragmáticas* were announced in AD 1518, 1538, 1542, 1543 or 1627 among others to protect and increase the forests, and to regulate their exploitation (De Aranda y Antón, 1999). In AD 1748, several *Ordenanzas de Marina* were enacted, setting under control of the Royal Navy all forests located within 25 leagues (i.e. 139 km) off the coasts and navigable rivers (De Aranda y Antón, 1990; García Fernández, 2005). During this period, the import of timber from Northern Europe first, and from the Americas afterwards, became particularly relevant (De Aranda y Antón, 1990).

3.6 Modern Era (AD 1850 onwards)

In AD 1846, the school of Forest Engineers was created in Spain. One of its first tasks was to prevent part of the public forests from being privatised during the confiscation of lands that took place in AD 1855 (García Álvarez, 2011).

The use of new technology and materials in shipbuilding reduced the demand of timber for this industry. However, with the introduction of railways in the first third of the 19th century, the need of wood for railroad sleepers emerged. Oak from Galicia and pine from the center and south of Spain was used for this purpose (Gil Sánchez, 1999). Half of the timber used for railroad sleepers originated from the Cazorla and Segura mountains alone. Between 1942 and 1949, more than 2.5 million logs (mostly

pine) were extracted from those mountains, illustrating the intense logging activities that were carried out in that area (Araque Jiménez, 2009; Tresaco Calvo, 1968).

4. THE RELEVANCE AND IMPACT OF SHIPBUILDING IN IBERIA

Ships connected cultures, facilitated trade, fishing, and allowed the exploration of new territories. Iberia being a mountainous peninsula with 4,123 km of coastline and more than 24,000 km of rivers, the use of timber for shipbuilding in the territory deserves special consideration, as ships became paramount pillars of the historical and economic development of Iberian cultures and empires.

Since antiquity until the 18th century, shipyards in the Iberian Peninsula were supplied by coastal forests first, and inland ones later on. During the 12th and 13th centuries, shipyards in the north of Iberia were specialised in the production of sailing, war, fishing and cargo ships (Bauer, 1980). These were mainly constructed with oak from the Cantabrian Mountains, whereas in the southern and Mediterranean shipyards, galleys, more suitable for Mediterranean waters, were built mostly with lighter pine species (Martínez Ruiz, 1999).

Merchantmen were often required to join the Castilian Navy in times of war, either to transport troops or to fight in battle. But keeping these vessels from their regular merchant activity was also counterproductive for the crown, a reason that motivated King Alfonso X (AD 1252-1284) to promote the construction of a Royal Navy (Bauer, 1980). The first royal shipyard or *atarazana* was built in Seville, city that would become the most important harbour of the Castilian Kingdom. This was followed by the construction of *atarazanas* in Guetaria/Zarauz (Basque Country region) and Barcelona (Catalonia).

Later on, the Age of Discovery (16th and 17th centuries) and the leading role of the Iberian empires could be realised thanks to their fleets, which were described by the poet Lope de Vega (1562-1635) as "true floating forests" (Bauer-Manderscheid, 1999). The construction of a middle-sized ship required ca. 4.000 trees (Albion, 1926; De Aranda y Antón, 1990). As Bauer (1980) describes, around AD 1585, the estimated volume of wood of the Spanish fleet could be set at 300,000 m^3, including the merchantmen (ca.175,000 m^3), the fishing fleet (ca. 50,000 m^3) and the warships (ca. 75,000 m^3). Such tonnage would need approximately 6 million trees. Given an optimistic estimate of 50 suitable trees per hectare of old woodland, the area needed to supply such a fleet would be 120,000 ha (1,200 km^2) of the best forests. In practice, suitable trees for compass timber were difficult to find, requiring a much larger area. Trees were selected by their shape (De Aranda y Antón, 1990), and in some areas such as the Basque Country, oaks were pruned and guided to produce several branches with the required shape for framing elements and knees (Aragón Ruano, 2009; Michel and Gil, 2013) (Fig. 2). Arming the ships also required firewood, hence trees that would not be suitable for shipbuilding were used for firewood and charcoal.

5. CURRENT STATE OF DENDROARCHAEOLOGY IN IBERIA

The history of Iberian civilizations and forests can be examined and placed in strict chronological order by means of dendrochronology. As independent archives, tree rings provide a unique source of information that allows placing events in time with annual resolution. In the Iberian Peninsula, wood scientists began to open these archives less than a half a century ago.

Figure 2. Compass timber; left: oaks in the Basque Country pruned to produce several branches and curved shapes (photo: M. Domínguez-Delmás); right: 18th century illustration showing parts of stems and branches needed for ship-timber elements (source: Marqués de la Victoria, MV-021, Museo Naval, Madrid).

5.1 Four decades of dendrochronological studies

The first dendrochronological studies in the Iberian Peninsula date back to the 1970s, when Creus Novau and Puigdefábregas (1976) developed a chronology of *P. uncinata* for the Pyrenees with the aim of studying the response of this species to climatic variations and reconstructing the climate of previous centuries at the sampled sites. Since then, numerous climatological, ecological and wood anatomical studies in or involving Iberia have been realised. These include studies on different pine species (*Pinus* spp.) and other conifers such as *A. alba*, *A. pinsapo* and *Juniperus thurifera* (e.g. Andreu et al., 2007; Bräker and Schweingruber, 1984; DeSoto et al., 2012; Génova, 1994; Linares and Camarero, 2012; Schweingruber, 1985; Serre-Bachet et al., 1992; Tardif et al., 2003; Waldner and Schweingruber, 1996), as well as on broadleaved species such as oak (*Quercus* spp.), beech (*F. sylvatica*) and chestnut (*C. sativa*) (e.g. García González, 2000; Gea-Izquierdo et al., 2011, 2012; Gea-Izquierdo and Canellas, 2014; Gutiérrez, 1987; Pérez Antelo, 1995; Rozas, 1999; Rozas et al., 2015; González-González et al., 2013).

5.2 The first dendroarchaeological research

The development of dendroarchaeology since its beginning in the mid-1980s has experienced a slower progress than dendroecology and dendroclimatology. The first attempt to launch this subdiscipline in the Iberian Peninsula was carried out through a collaborative project between Spanish and German institutes, involving the Spanish *Instituto Nacional de Iinvestigaciones Agrarias* (INIA), the Spanish Ministry of Culture, the German Universities of Hamburg and Bochum, and the *Deutsches Archäologisches Institut* (DAI) (Richter, 1988; Richter and Rodríguez Trobajo, 1985). This project aimed at creating a dendrochronological reference data-bank for the Iberian Peninsula, by targeting living trees of different species from strategic areas, and wood from historical buildings in their vicinity (Richter and Rodriguez Trobajo, 1986; Richter, 1986; Richter and Eckstein, 1986). The development of chronologies of different pine species in the centre, east and south of Spain was followed by the successful sampling and dating of timbers from several historical buildings in the provinces of Teruel and Cuenca (Richter, 1986; Richter and Rodríguez Trobajo, 1986) (Fig. 3 and Table S1 in supplementary material). This resulted in the extension of the newly-developed pine

chronologies back to the 11th century and allowed the construction of an almost millennium-long regional chronology for the centre-east of Iberia, demonstrating the dendroarchaeological potential of pine species in this area.

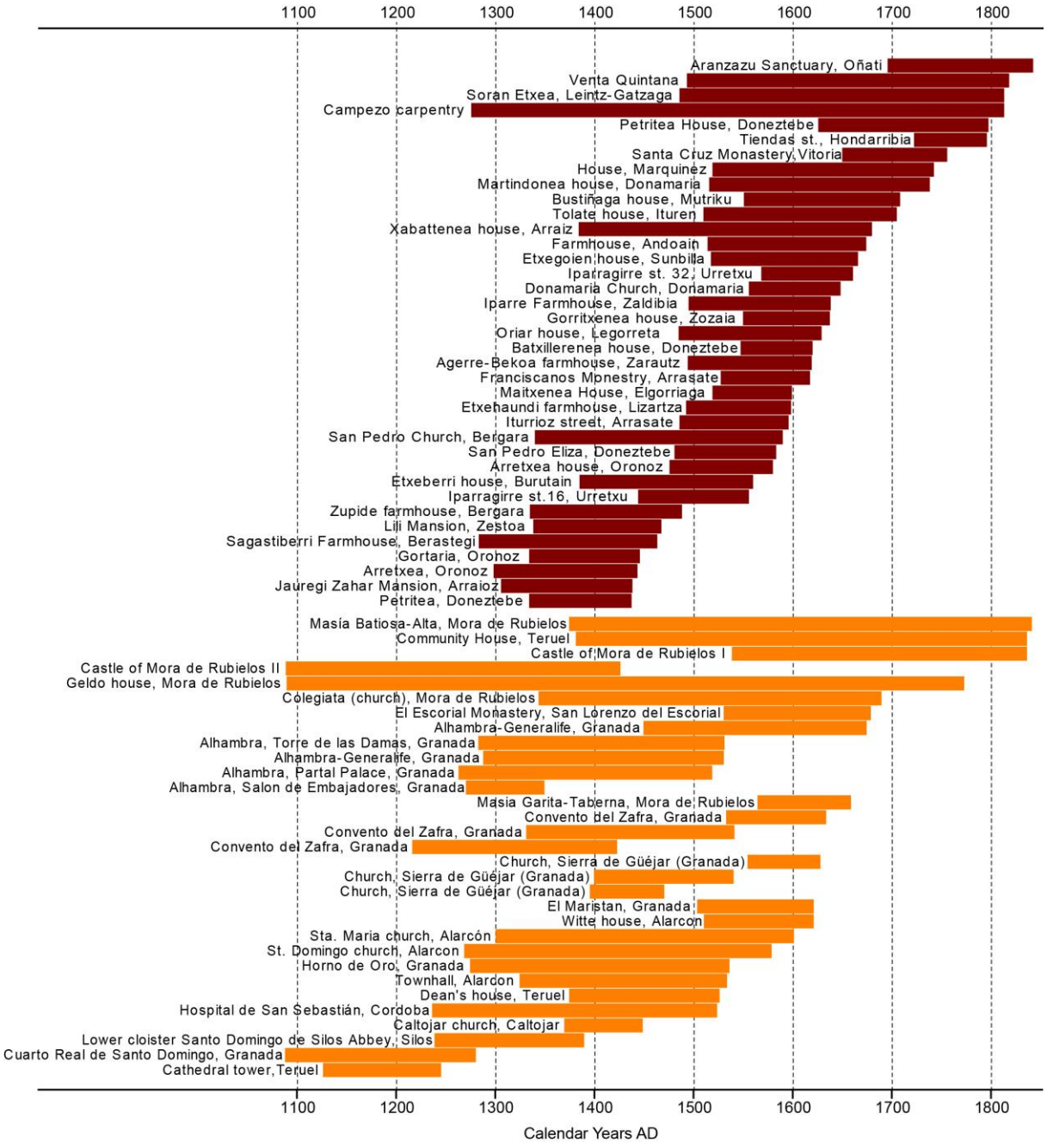

Figure 3. Time span of the absolutely dated chronologies from historical buildings currently existing in the Iberian Peninsula. Dark bars represent deciduous oaks (*Quercus* subg. *quercus*); light bars represent pines (*Pinus sylverstris/nigra/pinaster/halepensis*) (see Table S1 for a list of references and additional information).

5.3 Continuation of dendroarchaeology at the INIA

The pioneer dendroarchaeological work from the Spanish-German collaborative project was followed from the 1990s onwards by investigations carried out at the INIA in Madrid. Some studies involved investigations of archaeological remains, such as the waterwheels found at the Roman mines of Rio Tinto, in Huelva (southwest of Spain) (Fig. 4). Although they could not be dated by dendrochronology, the tree-ring series were registered, and radiocarbon dating placed them in the 1st century AD (Rodríguez Trobajo, 2006). Other research objects included wooden roof and ceiling structures from the Islamic period, such as the *Alhambra and Generalife* complex in Granada and the Great Mosque in Cordoba (both UNESCO World Heritage monuments), and also the Islamic city gates and wall of the historical town of Toledo (Rodríguez Trobajo, 2008). More medieval buildings were researched in the centre of Spain, such as Teruel Cathedral with its spectacular polychromatic Mudejar coffered ceiling (dated by dendrochronology to AD 1260), the cloister of the monastery of *Santo Domingo de Silos* (Burgos) (Rodríguez Trobajo, 2008), and the 10th-11th century mozarab churches of *San Baudelio de Berlanga* (Soria) (Rodríguez Trobajo, 2000), *Santiago de Peñalba* (León) and *San Miguel de Escalada* (León) (Rodríguez Trobajo, 2010b). Also noteworthy is the research carried out in several churches from the 1st millennium AD, such as *San Pedro de la Nave* (Zamora) and *San Juan de Baños* (Palencia) (Alonso Matthias et al., 2004), located in the Douro basin, or *San Miguel de Lillo* (Rodríguez Trobajo, 2010b) and *Santo Adriano de Tuñón* (Rodríguez Trobajo, 2010a) in Asturias. Although most of the tree-ring series from these early medieval buildings remain floating (i.e. not yet absolutely dated by dendrochronology), outstanding matches were found between some samples from different buildings. This allowed the development of several floating

Figure 4. Top: Roman waterwheel found in AD 1886 at the Rio Tinto mines in Huelva, south of Spain; the wood was dated by radiocarbon to 100-210 cal. AD; bottom: reconstruction of the waterwheel (source: Archivo Histórico Minero, Fundación Rio Tinto, pictures A-3-277 and A-3-279 respectively).

chronologies, which according to radiocarbon wiggle-matching dating cover part of the 1st millennium AD (Rodríguez Trobajo, 2008). Additionally, several altarpieces from the 15th and 16th century have been researched in recent years, such as the altarpiece of Baena (Cordoba), the altarpiece at the *Iglesia de Olano* (Araba) (Rodríguez Trobajo, 2011), and the altarpiece of the *Evangelistas* chapel at Seville Cathedral (Rodríguez-Trobajo and Domínguez-Delmás, 2015). The latter revealed the use of oak from the west of Sweden for the panels as an alternative source to the broadly used south-eastern Baltic oak, opening new questions regarding European-scale timber trade and wood procurement in the 16th century.

5.4 Dendroarchaeology in the Basque Country

In the Basque Country, northeast of Spain, dendroarchaeology began in the 1990s. Two decades of dendroarchaeological studies involving historical oak timbers have recently led to the development of long-span tree-ring oak chronologies for this area, hence this long and successful endeavour deserves special consideration.

The discovery of a Roman harbour in Irun, Basque Country in 1992, triggered the interest in absolute tree-ring dating in that region (Susperregi, 2007). With the aim of developping reference oak chronologies (*Q. robur, Q. petraea* and *Q. faginea*) for dating historical buildings and archaeological sites in the Basque Country, a laboratory for dendrochronological research was established at *Arkeolan* (now Arkeolan Foundation). Their arduous work sampling living trees in coastal and inland environments all over the territory resulted in the first major breakthrough when a chronology of *Q. faginea*, developed from an inland forest in Araba province, dated a 17th-century Basque farm house, extending the regional chronology back to the 14th century (Susperregi, 2007). Since then, the dendrochronological dataset from Arkeolan has been extended and improved with the collection of historical wood from Basque farm houses dating back to the 16th century, "tower houses" dating back to the 14th century, and other material salvaged from demolitions or renovations all over the Basque territory and Navarra region (Figs. 3 and 5). In 2012, collaboration between dendrochronologists at Arkeolan and the University of Trinity Saint David (Wales, UK) led to the absolute dating of a group of hull-planks from the *Newport* ship in the mid-15th century (Nayling and Susperregi, 2014). This dendrochronological result also places the origin of the hull planks in the Basque Country, pointing by inference to a harbour in the northern coast of Iberia as a likely location for the construction of the ship.

Preceding the success of Arkeolan, an attempt to develop oak reference chronologies in the Basque Country was carried out in the early 1990s within the framework of a French-Canadian cooperation. The aim was to date the timbers from the shipwrecks found at Red Bay, in Canada (LaRoche, 2007). Having obtained 236 samples from 22 buildings and 56 cores from living trees, the research failed to yield the expected results. Only nine object chronologies were built, and the synchronization of tree-ring series from different structures and forests proved unsuccessful.

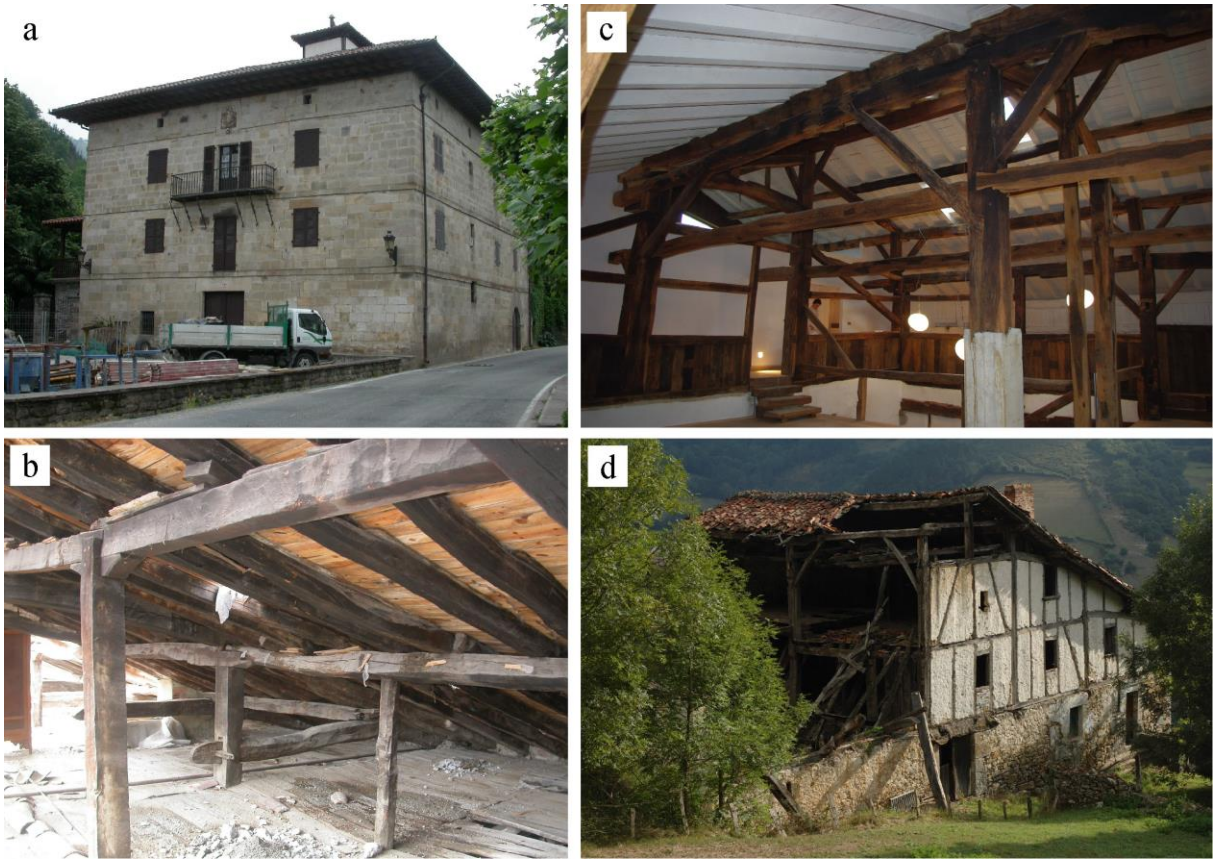

Figure 5. Examples of buildings researched in the Basque Country. a) Sagardia Palace in Ituren, Nafarroa; b) Clarisas convent in Salvatierra, Araba; c) *Caserío* Urdaneta-azpi in Legorreta, Gipuzkoa; d) *Caserío* Axura-Goiene in Lizartza, Gipuzkoa. Photos: Arkeolan Foundation.

5.5 Miscellaneous dendroarchaeological studies

Other dendroarchaeological studies, although scattered, evidence the potential of wood from different periods and of different species for dendroarchaeological, historical research in the Iberian Peninsula. These include:

- Research of oak (*Quercus* sp.) stakes, posts and planks from an early Neolithic site in the northeast of Spain (La Draga, in Catalonia). Tree-ring analyses were conducted at Latenium, in Switzerland, by Patrick Gassman. Although no absolute dates could be found using central European chronologies as reference, the research revealed several construction phases, and helped identifying some structures and establishing their relative timeline (Tarrús, 2008);
- Investigations of 16th and 17th century panel paintings in Portugal (Klein and Esteves, 2001), which evidenced the trade of Baltic oak for panel painting in Lisbon;
- Absolute dating of oak (*Quercus* subg. *quercus*) beams from historical barns (*horreos*) in Galicia, northwest of Spain, which were built with local wood (Domínguez Delmás, 2004);
- Investigations of Roman archaeological timbers of oak (*Quercus* subg. *quercus*), and of buildings and living trees in the centre and south of Navarra region, northeast of Spain (Lizeaga e-mail comm. February 2011);

- Dendroarchaeological research of wooden decks made of pine (*P. sylvestris*) from a canal excavated at the Old Mint in Segovia (Castilla y Leon region), which allowed the reconstruction of major flood events between the late 16th and the 18th century (Génova et al., 2011).
- Investigations of archaeological wooden remains in Catalonia, east of Spain (Ravolto, e-mail comm. June 2012). Among these is a Roman square pit lined by planks made of pine (*P. sylvestris/nigra*) and fir (*A. alba*), which provided floating chronologies still pending to be anchored in time.
- In Portugal, panel paintings at different museums in Lisbon, Coimbra and Sesimbra, and oak (*Quercus* subg. *quercus*) timbers from a 17th century launching ramp found at Praça de Dom Luís I in Lisbon are undergoing dendrochronological research within the project 'Development of long master tree-ring chronologies in Portugal - a tool for dating archeological findings and art pieces' (Lauw, e-mail comm. January 2015). This project is based at the *Instituto Superior de Agronomia* (ISA/ULisboa) and has been funded by the *Fundação para a Ciência e Tecnologia*.

5.6 The Iberian Heritage Project

In 2009, a two-year project entitled '*Filling in the blanks in European dendrochronology: building a multidisciplinary research network to assess Iberian wooden cultural heritage worldwide'* was launched by the *Rijksdienst voor het Cultureel Erfgoed* (Cultural Heritage Agency) in the Netherlands. This project gathered an international and multidisciplinary network of foresters, archaeologists, historians, dendrochronologists and restorers to promote historical dendrochronology in Spain and Portugal, and to expand the research network within Iberia as well as overseas. The international interest of this project, which became known as the Iberian Heritage Project, was mostly sparked by the hundreds of shipwrecks of potential Iberian origin that cannot be assessed yet by dendrochronology due to the lack of a high-resolution network of long-span tree-ring chronologies from different species for the Iberian Peninsula.

Pilot studies were carried out within the project. These involved the inspection, sampling and research of shipwrecks at different underwater-archaeology institutes in Spain and Portugal (Domínguez-Delmás, 2014; Domínguez-Delmás et al., 2013b; DCCD identifiers P:2010085/86/87), roof structures of historical buildings and relict forest stands of black pine in the south of Spain (Domínguez-Delmás et al., 2013a; DCCD identifiers P:2010092/93/94/95).

Additionally, an inventory of existing dendrochronological data from living trees for the Iberian Peninsula was carried out by searching in reference databases for all published literature about Iberian chronologies reaching before AD 1950. Only chronologies for which the coordinates and time span are provided were registered. This inventory has been updated for this publication, and it totals 406 chronologies, which are widespread throughout the main mountain ranges of the Peninsula (Fig. 6). Most of these chronologies (79.1%) are from conifer species, with only one third of them (n=106) reaching back further than AD 1800 (see Table S2 in supplementary material). The number of broadleaved chronologies is relatively low (n=85). Most of them represent several oak species, mainly in northern Spain, with only 21.2% reaching before AD 1800.

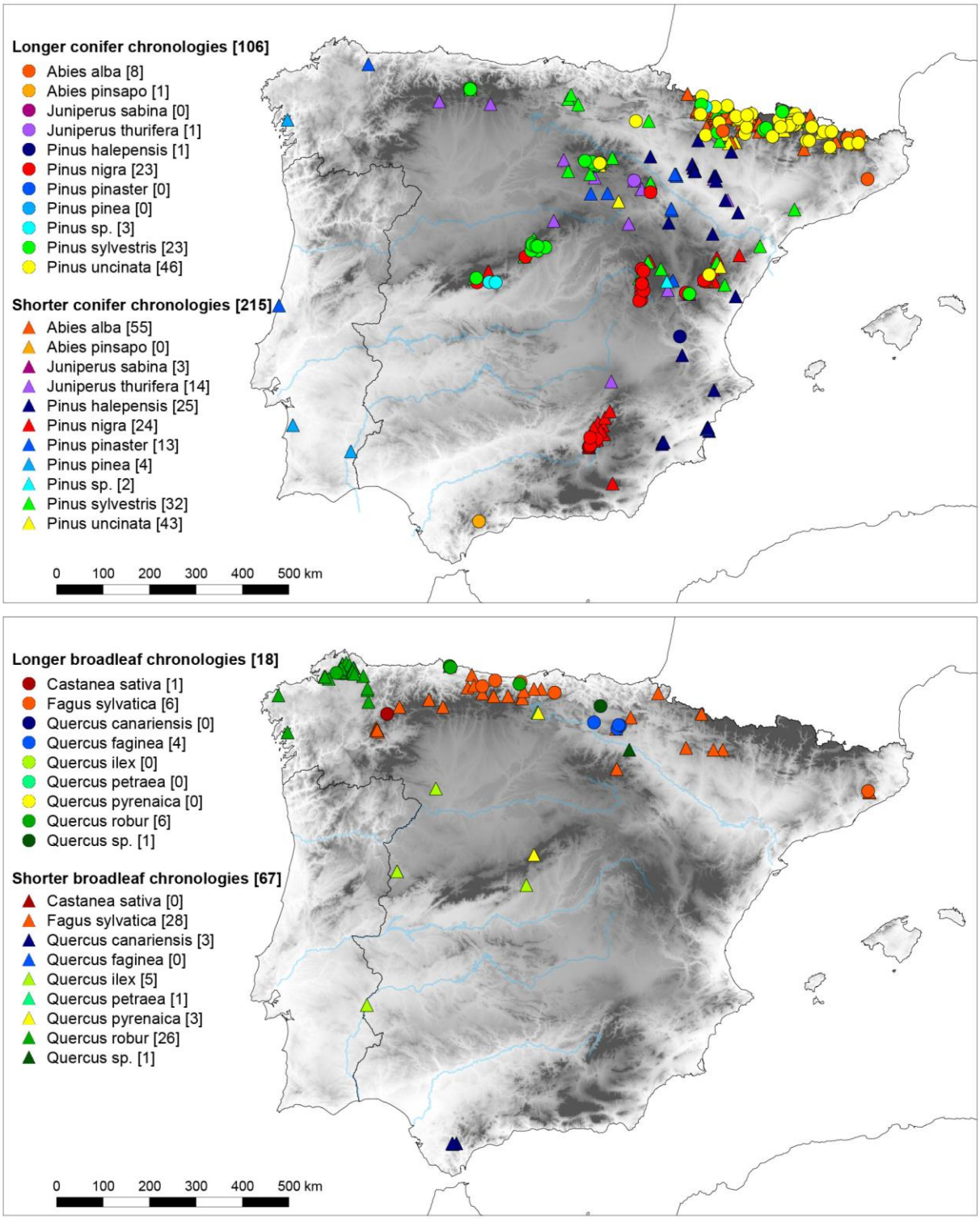

Figure 6. Sites and species of tree-ring chronologies from living trees published up to date in the Iberian Peninsula. Only chronologies reaching AD 1950 and before have been considered. They have been divided into chronologies up to AD 1800 (shorter chronologies)and chronologies spanning further back than AD 1800 (longer chronologies). See Table S2 for a list of references and additional information.

6. FUTURE PROSPECTS

The dendroarchaeological studies outlined so far illustrate the diverse possibilities of this discipline in the Iberian territory. In addition to the research of wood from different periods and contexts in Iberia and overseas, questions such as the transport and trade of timber would provide a broader dimension for future lines of research.

6.1 Potential resources of Iberian wood in Spain, Portugal and worldwide

6.1.1 Ancient vegetation remains

Wood is a perishable organic material and needs very specific conditions to avoid decay, such as waterlogged or stable and dry environments (Huisman and Klaassen, 2009). These types of environments occur across the Iberian Peninsula, and wood remains have been found at different sites. For example, small remains of hardwoods, as well as stumps and logs of *P. sylvestris* covering in discontinuous sequences the period 4500 BC to AD 1200 (dates obtained by radiocarbon dating) were found in high-elevation peat bogs in the Central System (Rubiales et al., 2007). Similar pine remains dating from the 7th millennium BC to the 7th century AD (ca. 9100 to 1300 cal. BP) were recovered from peat bogs in the central part of the Cantabrian Mountains (Rubiales et al., 2012). These remains contain valuable information about past environment and vegetation dynamics, and although the achievement of a continuous absolute tree-ring chronology covering the Holocene will take years to realise, they demonstrate the potential to obtain Iberian tree-ring based palaeo-datasets similar to those from northern Europe (e.g. Eckstein et al., 2011; Edvardsson et al., 2012).

6.1.2 Charcoal and wood from archaeological sites

Charcoal, timbers, wooden artefacts and even furniture have been unearthed at numerous archaeological sites spread throughout the Iberian Peninsula (some examples have been compiled in Badal et al., 2012). Tree-rings of carbonised wood provide insights into the human use of wood resources in ancient times, and are being the target of the emergent subdiscipline known as dendro-anthracology (Marguerie, 2011).

Wood from structures built in inland or coastal water-environments (e.g. harbours, revetments, bridges, watermills, etc.) are also likely to have survived in waterlogged conditions. For example, remains of foundation piles made with 1.5 m long pine logs were found in the centre of Seville during construction works (Collantes de Terán, 1977; Gil, 2009). Such piles were used to consolidate the foundations of buildings in swampy or marshy soils, hence they are likely to be found in cities such as Seville or Lisbon among others.

6.1.3 Shipwrecks

Underwater archaeology has led to the discovery of numerous shipwrecks from all periods along the coasts of Spain and Portugal. The oldest ones are two Phoenician vessels from the 7th century BC found in Mazarrón, Murcia. The first of these boats was found in AD 1988, and consisted of a fraction of the vessel including the keel and portions of nine strakes and four frames (Negueruela et al., 1995). The second vessel, found in AD 1994, was almost entirely preserved and included the planking on both sides as well as four frames (Negueruela, 2000). The wood species of the planking elements of both vessels was identified as Aleppo pine (*Pinus hapelensis*), whereas the framing elements were

identified as fig tree (*Ficus* sp.). Another remarkable wreck is the medieval ship found in the 1980s at Plaza Nueva, in Seville, dated by radiocarbon to the 10th-11th century (Cabrera-Tejedor, 2014). Although the conservation of the recovered timbers is very poor, dendrochronological and wood anatomical analyses are planned for the near future.

Shipwrecks dating to the 15th century have been excavated and documented at different sites in Spain and abroad, such as the *Barceloneta I* found in Barcelona (Soberón Rodríguez et al., 2012), the *Urbieta* shipwreck, found in Gernika (Izaguirre et al., 2001), and the *Newport* ship, found in the Welsh town by that name (Nayling and Jones, 2014). The latter is one of the most extensively dendrochronologically researched shipwreck assemblages in the world, representing the first shipwreck ever dated with Iberian tree-ring data (Nayling and Susperregi, 2014).

Potentially Iberian-built ships from the Early Modern Period have also been found in different parts of the world. In Scotland and Ireland, wrecks of the Spanish Armada from AD 1588 have been located along the coast (e.g. Birch and McElvogue, 1999; Martin, 1973). Some of these have been identified as ships built in Basque shipyards, such as the *Santa María de la Rosa*, built in San Sebastian in AD 1587. The Basque whaler *San Juan*, found in Red Bay, Canada (Loewen, 1998; LaRoche, 2007), is another good example of the potential for finding wood from trees grown in the Iberian Peninsula abroad.

However, the most extensive sources of wood from Iberian origin are probably the wrecks of ships from the Age of Discovery (16th and 17th centuries) (Fig. 7). The Spanish and Portuguese empires built large fleets during this period, and numerous ships sank along their routes due to combats, collisions with reefs, but mostly storms (Rappaport and Fernández-Partagás, 1997). The International Registry of Sunken Ships (http://www.shipwreckregistry.com) contains 2,362 entries of Portuguese and Spanish ships sunk until AD 1820 in different parts of the world (Brown, email comm. August 2010). This database is based on archival data and data from historical and written sources, and although it is unknown how much wood is still preserved, it gives an idea of the great source of timber that might be lying underwater.

Figure 7. Playa Damas shipwreck, a suspected 16th century Spanish ship found in the 1990s at Playa Damas, in the Atlantic coast of Panama (Castro and Fitzgerald, 2006; photos: K. Vandenhole). Dendrochronological research on the surviving timbers could shed some light on the chronology of the ship and area of construction, contributing to support the case for its protection as underwater cultural heritage.

Surviving wood of shipwrecks represents a direct link to the forests of the past. Ship timbers are archives of information about ancient forest management practices and technological choices such as selection of specific species and trees for different timber elements (Castro, 2008). In this manner, dendrochronology goes beyond the absolute dating of the wood, complementing existing documentary sources and providing evidence where no other information exists.

6.1.4 Standing buildings

The Iberian Peninsula has a rich built heritage over a broad temporal frame (Visigothic hermitages, churches, Islamic mosques, late medieval cloisters, convents and monasteries, cathedrals, etc.) with original wooden elements still preserved intact (see e.g. Nuere Matauco, 2003; Utrero Agudo, 2006). Timbers used in roof constructions, porches, coffered ceilings, walls, doors, windows and foundation structures represent the first link to extend the chronologies from living trees back in time, and to bridge gaps between dated and floating chronologies.

Research of timbers from buildings carried out at the INIA, focusing on aspects such as the provenance of the wood, the reuse of timber and the identification of construction phases, indicates that these wooden elements are also a valuable source of historical information. These dendroarchaeological investigations demonstrated that forests of *P. sylvestris/nigra* supplied timber for constructions in the Douro basin around the mid-1st millennium AD, and allowed establishing the exact chronology of Islamic and Mudejar building typologies at the Alhambra in Granada, the Great Mosque in Cordoba, and at Teruel Cathedral (Rodríguez Trobajo, 2008). The identification of typologies of Roman origin in the early-medieval buildings in the regions of Castilla y Leon and Asturias has also been a remarkable result (Alonso Matthias et al., 2004; Rodríguez Trobajo, 2010a), although those timbers are not yet absolutely dated. Future efforts should concentrate in buildings and archaeological material that can bridge the existing gaps. For example, catholic monuments that replaced medieval mosques, such as the *Colegial del Salvador* church in Seville (Mendoza, 2008) or Jaen Cathedral (Higueras Maldonado, 2009), are of particular interest to accomplish this goal, as they may contain timbers reused from the previous Islamic buildings.

In the Basque Country, the work of Arkeolan clearly illustrates the challenge that dendroarchaeology of oak species faces in the north of Spain, as it shows that there is a great variability of tree growth among valleys. This may partly explain the unsuccessful attempt of the French-Canadian collaboration to date the structural timbers of Red Bay wrecks with samples from several buildings and living trees in that region (LaRoche, 2007).

6.1.5 Art and furniture

The interiors of religious temples, palaces, castles, and some vernacular houses are filled with decorative wooden objects and furniture. Wooden chests, cabinets, tables and chairs of modest or more elaborated designs were common household items. Christian monumental buildings are decorated with paintings, sculptures and altarpieces made of wood (e.g. García Mogollón, 1985). From the 15th century onwards, the interest of the different Iberian monarchs in art favoured the production of such items, as well as their import, especially from Bruges and Antwerp (Martens and Peeters, 2002). The Spanish Golden Age (15th to 17th centuries) was therefore a period of great artistic production, and monarchs and aristocrats became avid art collectors.

The mobile character of works of art facilitates their trade; hence some paintings, sculptures, furniture and even altarpieces have changed owners and location up to several times over the centuries. Consequently, wood from Iberian forests can be found nowadays in works of art at private or public collections across the world. A good example is the impressive 15th century altarpiece of *Ciudad Rodrigo*, composed of 26 panel paintings made of pine, currently owned by the Kress Foundation and located at the Museum of Art of the University of Arizona, in Tucson (USA).

6.1.6 Industrial heritage

Industrial activities such as mining, where wooden frames were required to support galleries (Santullano, 1978), and the construction of railroad tracks are a resource of historical timber dating back to the second half of the 18th century. Between roughly 1850 and 1960, large amounts of oaks in Galicia and pines in Andalusia were logged for the production of railroad ties (Gil Sánchez, 1999). Recently, the use of new materials in railways has led to their steady replacement, but discarded wooden ties available, for example, in gardening centres represent a great source of tree-ring data that could help linking chronologies from living trees with those derived from older beams in buildings and shipwrecks.

6.2 Historical transport and trade of timber

A crucial question for dendroarchaeological studies in the Iberian Peninsula regards the transport and trade of timber, as the wood found in archaeological excavations, historical structures and objects may have originated from neighbouring inland regions, or from countries further away.

6.2.1 Logs, rafts and Iberian rivers

Transport of wood from forests to markets or construction sites such as shipyards was traditionally done via waterways, i.e. by rivers or by sea along the coast loaded on to ships. Transport over land was time consuming and costly; hence it was almost exclusively limited to covering the distance from the forest to the nearest waterway. Logs were dragged, whereas timber products (e.g. squared beams) were transported atop oxen and mules (Martínez Ruiz, 1999). Once at the waterways, wood could be transported either as loose logs or assembled into rafts (Córdoba de la Llave, 1995).

In the Andalusian region, these means for wood transportation have been employed for centuries. The floating of logs down the Guadalquivir river was documented for the first time in the Middle Ages (10th century) by geographer Al-Zuhri, but is likely to have occurred since Roman times, as it was easy to navigate to Castulo (nowadays Linares) (López Almansa, 1999; Martínez Ruiz, 1999). In the 19th and 20th century, driving of loose railroad ties downstream is also very well documented. Black pines were processed into railroad ties in the upper part of the Cazorla and Segura mountains, and these were transported to the lower part of the mountains via canalization systems built in the upper course of the Guadalimar and Guadalquivir rivers (Fig. 8). The first ties produced at the beginning of the logging season served for the canalization, which was dismantled from the upper to the lower elevations at the end of the season, transporting the ties by water to the nearest train station.

In the Ebro basin, documentary evidence describes the floating of logs in Pyrenean rivers such as the Esera and the Veral since the 16th century (Pallaruelo, 2008). Rafts were used in the Ebro and some of its subsidiaries such as the Aragon and the Cinca (Pallaruelo, 2008). In the rest of the peninsula, the

transport of wood in rafts is also described for the Tagus, Jucar, and Sado rivers (Martínez Ruiz, 1999), where the abundant flow of water allowed the transport of big volumes of wood grouped together.

Figure 8. Sequence of production and transport of black pine (*Pinus nigra*) railroad ties from forests in the Cazorla Mountains (south of Spain) down to the Guadalquivir valley. This manner of timber transportation was used until the mid-20th century. Source photos: Archivo Histórico del Museo del Ferrocarril de Madrid - Fundación de los Ferrocarriles Españoles.

The Iberian watersheds therefore must be taken into consideration when carrying out dendroarchaeological studies in the peninsula, as the wood may have originated hundreds of kilometres away from where it was used or found. Forests located within the geographical range of the watershed where the wood was found are more likely to be the procurement sources. In the case of shipyards or cities and villages located by the sea, a possible origin of the wood from further away, or from mountains in different watersheds should be considered.

6.2.2 Trade of timber and manufactured products to and from Iberia

Import of wood into Iberia occurred as early as in Roman times, as demonstrated by the find of fir (*Abies* sp.) and larch (*Larix decidua*) wood used in the Roman waterwheels from Rio Tinto mines in Huelva (Rodríguez Trobajo, 2006). Whereas fir is native to the Pyrenees, the nearest natural distribution area of larch is the Alps. This wood was therefore brought into the south of Spain, raising the question of the import of the wheels as a manufactured product or the wood as raw material for their fabrication on-site. Later on, in the 13th and 14th centuries, documentary sources and empirical evidence suggest that cedar (*Cedrus atlantica*) was imported from Morocco to be employed in Islamic buildings in Granada and in the construction of ships in Almeria (Rodríguez Trobajo, 2008).

Export of wood from Iberian forests towards the north of Africa (Morocco, Algeria and Tunis) and the eastern Mediterranean took place during the Middle Ages, and possibly also earlier (De Aranda y Antón, 1999; Martínez Ruiz, 1999). However, with the fall of the Islamic rule during the Late Middle Ages, the export of timber ceased, and Iberian forests were used to supply exclusively local and regional activities.

In the 16th and part of the 17th century, the political bonds between the Low Countries and Castile had a strong impact on the trade between both regions (Gómez Bárcena, 2004; Thomas and Stols, 2000). This is illustrated by the references to so-called 'Flemish' wood that can be found in Spanish archives and literature concerning 16th-century altarpieces and shipbuilding (García Mogollón, 1993; De Aranda y Antón, 1990). For instance, the commission contracts of the altarpiece of the *Concatedral de Cáceres* (Cáceres, Spain) and the altarpiece of the *Capilla Universitaria* at the *Iglesia de la Anunciación* (Seville, Spain) specify that the wood used for their construction should be Flemish oak. At that time, local oak wood was scarce in the Low Countries; hence oak timber was imported there from Germany, Scandinavia and the Baltic countries (Bogucka, 1969; Delmás and Van den Berselaar, 2009). Therefore, the real origin of the 'Flemish' wood found in Spain has still to be assessed.

Art-historical objects also provide good examples of imported artefacts. In the 16th century, the Iberian Peninsula was the main export market for Flemish art, and it is estimated that between AD 1543 and 1545, 34% of the exported paintings had the peninsula as destination (Martens and Peeters, 2002). Flemish altarpieces were also very well-known and valued all over Europe, and some of them are now displayed in Spanish and Portuguese churches and cathedrals (Gómez Bárcena, 2004; Kroesen, 2003). However, as Gómez Bárcena (2004) pointed out, the lack of documentation for some of those altarpieces hampers determining their exact chronology and provenance, questions for which dendroarchaeology could provide decisive answers.

Wood was also imported to Iberia for shipbuilding. From the mid-13th century onwards, the flourishing sea trade between Cantabrian harbours and north European countries (mostly France, England and Flanders) opened the market for the import of timber in the north of the Iberian Peninsula (Bauer, 1980), but this import was especially relevant during the Early Modern Period. In 1522, an inventory of ships available in Cantabrian harbours to assemble a fleet for the king described clinker-built ships made with oak and *borne* (Casado Soto, 1998 and references therein), the latter referring to oak wainscots imported to Spain from northern Europe (Bruquetas Galán, 2000; Rodríguez-Trobajo and Domínguez-Delmás, 2015). More examples of the importation of wood are found in historical records of the Spanish Royal Navy, which mention *Prussian pine* imported to Spain in the 16th century to be used for masts in Spanish warships (Bauer, 1980). From the second half of the 17th century, *Riga pine* was imported for the same purposes (Zunde, 1999), and in the 18th century historical records explain how Dutch ships carrying among others wood from Scandinavia and the Baltic countries delivered their cargo directly to Spain (Crespo Solana, 2000). From the 17th century onwards, bulky wood was also imported to Iberia from the Americas (Bauer, 1980; Bruquetas Galán, 2000).

The research of shipwrecks must be pursued under the premise that the wood may originate from everywhere, as ships were also rented and bought from other nations such as Italy (Genoa), England and later on Holland since the 13th century (Casado Soto, 2003). Often, great Armadas such as the so-called *Invencible* from AD1588 were in fact composed by fleets hired in different countries, and only part of the ships were built in Iberian shipyards (Menéndez Pidal, 2000), a paramount aspect to consider when looking for Iberian trees in sunken "Spanish" shipwrecks.

6.3 Provenancing of wood

The basic principle of dendro-provenancing is that, given a well-developed network of tree-ring chronologies, those producing the most outstanding statistical matches will represent the area where the wood under investigation originated from. However, the similarity between tree-ring series is not a linear function exclusively dependent on geographical distance. For example, strong elevation changes along short distances may induce microclimatic conditions that could hamper crossdating of trees from different elevations, as has been demonstrated for the Cazorla Mountains, in Andalusia (Domínguez-Delmás et al., 2013a). However, these differences in growth can turn into an advantage for dendro-provenance studies, as the development of chronologies at well-defined spots can assist in identifying the provenance of the wood rather accurately. The Iberian Peninsula is therefore an excellent territory to explore innovative methods for provenancing wood with high spatial resolution. Future efforts should aim at combining tree-ring data with thorough observations of wood anatomical features, isotopic and genetic markers in well-defined ecological areas.

7. CONCLUDING REMARKS

Millennia of wars, agriculture, wildfires, grazing, industry and reforestation have shaped the Iberian woodlands as we know them today. The remaining old forests are in many cases mere relics of what they were, but they represent the departure point for the development of reference tree-ring chronologies.

Far from being discouraging, the peculiarities outlined in this paper make the Iberian Peninsula yet more interesting from a dendroarchaeological perspective. Wood from archaeological contexts, art-historical objects and built structures is abundant and can serve as a key to unravel human–environment–climate interactions over the past millennia.

Campaigns of awareness about the potential of this discipline to assess cultural heritage are however still needed. The existing grid of tree-ring chronologies must be expanded to cover the wide spectrum of climatic and ecological conditions of the different regions, and must be extended back in time. Novel, high-resolution approaches for provenancing historical wood should be explored. The international character of Iberian heritage makes dendroprovenancing studies a highly relevant topic. As we have shown, not only wood from other geographical regions was imported to the peninsula, but also wood from trees grown in Iberia can be found worldwide in shipwrecks and works of art. Therefore multidisciplinary national and international collaboration is required to achieve these goals.

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References

Albion, R.G., 1926. Forests and Sea Power: the Timber Problem of the Royal Navy, 1652–1862. Harvard University Press, Cambridge.

Almagro-Gorbea, M., Ruiz Zapatero, G., 1992. Paleoetnología de la Península Ibérica. Reflexiones

y perspectivas de future, in: Ruiz Zapatero, G., Almagro-Gorbea, M. (coords.), Paleoetnología de la Península Ibérica : actas de la Reunión celebrada en la Facultad de Geografía e Historia de la Universidad Complutense, Madrid 13-15 diciembre de 1989, Vol. 2, 469-500.

Alonso Matthias, F., Rodríguez Trobajo, E., Rubinos, A., 2004. Datación de madera constructiva en San Pedro de la Nave (Zamora) y su interdatación con San Juan de Baños (Palencia), in: Caballero (Ed.), La Iglesia de San Pedro de la Nave, Zamora, pp. 209-237.

Andreu, L., Gutiérrez, E., Macias, M., Ribas, M., Bosch, O., Camarero, J.J., 2007. Climate increases regional tree-growth variability in Iberian pine forests. Glob Change Biol 13, 1–12.

Aragón Ruano, A., 2009. Los robles trasmochos guiados o ipinabarros: una apuesta sostenible de futuro para una técnica forestal olvidada. Cuad Soc Esp Cienc For 30, 137-142.

Araque Jiménez, E., 2009. La contribución de los montes del Protectorado español del norte de Marruecos al abastecimiento ferroviario de madera (1945-1958). Ería 78-79, 5-20.

Badal, E., Carrión, Y., Macías, M., Ntinou, M. (Cords.), 2012. Wood and Charcoal. Evidence for human and natural history. Saguntum Extra 13, Universitat de València, Valencia.

Baillie M.G.L., 1982. Tree-Ring Dating and Archaeology, University of Chicago Press, Chicago.

Bauer, E., 1980. Los montes de España en la historia, Ministerio de Agricultura, Madrid.

Bauer-Manderscheid, 1999. Los bosques españoles. Evolución forestal de España en el marco europeo, in: Marín Pageo, F., Domingo Santos, J., Calzado Carretero, A. (eds.), Los montes y su historia: una perspectiva política, económica y social. Collectanea 27, 139-149.

Becker, B., Delorme, A., 1978. Oak chronologies for Central Europe: their extension from medieval to prehistoric times. BAR International Series 51, 59–64.

Beeckman, H., 2005. The impact of forest management on wood quality. The case of medieval oak, in: Van de Velde, C., Beeckman, H., Van Acker, J., Verhaeghe, F. (Eds.), Constructing wooden images: proceedings of the symposium on the organization of labour and working practices of late gothic carved altarpieces in the Low Countries. VUB Press, Brussels, pp. 93–113.

Benito Garzón, M., Sánchez de Dios, R., Sainz Ollero, H., 2008. Effects of climate change on the distributions of Iberian forest. Appl Veg Sci 11, 169–178.

Bernabeu, J., Orozco Köhler, T., Diez Castillo, A., Gómez Puche, M., Molina Hernández, F.J., 2003. Mas d'Is (Penàguila, Alicante): aldeas y recintos monumentales del Neolítico Inicial en el valle del Serpis. Trabajos de Prehistoria 60 (2), 39-59.

Billamboz, A., 2003. Tree rings and wetland occupation in southwest Germany between 2000 and 500 BC: dendroarchaeology beyond dating in tribute to F.H. Schweingruber. Tree-Ring Res 59(1), 37-49.

Billamboz, A., 2008. Dealing with heteroconnections and short tree-ring series at different levels of dating in the dendrochronology of the Southwest German pile-dwellings. Dendrochronologia 26(3), 145-155.

Billamboz, A., 2014. Regional patterns of settlement and woodland developments: Dendroarchaeology in the Neolithic pile-dwellings on Lake Constance (Germany). The Holocene 24(10), 1278-1287.

Birch, S., McElvogue, D.M., 1999. La Lavia, La Juliana and the Santa Maria de Vison:

three Spanish Armada transports lost off Streedagh Strand, Co Sligo: an interim report, International J Nautical Archaeol 28 (3), 265-276.

Blanco, E., Casado, M.A., Costa, M., Escribano, R., García Antón, M., Génova, M., Gómez Manzaneque, A., Gómez Manzaneque, F., Moreno, J.C., Morla, C., Regato, P., Sainz Ollero, H., 1997. Los bosques ibéricos, Editorial Planeta, Barcelona.

Bleicher, N., 2014. Four levels of patterns in tree-rings: an archaeological approach to dendroecology. Veget. Hist. Archeobot. 23, 615-627. doi: 10.1007/s00334-013-0410-6.

Bogucka, M., 1969. Handel Gdanska z Plw. Iberyjskim w I polowie XVII wieku [Trade of Gdansk with the Iberian Peninsula in the first half of 17th century]. Przeglad Historyczny 60(1), 1-23.

Bridge, M., 2012. Locating the origins of wood resources: a review of dendroprovenancing. J Archaeol Sci 39, 2828-2834. doi: 10.1016/j.jas.2012.04.028

Bruquetas Galán, R., 2002. Técnicas y materiales de la pintura española en los Siglos de Oro. Fundación de Apoyo a la Historia del Arte Hispano, Madrid.

Bräker, O., Scheingruber, F., 1984. Standorts-Chronologien. Teil 1: Iberische Halbinsel. Publikation der Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft, Birmensdorf.

Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J.O., Herzig, F., Heussner, K.-U., Wanner, H., Luterbacher, J., Esper, J., 2011. 2500 years of European climate variability and human susceptibility. Science 331, 578-582.

Cabrera-Tejedor, C., 2014. El fondeadero de la Plaza Nueva de Sevilla: un ancla y una barca procedentes del antiguo puerto de *Hispalis*, in: Nieto Prieto, X., Ramírez Pernía, a., Recio Sánchez, P. (Coords. Eds.), Actas I Congreso Arqueología Náutica y Subacuática española. MECD, pp. 511-525. https://sede.educacion.gob.es/publiventa/detalle.action?cod=20070C.

Carrión, J.S., Andrade, A., Bennett, K.D., Navarro, C., Munuera, M., 2001. Crossing forest thresholds: inertia and collapse in a Holocene sequence from south-central Spain. The Holocene 11, 635-653.

Carrión, Y., Rosser, P., 2010. Revealing Iberian woodcraft: conserved wooden artefacts from south-east Spain. Antiquity 84, 747-764.

Carvalho, A.F., 2010. Chronology and geography of the Mesolithic-Neolithic transition in Portugal, in: Armbruester, T., Hegewisch, M. (Eds.), On Pre- and Earlier History of Iberia and Central Europe. Studies in honour of Philine Kalb. Studien zur Archäologie Europas 11, 45-61.

Casado Soto, J.L., 1998. Aproximación a la tipología naval cantábrica en la primera mitad del siglo XVI. Itsas Memoria 2, 169-191.

Casado Soto, J.L., 2003. El Cantábrico y las galeras hispanas de la Edad Media a la Moderna. Itsas Memoria 4, 537-552.

Castro, F., 2008. In search of unique Iberian ship design concepts. *Historical Archaeology* **42(2)**, 63-87.

Castro, F., Fitzgerald, C., 2006. The Playa Damas shipwreck: an early-sixteenth century shipwreck in Panama. In Robert Grenier, David Nutley, Ian Cochran (Eds.), *Heritage at risk: underwater cultural heritage at risk; managing natural and human impacts*, special edition, ICOMOS Heritage at Risk Series. UNESCO, Paris, France, pp. 38-41.

Chamorro, J.G., 1987. Survey of Archaeological Research on Tartessos. American J Archaeol 91 (2), 197-232.

Chapman, R. 1991. La formación de las sociedades complejas. El sureste de la Península Ibérica en el marco del Mediterráneo occidental, Editorial Crítica, Barcelona.

Collantes de Terán Delorme, F., 1977. Contribución al estudio de la topografía Sevillana en la Antigüedad y en la Edad Media, Real Academia de Bellas Artes de Santa Isabel de Hungría. Patronato José M.ª Quadrado del C.S. de I.C. Monte de Piedad y Caja de Ahorros de Sevilla, Sevilla.

Collins, R., 2004. Visigothic Spain (409-711), Blackwell Publishing, Oxford.

Córdoba de la Llave, R., 1995. Comunicaciones, transportes y albergues en el reino de Córdoba a fines de la Edad Media. Historia, Instituciones y Documentos 22, 87-118.

Crespo Solana, A., 2000. El comercio marítimo entre Amsterdam y Cádiz (1713-1778). Banco de España, servicio de estudios. Estudios de historia económica nº40, URL: http://digital.csic.es/bitstream/10261/14961/1/roja40.pdf

Creus Novau, J., Puigdefàbregas, J., 1976. Climatología histórica y dendrocronología de Pinus uncinata Ramond. Cuadernos de Investigación 2 (2), 17-30.

Čufar, K., 2007. Dendrochronology and past human activity – A review of advances since 2000. Tree-Ring Res 63(1), 47-60.

Crone, A., Mills, C.M., 2012. Timber in Scottish buildings, 1450–1800: a dendrochronological perspective, Proc Soc Antiq Scot 142, 329-369.

De Aranda y Antón, G., 1990. Los Bosques Flotantes: historia de un roble del siglo XVIII. Colección Técnica. Ministerio de Agricultura, Pesca y Alimentación. ICONA, Madrid.

De Aranda y Antón, G., 1999. Visión histórica de la selvicultura popular española, in: Marín Pageo, F., Domingo Santos, J., Calzado Carretero, A. (eds.), Los montes y su historia: una perspectiva política, económica y social. Collectanea 27, pp 9-31.

De la Cruz Aguilar, E., 1980. La Provincia Marítima de Segura de la Sierra, Boletín del Instituto de Estudios Giennenses CVII, Jaen.

Delmás, M., Van den Berselaar, H., 2009. Nederlands hout op drift. Vitruvius 2(6), 12-18.

DeSoto, L., Camarero, J.J., Olano, J.M., Rozas, V., 2012. Geographically structured and temporally unstable growth responses of Juniperus thurifera to recent climate variability in the Iberian Peninsula. European J Forest Res 131(4), 905-917, doi:10.1007/s10342-011-0564-7.

Devy-Vareta, N., 1985. Para uma geografia histórica da floresta portuguesa. As matas medievais e a 'coutada velha' do rei. Revista da Faculdade de Letras – Geografía I, 47-67.

Domínguez Delmás, M., 2004. Estudio dendrocronológico del *Quercus pyrenaica* Willd. en las sierras Galaico-Leonesas de Ancares y Courel. Unpublished MSc. Thesis University of Lleida, Lleida.

Domínguez-Delmás, M., 2014. Avances de la dendrocronología al servicio de la arqueología subacuática española: ¿qué información podemos extraer de la madera de los pecios?, in: Nieto Prieto, X., Ramírez Pernía, a., Recio Sánchez, P. (Coords. Eds.), Actas I Congreso

Arqueología Náutica y Subacuática española. MECD, pp. 1080-1094. https://sede.educacion.gob.es/publiventa/detalle.action?cod=20070C.

Domínguez-Delmás, M., Alejano-Monge, R, Wazny, T., García-González, I., 2013a. Radial growth variations of black pine along an elevation gradient in the Cazorla Mountains and their relevance for historical and environmental studies. European J Forest Res 132 (4), 635-652.

Domínguez-Delmás, M., Nayling, N., Wazny, T., V. Loureiro, Lavier, C., 2013b. Dendrochronological dating and provenancing of timbers from the *Arade 1* wreck, Portugal. International J Nautical Archaeol 42 (1), 118-136.

Domínguez-Delmás, M., Driessen, M., García-González, I., Van Helmond, N., Visser, R., Jansma, E., 2014. Long-distance oak supply in mid-2nd century AD revealed: the case of a Roman harbour (Voorburg-Arentsburg) in the Netherlands. J Archaeol Sci 41, 642-654.

Domergue, C., 1990. Les mines de la Península Ibérique dans l'antiquité romaine, École Française de Rome, Palais Farnèse, Roma.

Eckstein, D., Wrobel, S., 2007. Dendrochronological proof of origin of historic timber- retrospect and perspectives, in: Haneca, K., Beeckman, H., Gärtner, H., Helle, G., Schleser, G. (Eds.), TRACE - Tree Rings in Archaeology, Climatology and Ecology, Vol. 5, pp. 8–20.

Eckstein, J., Leuschner, H.H., Bauerochse, A., 2011. Mid-Holocene pine woodland phases and mire development – significance of dendroecological data from subfossil trees from northwest Germany. Journal of Vegetation Science 22 (5), 781–794.

Edvardsson, J., Leuschner, H.H., Linderson, H., Linderholm, H.W., Hammarlund, D., 2012. South Swedish bog pines as indicators of Mid-Holocene climate variability. Dendrochronologia 30 (2), 93-103.

Fraiture, P., 2009. Contribution of dendrochronology to understanding of wood procurement sources for panel paintings in the former Southern Netherlands from 1450 AD to 1650 AD. Dendrochronologia 27, 95-111.

Fritts, H.C., 1976. Tree rings and climate, Academic Press, London.

García Álvarez, A., 2011. História del cuerpo de ingenieros de montes (1853-2010), Colegio y Asociación de Ingenieros de Montes, Madrid.

García Fernández, N., 2005. Bosques, maderas y barcos para la armada durante el ministerio de Antonio Valdés. Semejanzas y diferencias con Inglaterra, in: Guimerá Ravina, A., Peralta Ruiz, V. (coord.), El equilibrio de los Imperios: de Utrech a Trafalgar, Actas de la VIII Reunión Científica de la Fundación Española de Historia Moderna, Madrid 2-4 junio 2004, vol. 2, pp. 761-778.

García González, 2000. Estudio dendroecológico de *Quercus robur* L. en el Norte de Galicia. PhD Thesis University of Santiago de Compostela.

García Mogollón, F.J., 1985. Una obra no documentada de Roque de Balduque en los territorios de la Orden Militar de Santiago: el San Sebastián de Arroyomolinos de Montánchez, in: Comité

español de história del arte, Actas del Simposio “El Arte y las Órdenes Militares”, Cáceres, pp. 65-72.

García Mogollón, F.J., 1993. Concatedral de Cáceres, Santa María la Mayor. Edilesa vol. 16, León.

Gea-Izquierdo, G., Cañellas, I., 2014. Local climate forces instability in long-term productivity of a Mediterranean oak along climatic gradients. Ecosystems 17, 228-241. DOI: 10.1007/s10021-013-9719-3

Gea-Izquierdo, G., Cherubini, P., Cañellas, I., 2011. Tree-rings reflect the impact of climate change on *Quercus ilex* L. along a temperature gradient in Spain over the last 100 years. Forest Ecology and Management 262, 1807-1816. doi: 10.1016/j.foreco.2011.07.025

Gea-Izquierdo, G., Fonti, P., Cherubini, P., Martín-Benito, D., Chaar, H., Cañellas, I., 2012. Xylem hydraulic adjustment and growth response of *Quercus canariensis* Willd. to climatic variability. Tree Physiology 32, 401-413. doi:10.1093/treephys/tps026

Génova, M., 1994. Dendroecologia de los Sistemas Central e Iberico. PhD Thesis, Cuidad Universitaria, Madrid.

Génova, M., Ballesteros-Cánovas, J.A., Díez-Herrero, A., Martínez-Callejo, B., 2011. Historical Floods and Dendrochronological Dating of a Wooden Deck in the Old Mint of Segovia, Spain. Geoarchaeology: An International Journal 26(5), 786–808. DOI:10.1002/gea.20369

Gil Sánchez, L., 1999. La transformación histórica del paisaje: la permanencia y la extinción local del pino piñonero, in: Marín Pageo, F., Domingo Santos, J., Calzado Carretero, A. (eds.), Los montes y su historia: una perspectiva política, económica y social. Collectanea 27, 151-185.

Gil, L. 2008. Pinares y rodenales. La diversidad que no se ve. Discurso Académico de entrada en la Real Academia de Ingeniería. URL: http://www.raing.es/es/publicaciones/discursos-de-ingresos/pinares-y-rodenales-la-diversidad-que-no-se-ve

Gil, L. 2009. Una desmedida devoción por los matorrales (o por qué estabilizar el paisaje humanizado). Conferencia magistral 5º Congreso Forestal Español. Avila. URL: http://www.secforestales.org/buscador/pdf/5CFE02-003.pdf

Gómez Bárcena, M., 2004. Arte y devoción en las obras importadas. Los retablos “flamencos” esculpidos tardogóticos: estado de la cuestión. Anales de la historia del Arte 14, 36-37.

González-González, B.D., Rozas, V., García-González, I., 2013. Earlywood vessels of the submediterranean oak Quercus pyrenaica have greater plasticity and sensitivity than those of the temperate Q. petraea at the Atlantic- Mediterranean boundary. Trees 27(6), 1571-1585.

Gutiérrez, E., 1987. Dendrocronologia de *Fagus silvatica*, *Pinus uncinata* y *Pinus syilvestris* en Cataluña. PhD Thesis University of Barcelona.

Haneca, K., Čufar, K., Beeckman, H., 2009. Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. J Archaeol Sci 36(1), 1–11.

Hernando, A., 1999. Los primeros agricultores de la Península Ibérica. Una

historiografía crítica del Neolítico, Síntesis, Madrid.

Higueras Maldonado, J., 2009. La catedral de Jaén. Su construcción renacentista (s. XVII-XVIII), Universidad de Jaén, Jaén.

Hollstein E., 1980. Mitteleuropäische Eichenchronologie, Verlag Philipp von Zabern, Mainz am Rhein.

Huisman, D.J., Klaassen, R.K.W.M, 2009. Wood, in: Huisman, D.J. (Ed.), Degradation of archaeological remains. Sdu Uitgeverij, Den Haag, pp. 17-32.

Ibáñez, J.J., Clemente Conte, I., Gassin, B., Gibajas, J.F., González Urquijo, J., Márquez, B., Philibert, S., Rodríguez Rodríguez, A., 2008. Harvesting technology during the Neolithic in South-West Europe, in: Longo, L., Nikolaevna Skakun, N. (Eds.), Prehistoric Technology 40 Years Later: Functional Studies and the Russian Legacy, Archaeopress, 183-195.

Izaguirre, M., Valdés, L., Matés, J.M., Pujana, I., 2001. State of the excavation works of the 15th century shipwreck in Urbieta (Gernika, Spain), in: Alvés, F. (Ed.), International Symposium on Archaeology of Medieval an Modern Ships of Iberian-Atlantic Tradition. Hull remains, manuscripts and ethnographic sources: a comparative approach. Proceedings, Trabalhos de Arqueologia 18, Lisboa, 449-454.

Jansma, E., 1995. RemembeRING: the development and application of local and regional tree-ring chronologies of oak for the purposes of archaeological and historical research in the Netherlands. Nederlandse Archeologische Rapporten 19; PhD Thesis Amsterdam University.

Jansma, E., 2013. Towards sustainability in dendroarchaeology: the preservation, linkage and reuse of tree-ring data from the cultural and natural heritage in Europe, in: Bleicher et al. (eds), DENDRO –Chronologie, -Typologie, Ökologie. Freiburg, 169-176.

Jansma, E., Hanraets, E., Vernimmen, T., 2004. Tree-ring research on Dutch and Flemish art and furniture, in: Jansma, E., Bräuning, A., Gärtner, H., Schlesser, G. (Eds.), TRACE - Tree Rings in Archaeology, Climatology and Ecology 2. Proceedings of the Dendrosymposium 2003, Utrecht, The Netherlands. Schriften des Forschungszentrum Jülich, Reinhe Umwelt 44. Forschungszentrum Jülich, Jülich, 139-146.

Jansma, E., Van Lanen, R.J, Brewer, P.W., Kramer, R, 2012. The DCCD: a digital data infrastructure for tree-ring research. Dendrochronologia 30 (4), 249-251.

Kaplan, J.O., Krumhardt, K.M., Zimmerman, N., 2009. The prehistoric and preindustrial deforestation of Europe. Quaternary Sci Rev 28, 3016–3034.

Klein, P., Esteves, L., 2001. Dendrochronological analyses in Portuguese panel paintings, in: Van Schoute, R., Verougstraete, H. (Eds.), La peinture et le laboratoire: procédés, méthodologie, applications, Colloque XIII Bruges 15-17 septembre 1999, Peeters Leuven, pp. 213-220.

Kroesen, J.E.A., 2003. Het middeleeuwse altaarretabel op het Iberisch Schiereiland. Vorm,plaats, boodschap. PhD Thesis Rijksuniversiteit Groningen.

Kuniholm, P.I., 1996. Long tree-ring chronologies for the eastern Mediterranean, in: Demirci, S., Ozer, A.M., Summers, G.D. (Eds.), Archaeometry 94: the Proceedings of the 29th

International Symposium on Archaeometry, Ankara 9-14 May 1994, Tubitak, Turkey, pp. 401-409.

LaRoche, D., 2007. A synthesis of dendrochronological studies, in: Grenier, R., Bernier, M.A., Stevens, W. (Eds.), The Underwater Archaeology of Red Bay: Basque Shipbuilding and Whaling in the 16th Century, Parks Canada Vol. IV, Ottawa, pp. 75-81.

Leuschner, H.H., Delorme, A., 1988. Tree-ring work in Göttingen: Absolute oak chronologies back to 6255 B.C., in: Hackens, T., Munaut, A.V., Till, C. (Eds.), Wood and Archaeology. PACT 22, pp. 123-132.

Linares, J.C., Camarero, J.J., 2012. From pattern to process: linking intrinsic water-use efficiency to drought-induced forest decline. Global Change Biology 18(3), 1000-1015, doi:10.1111/j.1365-2486.2011.02566.x.

Loewen, B., 1998. The Red Bay vessel. An example of a 16th-century Biscayan ship. Itsas memoria. Revista de Estudios Marítimos del País Vasco 2, 193-199.

López Almansa, J.C., 1999. Aprovechamientos forestales y evolución de la vegetación en el macizo del Segura. Cuadernos de la S.E.C.F. 8, 67-74.

Marguerie, D., 2011. Short tree ring series: the study materials of the dendro-anthracologist, in: Badal, E., Carrión, Y., Grau, E., Macías, M., Ntinou, M. (Eds.), The charcoal as cultural and biological heritage, 5th International Meeting of Charcoal Analysis, Saguntum Extra 11, pp. 15-16.

Martens, M.P.J, Peeters, N., 2002. El Renacimiento en el mundo flamenco y las relaciones artísticas con España, in Sociedad Estatal para la Acción Cultural Exterior (ed.), Erasmo en España: la recepción del humanismo en el primer renacimiento español: Escuelas Menores de la Universidad de Salamanca 26 de septiembre de 2002 - 6 de enero de 2003, pp. 158-167.

Martin, C.J.M., 1973. The Spanish Armada Expedition, 1968-70, in: Blackman,D.J. (Ed.), Marine Archaeology: Proceedings of the Twenty-third Symposium of the Colston Research Society Held in the University of Bristol, April 4th to 8th, 1971, Colston Papers 23, Colston Research Society and Butterworths, London. 439-461.

Martínez Ruiz, E. 1999. Los montes en la cultura islámica. El bosque de al-Andalus desde el siglo VIII al XIII, in: Marín Pageo, F., Domingo Santos, J., Calzado Carretero, A. (eds.), Los montes y su historia: una perspectiva política, económica y social. Collectanea 27, 63-87.

Mendoza, F., 2008. La Iglesia del Salvador de Sevilla. Biografía de una Colegiata, Sevilla.

Menéndez Pidal, R. 2000. Historia de España. Espasa Calpe S.A. Vol. Casa de Borbón (s. XVIII).

Michel, M., Gil, L., 2013. La transformación histórica del paisaje forestal en la Comunidad Autónoma de Euskadi. Servicio Central de Publicaciones del Gobierno Vasco, Vitoria-Gasteiz.

Nailing, N., Jones, T., 2014. The Newport medieval ship, Wales, United Kingdom. International J Nautical Archaeol 43(2), 239–278. DOI: 10.1111/1095-9270.12053.

Nayling, N., Susperregi, J., 2014. Iberian dendrochronology and the Newport Medieval Ship. International J Nautical Archaeol 43(2), 279–291. DOI: 10.1111/1095-9270.12052.

Negueruela, I., 2000. Managing the maritime heritage: the National Maritime Archaeological Museum and National Centre for Underwater Research, Cartagena, Spain. International J Nautical Archaeol 29 (2), 179–198.

Negueruela, I., Pinedo, J., Gomez, M., Minano, A., Arellano, I., Barba, S., 1995, Seventh-century BC Phoenician vessel discovered at Playa de la Isla, Mazarron, Spain. International J Nautical Archaeol 24, 189–197.

Nocete, F., Sáez, R., Bayona, M.R., Peramo, A., Inacio, N., Abril, D., 2011. Direct chronometry (14C AMS) of the earliest copper metallurgy in the Guadalquivir Basin (Spain) during the Third millennium BC: first regional database. J Archaeol Sci 38 (12), 3278-3295.

Nuere Matauco, E., 2003. La carpintería de armar española, Munillaleria, Madrid.

Pallaruelo, S., 2008. Navateros, Prames, Zaragoza.

Pérez Antelo, A., 1993. Dendrocronología de *Quercus petraea* (Mattuschka) Liebl., *Quercus pyrenaica* Willd., *Quercus robur* L., sus nothotáxones y *Castanea sativa* Miller en Galicia (España). PhD thesis Autonoma University of Madrid.

Rappaport, E.N., Fernández-Partagás, J.J., 1997. History of the deadliest Atlantic tropical cyclones since the discovery of the New World, in: Diaz, H.F., Pulwarty, r.S. (Eds.), Hurricanes:climate and socioeconomic impacts. Springer-Verlag, Berlin Heidelberg, pp. 93-108.

Richter, K., 1986. Dendrocronología aplicada en la provincia de Teruel.Primer avance 1985/86. Kalathos 5-6, 199-210.

Richter, K., 1988. Dendrochronologische und Dendroklimatologische Untersuchungen an Kiefern (*Pinus sp*.). PhD thesis University of Hamburg.

Richter, K., Rodríguez Trobajo, E., 1985. Dendrocronología en España. Montes 5, 12-20.

Richter, K., Rodríguez Trobajo, E., 1986. El Banco de datos dendrocronológicos para la Península Ibérica. Koiné 1, 66-77.

Richter, K., Eckstein, D., 1986. Estudio dendrocronológico en España. Dendrochronologia 4, 59-71.

Rodríguez Neila, J.F., 1999. El trabajo en las ciudades de la Hispania Romana, in: Rodríguez Neila, J.F., González Román, C., Mangas, J., Orejas, A. (Eds.), El trabajo en la Hispania romana. Silex, Madrid, 9-118.

Rodríguez Trobajo, E., 2000. Dendrometría de maderas altomedievales en la península ibérica: S. Baudelio de Berlanga (Soria), 3º Congreso de Arqueología Peninsular, Porto, vol. IX, 223-238.

Rodríguez Trobajo, E., 2006. Material y cronología de las *rotae* del Museo de Huelva, in: La rueda elevadora de agua de las minas romanas de Riotinto: memoria de intervención, 41-61.

Rodríguez Trobajo, E., 2008. Procedencia y uso de la madera de pino silvestre y pino laricio en edificios históricos de Castilla y Andalucia. Arqueología de la Arquitectura 5, 33-53.

Rodríguez Trobajo, E., 2010a. Datación de madera estructural en la iglesia de Santo Adriano de Tuñón (Asturias). Anejos de Archivo Español de Arqueología LIV, 155-177.

Rodríguez Trobajo, E., 2010b. Datación de dos puntales de madera en la iglesia de San Miguel de Lillo (Asturias). Anejos de Archivo Español de Arqueología LIV, 179-184.

Rodríguez Trobajo, E., 2011. Dendrocronología: una aproximación a la técnica constructiva y datación de retablos, in: Estructuras y Sistemas constructivos en Retablos: Estudios y Conservación, pp. 89-105.

Rodríguez-Trobajo, E., Domínguez-Delmás, M., 2015. Swedish oak, planks and panels: dendroarchaeological investigations on the 16th century *Evangelistas* altarpiece at Seville Cathedral (Spain). J Arch Sci 54, 148–161.

Rovira, S., 2002. Metallurgy and Society in Prehistoric Spain, in: Ottaway, B.S., Wager, E.S. (Eds.), Metals and Society: papers from a session held at the European Association of Archaeologists Sixth annual meeting in Lisbon 2000, Oxford, 5-20.

Rozas, V., 1999. Estructura, dinámica y tendencias sucesionales en un bosque de roble y haya de la Cornisa Cantábrica. PhD Thesis Universidad de Oviedo.

Rozas, V., Camarero, J.J., Sangüesa-Barreda, G., Souto, M., García-González, I., 2015. Summer drought and ENSO-related cloudiness distinctly drive Fagus sylvatica growth near the species rear-edge in northern Spain. Agricultural and Forest Meteorology 201, 153-164.

Rubiales, J.M., García-Amorena, I., Génova, M., Gómez Manzaneque, F., Morla, C., 2007. The Holocene history of highland pine forests in a submediterranean mountain: the case of Gredos mountain range (Iberian Central range, Spain). Quaternary Sci Rev 26, 1759-1770.

Rubiales, J.M., Ezquerra, J., Muñoz Sobrino, C., Génova, M.M., Gil, L., Ramil-Rego,P., Gómez Manzaneque, F., 2012. Holocene distribution of woody taxa at the westernmost limit of the Circumboreal/Mediterranean boundary: Evidence from wood remains. Quaternary Sci Rev 33, 74-86.

Ruiz, D., Fernández, J., 1986. El yacimiento metalúrgico de época tartésica de San Bartolomé de Almonte, Huelva Arqueológica VIII, Diputación de Huelva.

Ruiz de la Torre, J., 2006. Flora Mayor. Organismo Autónomo de Parques, Dirección General para la Biodiversidad, Madrid.

Sánchez Albornoz, C., 1956. España, un enigma histórico, Vol. I, 10ª ed., 1985, EDHASA, Barcelona.

Santullano, G., 1978. Historia de la minería asturiana. Ayalga, D.L., Salinas.

Sass-Klaassen, U., Hanraets, E., 2006. Woodlands of the past: The excavation of wetland woods at Zwolle-Stadshagen (the Netherlands): Growth pattern and population dynamics of oak and ash. Geologie en Mijnbouw 85 (1), 61-71.

Sass-Klaassen, U., Vernimmen, T., Baittinger, C., 2008. Dendrochronological dating and provenancing of timber used as foundation piles under historic buildings in The Netherlands. International Biodeterioration & Biodegradation 61, 96–105.

Schweingruber, F.H., 1996. Tree rings and environment dendroecology, Paul Haupt Verlag, Berne.

Schulten, A., 1952. Estrabón, Geografía de Iberia. Fontes Hispaniae Antiquae VI. Universidad de Barcelona, Barcelona.

Serre-Bachet, F., Guiot, J., Tessier, L., 1992. Dendroclimatic evidence from southwestern Europe and northwestern Africa, in: Bradley, R.S., Jones, P.D. (eds.), Climate since A.D. 1500. Routledge Press, London, pp. 349-365.

Soberón Rodríguez, M., Pujol Hamelink, M., Llergo López, Y., Riera Mora, S., Juliá Brugues, R., Domínguez Delmás, M., 2012. El Barceloneta I. Una embarcación medieval a tingladillo en Barcelona. ITSAS Memoria 7, 411-422.

Spurk, M., Friedrich, M., Hofmann, J., Remmele, S., Frenzel, B., Leuschner, H.H., Kromer, B. 1998. Revisions and extension of the Hohenheim oak and pine chronologies: New evidence about the timing of the Younger Dryas/Preboreal transition. Radiocarbon 40 (3), 1107-1116.

Susperregi, J., 2007. Oak dendrochronology at the Basque Country, in: Haneca, K., Verheyden, A., Beekman, H., Gärtner, H., Helle, G., Schleser, G. (Eds.), TRACE - Tree Rings in Archaeology, Climatology and Ecology, Vol. 5: Proceedings of the DENDROSYMPOSIUM 2006, April 20th – 22nd 2006, Tervuren, Belgium. Schriften des Forschungszentrums Jülich, Reihe Umwelt Vol. 74, p. 35 - 42.

Tardif, J., Camarero, J.J., Ribas, M., Gutirrez´, E., 2003. Spatiotemporal variability in tree growth in the central Pyrenees: climatic and site influences. Ecological Monographs 73, 241–257.

Tarrús, J., 2008. La Draga (Banyoles, Catalonia), an Early Neolithic Lakeside Village in Mediterranean Europe. Catalan Historical Review 1, 17-33.

Tegel, W., Elburg, R., Hakelberg, D., Stäuble, H., Büntgen, U., 2012. Early Neolithic Water Wells Reveal the World's Oldest Wood Architecture. PLoSONE 7(12), e51374. DOI: 10.1371/journal.pone.0051374

Thomas, W., Stols, E., 2000. La integración de Flandes en la Monarquía Hispánica, in: Thomas, W., Verdonk, R. (eds.), Encuentros en Flandes, Relaciones e intercambios hispanoflamencos a inicios de la Edad Moderna, Leuven, 39.

Tresaco Calvo, J., 1968. Flotaciones de traviesas por ríos de Andalucía. Montes 141, 261-267.

Utrero Agudo, M. A., 2006. Iglesias tardoantiguas y altomedievales en la península ibérica: análisis arqueológico y sisemas de abovedamiento. Anejos del Archivo español de arqueología XL, Madrid.

Waldner, P.O., Schweingruber, F.H., 1996. Temperature influence on decennial tree-ring width and density fluctuations of subalpine and boreal conifers in western Europe since 1850 A.D.. Dendrochronologia 14, 127-151.

Wazny, T., 1990. Aufbau und Anwendung der Dendrochronologie für Eichenholz in Polen, PhD Thesis University of Hamburg.

Wazny, T., 2005. The origin, assortments and transport of Baltic timber: historic-dendrochronological evidence, in: Van de Velde, C., Beeckman, H., Van Acker, J., Verhaeghe, F. (Eds.), Constructing Wooden Images: proceedings of the symposium on the organization of labour and working practices of late gothic carved altarpieces in the Low Countries, Brussels 25-26 October 2002. VUB Press, Brussels, 115-126.

Williams, M., 2006. Deforesting the Earth. From Prehistory to Global Crisis: An abridgement, University Chicago Press, Chicago.

Zunde, M., 1999. Timber export from old Riga and its impact on dendrochronological dating in Europe. Dendrochronologia 16-17, 119-130.

Web references

DCCD repository, URL: http://dendro.dans.knaw.nl

Galán, P., Gamarra, R., García-Viñas, J.I., Alvarez, S. 2013. Sobre árboles ibéricos. URL: http://www.arbolesibericos.es

ICNF 2013. IFN6. Areas dos usos do solo e das especies florestais de Portugal continental. Resultados preliminares. Instituto de Conservaçao de Natureza e das Florestas. Lisboa. URL: http://www.icnf.pt/portal/florestas/ifn/resource/ficheiros/ifn/ifn6-res-prelimv1-1

MAGRAMA. 2013. III Inventario Forestal Nacional (IFN3). URL http://www.magrama.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/tablas_resumen_IFN3.aspx

Table S1. Absolutely-dated object chronologies currently existing in the Iberian Peninsula derived from historical wood (data presented in Fig. 3). References are included in the text and the reference list.

Nr	Object name	Object	Location	Province	Begin date	End Date	Species	References
1	House	Building	Marquinez	Alava	1520	1743	Quercus subg. quercus	Nayling and Susperregi (2014)
2	Venta Quintana	Building	Quintana	Alava	1494	1819	Quercus subg. quercus	Nayling and Susperregi (2014)
3	Santa Cruz Monastery	Building	Vitoria	Alava	1651	1757	Quercus subg. quercus	Nayling and Susperregi (2014)
4	Campezo Carpentry	Building, Furniture	Campezo	Alava	1277	1814	Quercus subg. quercus	Nayling and Susperregi (2014)
5	SoranEtxea	Building	Leintz-Gatzaga	Gipuzkoa	1487	1765	Quercus subg. quercus	Nayling and Susperregi (2014)
6	Iturrioz Street	Building	Arrasate	Gipuzkoa	1526	1597	Quercus subg. quercus	Nayling and Susperregi (2014)
7	Franciscanos Monastery	Building	Arrasate	Gipuzkoa	1528	1618	Quercus subg. quercus	Nayling and Susperregi (2014)
8	Aranzazu Sanctuary	Building	Oñati	Gipuzkoa	1697	1843	Quercus subg. quercus	Nayling and Susperregi (2014)
9	Iparragirre Street, Nº 32	Building	Urretxu	Gipuzkoa	1569	1662	Quercus subg. quercus	Nayling and Susperregi (2014)
10	Iparragirre Street, Nº 16	Building	Urretxu	Gipuzkoa	1445	1557	Quercus subg. quercus	Nayling and Susperregi (2014)
11	Iparre Farmhouse	Building	Zaldibia	Gipuzkoa	1496	1639	Quercus subg. quercus	Nayling and Susperregi (2014)
12	Oriar House	Building	Legorreta	Gipuzkoa	1486	1630	Quercus subg. quercus	Nayling and Susperregi (2014)
13	Etxehaundi Farmhouse	Building	Lizartza	Gipuzkoa	1493	1599	Quercus subg. quercus	Nayling and Susperregi (2014)
14	Farmhouse	Building	Andoain	Gipuzkoa	1515	1675	Quercus subg. quercus	Nayling and Susperregi (2014)
15	Agerre-Bekoa Farmhouse	Building	Zarautz	Gipuzkoa	1495	1620	Quercus subg. quercus	Nayling and Susperregi (2014)
16	Bustiñaga House	Building	Mutriku	Gipuzkoa	1552	1709	Quercus subg. quercus	Nayling and Susperregi (2014)
17	Tiendas Street	Building	Hondarribia	Gipuzkoa	1723	1797	Quercus subg. quercus	Nayling and Susperregi (2014)
18	Tolate House	Building	Ituren	Navarra	1511	1706	Quercus subg. quercus	Nayling and Susperregi (2014)
19	Batxillerenea House	Building	Doneztebe	Navarra	1548	1621	Quercus subg. quercus	Nayling and Susperregi (2014)
20	San Pedro Eliza	Building	Doneztebe	Navarra	1482	1584	Quercus subg. quercus	Nayling and Susperregi (2014)
21	Petritea House	Building	Doneztebe	Navarra	1627	1798	Quercus subg. quercus	Nayling and Susperregi (2014)
22	Petritea	Building	Doneztebe	Navarra	1335	1438	Quercus subg. quercus	Nayling and Susperregi (2014)
23	Etxegoien House	Building	Sunbilla	Navarra	1518	1667	Quercus subg. quercus	Nayling and Susperregi (2014)
24	Xabattenea House	Building	Arraiz	Navarra	1385	1681	Quercus subg. quercus	Nayling and Susperregi (2014)
25	Arretxea House	Building	Oronoz	Navarra	1477	1581	Quercus subg. quercus	Nayling and Susperregi (2014)
26	Arretxea	Building	Oronoz	Navarra	1299	1444	Quercus subg. quercus	Nayling and Susperregi (2014)
27	Donamaria Church	Building	Donamaria	Navarra	1557	1649	Quercus subg. quercus	Nayling and Susperregi (2014)
28	Maitxenea House	Building	Elgorriaga	Navarra	1520	1600	Quercus subg. quercus	Nayling and Susperregi (2014)
29	Martindonea House	Building	Donamaria	Navarra	1517	1739	Quercus subg. quercus	Nayling and Susperregi (2014)
30	Gorritxenea House	Building	Zozaia	Navarra	1551	1638	Quercus subg. quercus	Nayling and Susperregi (2014)
31	Etxeberri House	Building	Burutain	Navarra	1386	1561	Quercus subg. quercus	Nayling and Susperregi (2014)
32	Lili Mansion	Building	Zestoa	Gipuzkoa	1339	1468	Quercus subg. quercus	Nayling and Susperregi (2014)
33	Sagastiberri Farmhouse	Building	Berastegi	Gipuzkoa	1284	1464	Quercus subg. quercus	Nayling and Susperregi (2014)

34	JauregiZahar Mansion	Building	Arraioz	Navarra	1307	1439	Quercus subg. quercus	Nayling and Susperregi (2014)
35	Gortaria	Building	Oronoz	Navarra	1335	1447	Quercus subg. quercus	Nayling and Susperregi (2014)
36	San Pedro Church	Building	Bergara	Gipuzkoa	1341	1591	Quercus subg. quercus	Nayling and Susperregi (2014)
37	Zupide Farmhouse	Building	Bergara	Gipuzkoa	1336	1489	Quercus subg. quercus	Nayling and Susperregi (2014)
38	Cuarto Real de Santo Domingo	Building	Granada	Granada	1088	1281	Pine (n.s.)	Rodríguez Trobajo (2008)
39	Iglesia de Caltojar	Building	Caltojar	Soria	1370	1449	Pinus sylvestris/P. Pinaster	Rodríguez Trobajo (2008)
40	Lower Cloister Santo Domingo de Silos Abbey	Building	Silos	Burgos	1239	1390	Pinus sylvestris	Rodríguez Trobajo (2008)
41	Hospital de San Sebastián	Building	Cordoba	Cordoba	1237	1524	Pinus sylvestris/nigra	Richter (1988), PhD thesis
42	Alhambra-Generalife (not specified)	Building	Granada	Granada	1288	1675	Pinus sylvestris/nigra	Richter (1988), PhD thesis and Rodríguez Trobajo (2008)
43	Alhambra, Salón de Embajadores	Building	Granada	Granada	1271	1350	Pinus halepensis	Rodríguez Trobajo (2008)
44	Alhambra, armaduras Palacio del Partal	Building	Granada	Granada	1264	1519	Pinus nigra	Rodríguez Trobajo (2008)
45	Alhambra, Torre de las Damas	Building	Granada	Granada	1284	1532	Pine (not specified)	Rodríguez Trobajo (2008)
46	Horno de Oro	Building	Granada	Granada	1275	1537	Pinus sylvestris/nigra	Richter (1988), PhD thesis
47	El Maristán	Building	Granada	Granada	1504	1622	Pinus sylvestris/ngra	Richter (1988), PhD thesis
48	Convento del Zafra	Building	Granada	Granada	1217	1634	Pinus sylvestris/nigra	Richter (1988), PhD thesis
49	Church	Building	Güéjar Sierra	Granada	1396	1628	Pinus sylvestris/nigra	Richter (1988), PhD thesis
50	Sta. Maria church	Building	Alarcón	Madrid	1301	1602	Pinus sylvestris/nigra	Richter (1988), PhD thesis
51	Witte house	Building	Alarcón	Madrid	1511	1622	Pinus sylvestris/nigra	Richter (1988), PhD thesis
52	Town hall	Building	Alarcón	Madrid	1325	1534	Pinus sylvestris/nigra	Richter (1988), PhD thesis
53	Sto. Domingo church	Building	Alarcón	Madrid	1269	1579	Pinus sylvestris/nigra and P. Pinaster	Richter (1988), PhD thesis
54	El Escorian monastery	Building	San Lorenzo de El Escorial	Madrid	1531	1679	Pinus sylvestris/nigra	Richter (1988), PhD thesis
55	Masía Garita-Taberna	Building	Mora de Rubielos	Teruel	1565	1659	Pinus sylvestris/nigra	Richter (1986)
56	Castillo de Mora I	Building	Mora de Rubielos	Teruel	1539	1837	Pinus sylvestris/nigra	Richter (1986)
57	Castillo de Mora II	Building	Mora de Rubielos	Teruel	1090	1427	Pinus sylvestris/nigra	Richter (1986)
58	Masía Batiosa-Alta	Building	Mora de Rubielos	Teruel	1375	1842	Pinus sylvestris/nigra	Richter (1986)
59	Colegiata (Church)	Building	Mora de Rubielos	Teruel	1345	1690	Pinus sylvestris/nigra	Richter (1986)
60	Casa de la Comunidad	Building	Teruel	Teruel	1382	1837	Pinus sylvestris/nigra	Richter (1986)
61	Dean's house	Building	Teruel	Teruel	1375	1527	Pinus pinaster	Richter (1986)
62	Cathedral tower	Building	Teruel	Teruel	1127	1246	Pinus sylvestris/nigra	Richter (1986)
63	Geldo's house	Building	Mora de Rubielos	Teruel	1068	1773	Pinus sylvestris/nigra	Richter (1986)

Table S2. List of chronologies spanning before 1950 as reported in literature for the Iberian Peninsula (data used in Fig. 6). Ref. nr: references are listed below, after the table.

Ref. nr	Latitude	Longitude (-W)	Site	Species	Time span begin	Time span end
1	38,133	-2,683	n8w	Pinus nigra	1817	1994
1	40,117	-1,083	n2	Pinus nigra	1585	1993
1	40,283	-0,533	n5	Pinus nigra	1817	1999
1	40,333	-1,917	n9	Pinus nigra	1817	1995
1	40,583	-1,783	n4	Pinus nigra	1817	1999
1	40,667	-0,050	n7	Pinus nigra	1817	1999
1	42,533	0,150	n1	Pinus nigra	1819	1999
1	37,250	-2,500	n6	Pinus nigra	1817	1999
1	37,800	-2,950	n3	Pinus nigra	1331	2002
1	40,233	-0,333	s6	Pinus sylvestris	1817	2000
1	40,467	-1,567	s9	Pinus sylvestris	1817	1999
1	41,333	1,017	s7	Pinus sylvestris	1817	1999
1	41,967	-2,817	s11	Pinus sylvestris	1817	1999
1	42,317	-0,433	s1w	Pinus sylvestris	1817	1999
1	42,467	0,483	s3	Pinus sylvestris	1817	1999
1	42,717	-0,483	s12	Pinus sylvestris	1817	1993
1	43,067	-5,250	s5	Pinus sylvestris	1817	2002
1	40,800	0,350	s2w	Pinus sylvestris	1817	2000
1	42,550	0,900	s8	Pinus sylvestris	1817	1995
1	42,600	1,100	s10	Pinus sylvestris	1817	1999
1	42,800	-0,367	s4	Pinus sylvestris	1817	1993
1	42,000	-2,750	u17	Pinus uncinata	1817	1999
1	42,383	2,133	u11	Pinus uncinata	1817	2001
1	42,533	0,917	u9	Pinus uncinata	1817	1997
1	42,567	0,950	u5	Pinus uncinata	1817	1995
1	42,583	1,000	u14	Pinus uncinata	1817	1996
1	42,633	0,750	u4	Pinus uncinata	1817	1994
1	42,633	-0,067	u10	Pinus uncinata	1817	1998
1	42,683	0,083	u7	Pinus uncinata	1817	1993
1	42,717	0,183	u3	Pinus uncinata	1817	1996
1	40,500	-0,417	u15	Pinus uncinata	1817	1996
1	42,400	2,283	u13	Pinus uncinata	1817	1999
1	42,450	1,617	u12	Pinus uncinata	1817	1997
1	42,550	1,067	u6	Pinus uncinata	1817	1996
1	42,600	0,983	u2	Pinus uncinata	1817	1995
1	42,600	1,050	u16	Pinus uncinata	1817	1995
1	42,700	1,033	u1	Pinus uncinata	1817	1996
1	42,950	-0,783	u8	Pinus uncinata	1817	1999
2	37,800	-2,950	pnCaz	Pinus nigra	1800	2002
2	42,000	-2,817	psUrb	Pinus sylvestris	1800	1999
2	43,050	-5,250	psLil	Pinus sylvestris	1800	2002
2	41,967	-2,750	puUrb	Pinus uncinata	1800	1999
2	42,233	1,700	puPed	Pinus uncinata	1800	2003
3	37,800	-2,950	pnCaz	Pinus nigra	1125	2002
3	41,970	-2,820	psUrb	Pinus sylvestris	1612	1999
3	43,050	-5,250	psLil	Pinus sylvestris	1511	2002
3	42,000	-2,750	puUrb	Pinus uncinata	1752	1999
3	42,230	1,700	puPed	Pinus uncinata	1269	2002
4	42,383	2,133	OU	Pinus uncinata	1825	2000
4	42,433	1,533	RU	Pinus uncinata	1835	2000
4	42,467	0,817	DU	Pinus uncinata	1865	2000
4	42,517	0,750	PU	Pinus uncinata	1630	2000

4	42,517	1,350	LU	Pinus uncinata	1760	2000
4	42,533	0,883	SU	Pinus uncinata	1850	2000
4	42,400	2,317	BU	Pinus uncinata	1825	2000
4	42,450	1,733	GU	Pinus uncinata	1775	2000
4	42,550	0,933	EU	Pinus uncinata	1820	2000
4	42,550	1,383	FU	Pinus uncinata	1805	2000
4	42,550	1,417	CU	Pinus uncinata	1820	2000
5	40,649	-4,202	ESP	Pinus sylvestris	1811	2005
5	41,846	-2,930	AMO	Pinus sylvestris	1949	2005
5	41,884	-3,359	ARA	Pinus sylvestris	1846	2005
5	42,077	-2,505	MOL	Pinus sylvestris	1945	2005
5	42,913	-3,358	MIN	Pinus sylvestris	1867	2005
5	42,973	-3,303	OÙA	Pinus sylvestris	1932	2005
6	41,835	-1,277	P16201	Pinus pinaster	1947	2005
6	41,568	-2,598	P42002	Pinus pinaster	1916	2005
6	41,319	-1,355	P44002	Pinus pinaster	1844	2005
6	41,346	-1,365	P44005	Pinus pinaster	1847	2005
6	41,562	-2,921	P42201	Pinus pinaster	1946	2005
6	41,816	-1,260	P16008	Pinus pinaster	1947	2005
6	41,838	-1,270	P16106	Pinus pinaster	1879	2005
6	41,841	-1,298	P16208	Pinus pinaster	1886	2005
7	42,533	0,800	Erill la Vall	Pinus uncinata	1922	1990
7	42,450	1,683	Lles de Cerdanya	Pinus uncinata	1850	1990
8	42,033	-2,700	QUINT	Pinus sylvestris	1842	1977
8	40,800	-4,033	NAVA	Pinus sylvestris	1663	1977
8	36,667	-5,083	RON TA	Abies pinsapo	1728	1982
8	42,667	-0,117	ORDES	Pinus uncinata	1609	1977
8	42,683	-0,567	JACA	Pinus uncinata	1808	1977
8	41,450	-2,383	LLIPO	Pinus uncinata	1839	1977
8	42,600	-2,050	PERCH	Pinus uncinata	1769	1977
8	40,383	-0,667	ALCA	Pinus sp.	1820	1977
9	42,633	1,100	GER	Pinus uncinata	924	2005
9	42,683	0,100	SOB	Pinus uncinata	1499	2005
9	42,600	-1,800	1 Pamplona	Pinus sylvestris	1933	2005
9	42,400	-0,700	2 Turbon Ordessa	Pinus uncinata	1609	1977
9	42,440	-0,470	4 Viella Monte Vilach	Pinus sylvestris	1752	1985
9	42,590	-0,450	5 Arette Col St. Martin	Abies alba	1743	1977
9	42,580	-0,440	7 Pic d’ Anie	Pinus uncinata	1659	1977
9	42,480	-0,440	9 Val de Hecho	Pinus uncinata	1829	2005
9	42,460	-0,370	10 Pic Aubas	Abies alba	1784	1977
9	42,410	-0,340	12 Las Blancas Jaca	Pinus uncinata	1808	1977
9	42,300	-0,130	14 Sant Maurici	Pinus uncinata	1811	1996
9	42,420	0,060	15 Sobrestivo	Pinus uncinata	1499	2005
9	42,510	0,090	17 Lac d’Aumer	Pinus uncinata	1324	2005
9	42,480	0,420	19 Hecho Puerto de Acher	Pinus sylvestris	1605	1985
9	42,500	0,470	20 Anso Zuriza	Pinus sylvestris	1696	1985
9	42,380	0,590	21 Gerber	Pinus uncinata	924	2005
9	42,320	1,250	35 Port de Cabus	Pinus uncinata	1377	2005
9	42,320	1,300	37 Bosque de Rabassa	Pinus uncinata	1793	1977
9	42,360	2,030	39 Roc de Perches Blancas	Pinus uncinata	1769	1977
9	42,360	2,040	41 Formi-gueres	Abies alba	1742	1977
9	42,280	2,070	43 Eyne	Pinus uncinata	1736	2004
9	42,270	2,230	45 Llipodere	Pinus uncinata	1839	1977
9	42,280	2,240	47 Miraules Refuge	Abies alba	1831	1977
9	42,290	2,250	49 Pic de sept Hommes	Pinus uncinata	1798	2005

10	41,855	-2,916		Pinus sylvestris	1837	2011
11	42,750	-0,867	Paco Ezpela-high PE	Abies alba	1916	1999
11	42,750	-0,867	Paco Ezpela-low PZ	Abies alba	1917	1999
11	42,767	-0,867	Lopetón LO	Abies alba	1916	1999
11	42,883	-0,800	Gamueta GA	Abies alba	1883	2000
11	42,833	-0,700	Selva de Oza-high SZ	Abies alba	1925	1999
11	42,833	-0,717	Selva de Oza-low SO	Abies alba	1901	1999
11	42,517	-0,683	S. Juan de la Peña JP	Abies alba	1931	1999
11	42,700	-0,633	Paco Mayor-high PM1	Abies alba	1925	1999
11	42,700	-0,633	Paco Mayor-low PM2	Abies alba	1935	1999
11	42,767	-0,633	Puente Corralones PC	Abies alba	1936	1999
11	42,700	-0,550	Lierde LI	Abies alba	1934	1999
11	42,517	-0,533	Peña Oroel-high OO	Abies alba	1931	1999
11	42,517	-0,533	Peña Oroel-low PO	Abies alba	1933	1999
11	42,717	-0,533	Los Abetazos AB	Abies alba	1931	2000
11	42,650	-0,517	Castiello de Jaca CA	Abies alba	1889	2000
11	42,750	-0,517	Izquierda del Aragón IA	Abies alba	1910	2000
11	42,683	-0,500	Paco de Villanúa-high VN	Abies alba	1929	2000
11	42,683	-0,500	Paco de Villanúa-low VI	Abies alba	1926	2000
11	42,650	-0,300	Paco Asieso AS	Abies alba	1939	2000
11	42,733	-0,300	Panticosa PA	Abies alba	1924	2000
11	42,650	-0,217	Yésero YE	Abies alba	1930	2000
11	42,300	-0,200	Guara GU	Abies alba	1931	1999
11	42,633	-0,100	Diazas DI	Abies alba	1931	2000
11	42,567	0,000	Orús OR	Abies alba	1906	2000
11	42,650	0,167	Montinier MO	Abies alba	1912	1999
11	42,650	0,167	Azirón AZ	Abies alba	1933	2000
11	42,450	0,333	Peña Montañesa PN	Abies alba	1936	2000
11	42,467	0,000	Collubert CO	Abies alba	1930	2000
11	42,567	0,333	Selva Negra SN	Abies alba	1934	2000
11	42,550	0,833	Collado de Sahún SA	Abies alba	1930	2000
11	42,633	0,833	Ballibierna BA	Abies alba	1923	2000
11	42,733	-0,883	Fago FA	Abies alba	1925	2000
12	42,631	-0,094	DI	Abies alba	1900	1999
12	42,657	-0,275	AS	Abies alba	1900	1999
13	37,740	-7,560	several	Pinus pinea	1917	2002
13	38,140	-8,681	several	Pinus pinea	1896	2003
13	38,633	-7,250		Quercus ilex	1876	2001
14	38,100	-0,667		Pinus halepensis	1936	2000
14	38,100	-0,667		Pinus pinea	1936	2000
14	38,050	-0,633	GUA	Pinus halepensis	1919	2000
14	38,100	-0,667	MAI	Pinus halepensis	1919	2000
15	42,878	-5,851	LU	Juniperus thurifera	1876	2002
15	38,799	-2,526	VI	Juniperus thurifera	1922	2006
15	40,129	-1,974	BU	Juniperus thurifera	1920	2006
15	40,157	-1,431	VE	Juniperus thurifera	1840	2006
15	41,129	-2,189	CH	Juniperus thurifera	1920	2006
15	41,168	-3,638	SI	Juniperus thurifera	1894	2006
15	41,467	-0,275	RE	Juniperus thurifera	1945	2005
15	41,629	-1,938	CI	Juniperus thurifera	1911	2006
15	41,776	-0,541	SA	Juniperus thurifera	1924	2006
15	41,794	-2,845	CA	Juniperus thurifera	1850	2004
15	42,047	-3,445	AR	Juniperus thurifera	1925	2007
15	42,842	-4,860	LA	Juniperus thurifera	1902	2006
15	40,320	-0,734	OL	Juniperus thurifera	1909	2005

16	37,810	-2,958	CBS	Pinus nigra	1331	2010
16	37,894	-2,914	PMB	Pinus nigra	1544	2009
16	37,922	-2,906	LIN	Pinus nigra	1840	2009
16	37,929	-2,805	NAV	Pinus nigra	1698	2009
17	42,233	1,700	Pedraforca	Pinus uncinata	1900	2006
18	42,633	1,067	Mata de València (MA)	Pinus uncinata	1668	1997
18	42,550	1,050	Estany de Lladres (LA)	Pinus uncinata	1390	2009
18	42,700	1,033	Airoto (AI)	Pinus uncinata	1651	1996
18	42,583	1,033	Tessó de Son (TS)	Pinus uncinata	1537	1995
18	42,550	1,033	Estany Negre (NE)	Pinus uncinata	1393	2009
18	42,617	0,983	Estany Gerber (GE)	Pinus uncinata	1270	2010
18	42,583	0,983	Estany d'Amitges (AM)	Pinus uncinata	1592	2009
18	42,583	0,983	Mirador (MI)	Pinus uncinata	1390	2009
18	42,583	0,983	Ratera (RA)	Pinus uncinata	1818	2009
18	42,583	0,983	Sant Maurici (SM)	Pinus uncinata	1811	1996
18	42,567	0,983	Monestero (MO)	Pinus uncinata	1481	2009
18	42,567	0,933	Corticelles (CO)	Pinus uncinata	1509	1995
18	42,533	0,917	Barranc de Llacs (LL)	Pinus uncinata	1338	1997
18	42,617	0,733	Conangles (CG)	Pinus uncinata	1510	1994
18	42,617	0,717	Vall de Mulleres (VM)	Pinus uncinata	1476	1994
18	42,700	0,183	Bielsa (BI)	Pinus uncinata	1707	1996
18	42,667	0,100	Sobrestivo (SB)	Pinus uncinata	1512	2009
18	42,617	0,100	Foratarruego (FR)	Pinus uncinata	1438	1947
18	42,633	-0,050	Senda Cazadores (SC)	Pinus uncinata	1421	2010
18	42,633	-0,050	Ordesa-Cara Norte (ON)	Pinus uncinata	1531	1998
18	42,633	-0,067	Mirador del Rey (MR)	Pinus uncinata	1795	1998
18	42,450	1,583	Estanys de la Pera (EP)	Pinus uncinata	1586	1997
18	42,617	-0,083	Las Cutas (CU)	Pinus uncinata	1871	1997
18	42,283	-0,250	Guara (GU)	Pinus uncinata	1800	2011
18	42,817	-0,283	Respomuso (RE)	Pinus uncinata	1572	2010
18	42,800	-0,517	Pic d'Arnousse (PA)	Pinus uncinata	1755	1994
18	40,383	-0,633	Valdelinares-Teruel (TE)	Pinus uncinata	1730	2008
18	42,950	-0,767	Larra-La Contienda (CN)	Pinus uncinata	1364	2010
18	42,000	-2,733	Castillo de Vinuesa (VI)	Pinus uncinata	1561	2010
19	43,571	-7,724	Arganzo (A Coruña)	Quercus robur	1906	1997
19	43,580	-7,724	Ribeira do Bispo. Ourol (Lugo)	Quercus robur	1871	1997
19	43,453	-7,628	Río Boó. Muras (Lugo)	Quercus robur	1867	1998
19	43,597	-7,650	Bravos (Lugo)	Quercus robur	1927	1998
19	43,403	-8,074	Fraga de Caaveiro (A Coruña)	Quercus robur	1912	1996
19	43,455	-7,838	O Cabalar. As Pontes (A Coruña)	Quercus robur	1775	1997
19	43,213	-7,239	Carballal das Carrierias. Meira (Lugo)	Quercus robur	1916	1995
19	43,569	-7,588	Castrosol (Lugo)	Quercus robur	1904	1995
19	43,375	-7,988	Cerqueiros. Monfero (A Coruña)	Quercus robur	1882	1998
19	43,403	-8,061	A Capela-Fraga de Caaveiro (A Coruña)	Quercus robur	1875	1996
19	43,523	-7,503	Frexulfe. Valadouro (Lugo)	Quercus robur	1902	1996
19	43,454	-7,702	Castelo de Goía. Muras (Lugo)	Quercus robur	1894	1994
19	43,463	-7,751	Prado do Inferno. Muras (Lugo)-Solana	Quercus robur	1894	1995
19	43,463	-7,751	Prado do Inferno. Muras (Lugo)-Umbría	Quercus robur	1891	1995
19	43,523	-7,515	Fraga das Lerias. O Valadouro (Lugo)	Quercus robur	1905	1995
19	43,413	-7,320	Lindín. Mondoñedo (Lugo)	Quercus robur	1892	1995
19	43,240	-7,239	Murias. Meira (Lugo)	Quercus robur	1940	1996
19	43,478	-7,529	O Pereiro. Alfoz (Lugo)	Quercus robur	1898	1995
19	43,499	-7,751	Carballás (A Coruña)	Quercus robur	1857	1997
19	43,517	-7,750	Tras da Serra. Muras (Lugo)	Quercus robur	1879	1998
19	43,442	-7,493	Fraga das Vigas. Mondoñedo (Lugo)	Quercus robur	1895	1995

20	40,567	-1,817	AT	Juniperus sabina	1896	2009
20	41,717	-1,767	MO	Juniperus sabina	1863	2010
20	40,100	-1,017	JA	Juniperus sabina	1887	2010
20	40,567	-1,817	AT	Pinus sylvestris	1918	2009
20	41,717	-1,767	MO	Pinus sylvestris	1934	2010
20	40,100	-1,017	JA	Pinus sylvestris	1766	2010
21	40,417	-4,167	MAD	Quercus ilex	1831	2005
21	40,617	-6,667	SAL	Quercus ilex	1864	2004
21	41,817	-5,917	ZAM	Quercus ilex	1894	2008
22	36,520	-5,520	ALClow	Quercus canariensis	1870	2008
22	36,510	-5,590	ALCmid	Quercus canariensis	1906	2008
22	36,520	-5,600	ALChigh	Quercus canariensis	1910	2008
23	40,617	-6,667	SAL001	Quercus ilex	1864	2004
24	40,860	-4,020	0	Quercus pyrenaica	1864	2011
24	40,860	-4,010	1	Pinus sylvestris	1870	2011
24	40,900	-4,020	2	Pinus sylvestris	1915	2011
24	40,840	-4,060	3	Pinus sylvestris	1785	2011
25	43,065	-5,257	Lillo	Pinus sylvestris	1546	1995
26	40,015	-1,945	torreton	Pinus nigra	1485	1988
26	40,105	-1,944	boqueron	Pinus nigra	1688	1988
26	40,196	-1,943	tierramuerta	Pinus nigra	1615	1988
26	40,271	-5,117	andrinal	Pinus nigra	1687	1989
26	40,466	-1,938	tajo	Pinus nigra	1610	1988
26	40,645	-4,183	riscopol	Pinus nigra	1325	1988
26	40,275	-4,882	cercelas	Pinus sp.	1754	1991
26	40,270	-4,760	penahorcada	Pinus sp.	1667	1988
26	40,734	-3,947	pedriza	Pinus sylvestris	1527	1988
26	40,736	-4,066	sietepicos	Pinus sylvestris	1715	1988
27	41,583	-1,767	Dehesa Espinada	Pinus nigra	1653	1998
28	40,430	-4,900		Pinus nigra	1806	2006
29	42,700	-0,800	PUVIEI	Pinus uncinata	1836	1983
29	42,700	-0,800	PUVIEM	Pinus uncinata	1842	1983
29	42,700	-0,800	PUVIES	Pinus uncinata	1548	1984
30	43,400	-8,050		Quercus robur	1925	1996
31	42,894	-3,935	Monte HIjedo	Quercus pyrenaica	1927	2007
31	42,903	-3,952	Monte Hijedo	Quercus petraea	1904	2007
32	42,619	-8,784		Pinus pinea	1876	2000
32	42,619	-8,784		Quercus pyrenaica	1901	2000
32	42,619	-8,784		Quercus robur	1896	2000
33	42,633	-0,550	Castiello	Abies alba	1900	1999
33	42,733	-0,750	Echo	Abies alba	1900	1999
33	42,700	-0,667	Aragu/e⌶s	Abies alba	1900	1999
33	42,750	-0,833	Anso⌶	Abies alba	1900	1999
33	42,750	-0,517	Canfranc	Abies alba	1900	1999
33	42,717	-0,550	AB	Abies alba	1900	2000
33	42,767	-0,867	LO	Abies alba	1900	2000
33	42,883	-0,800	GA	Abies alba	1900	2000
33	42,700	-0,633	PM	Abies alba	1900	2000
33	42,700	-0,550	LI	Abies alba	1900	2000
33	42,750	-0,867	PE	Abies alba	1900	2000
33	42,750	-0,867	PZ	Abies alba	1900	2000
33	42,750	-0,517	IA	Abies alba	1900	2000
34	38,000	-2,667	CM	Pinus nigra	1920	2004
34	37,817	-2,967	PP	Pinus nigra	1920	2004
34	37,883	-2,967	CI	Pinus nigra	1920	2004

34	37,917	-2,800	BG	Pinus nigra	1920	2004
34	37,917	-2,950	VA	Pinus nigra	1920	2004
34	37,900	-2,867	NC	Pinus nigra	1920	2004
34	38,050	-2,733	PT	Pinus nigra	1920	2004
34	38,100	-2,867	PA	Pinus nigra	1920	2004
34	38,250	-2,650	YE	Pinus nigra	1920	2004
34	38,350	-2,550	BT	Pinus nigra	1920	2004
35	42,200	1,200	Boumort	Abies alba	1804	1999
35	42,300	-0,200	Guara	Abies alba	1893	1999
35	42,310	1,810	Moixer□o	Abies alba	1852	1999
35	42,390	2,270	Setcases	Abies alba	1777	1999
35	42,550	-0,530	Pena Oroel	Abies alba	1889	2000
35	42,630	0,780	Conangles	Abies alba	1578	1999
35	42,630	1,060	La Mata de Valencia	Abies alba	1767	1999
35	42,680	1,320	Boavi	Abies alba	1878	1999
35	41,770	2,430	Montseny	Abies alba	1587	1999
35	42,900	-0,780	Aztparreta	Abies alba	1749	1999
36	38,180	-2,780	South	Pinus nigra	1833	2005
36	40,210	-1,950	Center	Pinus nigra	1891	2006
36	40,460	-0,560	North	Pinus nigra	1833	2006
37	42,669	-2,407	BUJ3	Quercus faginea	1574	2008
37	42,714	-2,356	CAV3	Quercus faginea	1582	2008
37	42,721	-2,383	OTE12	Quercus faginea	1565	2006
37	42,760	-2,860	QFAG3	Quercus faginea	1635	2003
37	42,372	-2,177	IBL04	Quercus sp.	1810	2003
37	42,990	-2,733	MUR2	Quercus sp.	1794	2006
38	41,750	-2,083		Juniperus thurifera	1820	2004
39	37,854	-1,543	M3	Pinus halepensis	1915	2008
39	37,881	-1,538	M2	Pinus halepensis	1915	2008
39	37,881	-1,510	M1	Pinus halepensis	1932	2008
39	41,816	-0,538	Za1	Pinus halepensis	1919	2007
39	41,934	-0,940	Za2	Pinus halepensis	1926	2007
40	41,986	-0,959	Castejón - Zuera (CV)	Pinus halepensis	1928	2009
40	41,895	-0,909	Castejón de Valdejasa (CS)	Pinus halepensis	1900	2009
40	41,883	-0,909	Villanueva de Gállego (VL)	Pinus halepensis	1878	2006
40	41,818	-0,504	Puerto de Alcubierre (PU)	Pinus halepensis	1943	2009
40	41,746	-0,500	San Caprasio (CP)	Pinus halepensis	1927	2006
40	41,470	-0,319	Fraga (FR)	Pinus halepensis	1844	2006
40	41,289	-0,073	Caspe (CA)	Pinus halepensis	1845	2007
40	41,140	-1,414	Daroca (DA)	Pinus halepensis	1934	2006
40	40,979	-0,565	Alloza (AL)	Pinus halepensis	1888	2006
40	40,065	-0,120	Oropesa (OR)	Pinus halepensis	1921	2003
40	39,471	-1,199	Requena (RE)	Pinus halepensis	1789	2003
40	39,191	-1,154	Jalance (JA)	Pinus halepensis	1863	2003
40	38,667	-0,538	Font Roja (FN)	Pinus halepensis	1863	2006
40	38,101	-0,653	Guardamar (GU)	Pinus halepensis	1912	2006
40	42,326	-0,844	Ayerbe (AY)	Pinus halepensis	1946	2006
40	42,163	-0,203	El Grado (GR)	Pinus halepensis	1946	2006
40	42,095	-1,769	Valare˜na (VA)	Pinus halepensis	1925	2009
41	41,760	2,470	LFL	Fagus sylvatica	1884	2003
41	41,770	2,460	CFA	Fagus sylvatica	1861	2003
41	41,780	2,440	HFL	Fagus sylvatica	1775	2003
42	42,880	-6,860	Lalin	Castanea sativa	1759	1990
43	41,967	-2,817	Tejeros	Pinus sylvestris	1739	1999
43	42,000	-2,750	Vinuesa	Pinus uncinata	1679	1999

44	38,080	-0,686	Guardamar	Pinus halepensis	1918	1999
44	38,080	-0,686	Guardamar	Pinus pinaster	1911	1999
45	40,000	-1,983	CUE1	Pinus nigra	1728	1984
45	37,817	-2,950	CAZ2	Pinus nigra	1585	1985
45	37,833	-2,933	CAZ3	Pinus nigra	1698	1985
45	40,267	-1,933	CUE6	Pinus nigra	1644	1985
45	40,283	-0,700	GUD3	Pinus nigra	1679	1985
45	40,433	-1,900	CUES	Pinus nigra	1794	1983
45	40,633	-0,483	GUD5	Pinus nigra	1829	1985
45	37,950	-2,933	CAZI	Pinus nigra	1745	1985
45	40,150	-1,900	CUE2	Pinus nigra	1711	1983
45	40,250	-1,933	CUE4	Pinus nigra	1638	1985
45	40,300	-0,733	GUDl	Pinus nigra	1681	1984
45	37,967	-2,933	CAZ4	Pinus pinaster	1836	1985
45	40,300	-1,333	ALB2	Pinus pinaster	1821	1985
45	40,283	-1,450	ALB1	Pinus sp.	1887	1985
45	42,800	-0,700	PYR1	Pinus sp.	1605	1985
45	42,000	-2,850	URB1	Pinus sylvestris	1681	1983
45	40,333	-1,983	CUE3	Pinus sylvestris	1809	1983
45	40,333	-5,133	GRE1	Pinus sylvestris	1769	1985
45	40,333	-5,167	GRE2	Pinus sylvestris	1812	1985
45	40,567	-0,483	GUD4	Pinus sylvestris	1844	1985
45	40,783	-3,800	GUA4	Pinus sylvestris	1769	1985
45	40,817	-4,050	GUA2	Pinus sylvestris	1726	1983
45	41,983	-2,867	URB3	Pinus sylvestris	1567	1983
45	42,017	-2,900	URB2	Pinus sylvestris	1671	1983
45	42,033	-3,033	URB4	Pinus sylvestris	1593	1985
45	42,733	0,783	PYR3	Pinus sylvestris	1752	1985
45	42,833	-0,783	PYR2	Pinus sylvestris	1696	1985
45	42,833	-3,167	ZAD	Pinus sylvestris	1802	1985
45	40,300	-0,683	GUD2	Pinus sylvestris	1859	1985
45	40,800	-3,983	GUAI	Pinus sylvestris	1749	1983
45	40,800	-3,950	GUA3	Pinus sylvestris	1599	1984
46	43,300	-4,300		Fagus sylvatica	1773	1997
46	43,300	-4,300		Quercus robur	1772	1997
46	43,533	-5,633	AD2	Quercus robur	1795	2000
46	43,533	-5,633	AD3	Quercus robur	1530	2000
46	43,550	-5,650		Quercus robur	1905	2000
46	43,550	-5,650		Quercus robur	1775	2000
46	43,550	-5,650		Quercus robur	1664	2000
47	43,230	-3,880	ALO	Fagus sylvatica	1890	2008
47	43,180	-3,620	ASO	Fagus sylvatica	1793	2008
47	43,170	-1,620	BER	Fagus sylvatica	1874	2008
47	43,330	-4,280	CAV	Fagus sylvatica	1775	2007
47	43,350	-4,770	CUE	Fagus sylvatica	1777	1998
47	42,100	-2,420	DIU	Fagus sylvatica	1924	2012
47	42,630	-7,030	FON	Fagus sylvatica	1915	2012
47	43,130	-4,800	FUE	Fagus sylvatica	1863	2007
47	42,880	-0,780	GAM	Fagus sylvatica	1831	2000
47	42,900	-3,950	HIJ	Fagus sylvatica	1878	2007
47	42,670	-2,430	IZK	Fagus sylvatica	1906	2008
47	42,680	-7,070	LIN	Fagus sylvatica	1916	2012
47	42,400	-1,080	LUE	Fagus sylvatica	1938	2012
47	42,370	-0,370	MON	Fagus sylvatica	1919	2009
47	43,250	-5,300	MUN	Fagus sylvatica	1879	2008

47	42,370	-0,550	PEI	Fagus sylvatica	1927	2011
47	43,270	-5,020	POM	Fagus sylvatica	1760	2008
47	42,980	-6,620	RAN	Fagus sylvatica	1854	2009
47	43,130	-4,520	SAG	Fagus sylvatica	1909	2007
47	43,100	-4,250	SAJ	Fagus sylvatica	1908	2007
47	42,650	-7,070	SIS	Fagus sylvatica	1942	2001
47	43,170	-5,020	SOT	Fagus sylvatica	1901	2008
47	43,430	-5,220	SUE	Fagus sylvatica	1892	2008
47	43,230	-4,020	TEJ	Fagus sylvatica	1922	2007
47	43,280	-5,180	TEX	Fagus sylvatica	1881	1999
47	43,200	-4,220	UCI	Fagus sylvatica	1894	2007
47	42,830	-2,150	URB	Fagus sylvatica	1847	2008
47	42,980	-5,780	VAL	Fagus sylvatica	1868	2008
47	43,080	-6,050	VEN	Fagus sylvatica	1858	2008
47	42,650	-7,050	ZAN	Fagus sylvatica	1927	2001
48	43,050	-7,220	EST	Quercus robur	1909	2007
48	43,140	-8,960	BAI	Quercus robur	1867	2006
48	43,580	-7,720	BIS	Quercus robur	1872	2006
49	41,750	-2,083		Juniperus thurifera	1674	2004
49	43,400	-7,220	TRA	Pinus pinaster	1949	2006
50	42,014	-2,744		Pinus uncinata	1900	1987
51	42,983	-1,050	Not specified	Abies alba	1893	2003
51	42,983	-1,050	Not specified	Abies alba	1912	2003
52	39,930	-8,950	Pinhal de Leiria	Pinus pinaster	1818	2006

References Table S2

1. Andreu, L., Gutierrez, E., Macias, M., Ribas, M., Bosch, O., Camarero, J.J., 2007. Climate increases regional tree-growth variability in Iberian pine forests. *Global Change Biology* **13(4),** 804-815.

2. Andreu, L., Planells, O., Gutierrez, E., Helle, G., Schleser, G.H.,2008. Climatic significance of tree-ring width and delta C-13 in a Spanish pine forest network. *Tellus Series B-Chemical and Physical Meteorology* **60(5)**, 771-781.

3. Andreu-Hayles, L., Planells, O., Gutierrez, E., Muntan, E., Helle, G., Anchukaitis, K.J., Schleser, G.H., 2011. Long tree-ring chronologies reveal 20th century increases in water-use efficiency but no enhancement of tree growth at five Iberian pine forests. *Global Change Biology* **17(6)**, 2095-2112.

4. Batllori, E., Gutierrez, E., 2008. Regional tree line dynamics in response to global change in the Pyrenees. *Journal of Ecology* **96(6)**, 1275-1288.

5. Bogino, S., Nieto, M.J.F., Bravo, F., 2009. Climate effect on radial growth of Pinus sylvestris at its southern and western distribution limits. *Silva Fennica* **43(4)**, 609-623.

6. Bogino, S.M., Bravo, F., 2008. Growth response of Pinus pinaster Ait. to climatic variables in central Spanish forests. *Annals of Forest Science* **65(5)**, Art. No. 506.

7. Bosch, O., Gine, L., Ramadori, E.D., Bernat, A., Gutierrez, E., 1992. Disturbance, age and size structure in stands of Pinus uncinata Ram. *Pirineos* **140**, 5-14.

8. Braker, O.U., Schweingruber, F.H., 1984. Standorts-Chronologien. Teil 1: Iberische Halbinsel. Eidg. Anst. Forstl. Versuchswes, Birrnensdorf.

9. Buntgen, U., Frank, D., Grudd, H., Esper, J., 2008. Long-term summer temperature variations in the Pyrenees. *Climate Dynamics* **31(6),** 615-631.

10. Büntgen, U., Martínez-Peña, F., Aldea, J., Rigling, A., Fischer, E.M., Camarero, J.J., Hayes, M.J., Fatton, V., Egli, S., 2013. Declining pine growth in Central Spain coincides with increasing diurnal temperature range since the 1970s. *Global and Planetary Change* **107**, 177-185.

11. Camarero, J.J, Bigler, C., Linares, J.C., Gil-Pelegrín, E., 2011. Synergistic effects of past historical logging and drought on the decline. *Forest Ecology and Management* **262(5)**, 759–769.

12. Camarero, J.J., Martin, E., Gil-Pelegrin, E., 2003. The impact of needleminer (Epinotia subsequana) outbreak on radial growth of silver fir (Abies alba) in the Aragon Pyrenees: A dendrochronological assessment. *Dendrochronologia* **21(1)**, 3-12.

13. Campelo, F., Nabais, C., Freitas, H., Gutierrez, E., 2007. Climatic significance of tree-ring width and intra-annual density fluctuations in Pinus pinea from a dry Mediterranean area in Portugal. *Annals of Forest Science* **64(2)**, 229-238.

14. De Luis, M., Novak, K., Cufar, K., Raventos, J., 2009. Size mediated climate-growth relationships in Pinus halepensis and Pinus pinea. *Trees - Structure and Function* **23(5)**, 1065-1073.

15. DeSoto, L., Camarero, J.J., Olano, J.M., Rozas, V., 2012. Geographically structured and temporally unstable growth responses of Juniperus thurifera to recent climate variability in the Iberian Peninsula. *European Journal of Forest Research* **131(4)**, 905-917, doi:10.1007/s10342-011-0564-7.

16. Domínguez-Delmás, M., Alejano-Monge, R, Wazny, T., García-González, I., 2013. Radial growth variations of black pine along an elevation gradient in the Cazorla Mountains and their relevance for historical and environmental studies. *European Journal for Forest Research* **132(4)**, 635-652.

17. Dorado Liñán, I., Gutiérrez, E., Heinrich, I., Andreu-Hayles. L., Muntán, E., Campelo, F. & Helle, G., 2012. Age effects and climate response in trees: a multi-proxy tree-ring test in old-growth life stages. *European Journal of Forest Research* **131**, 933–944.

18. Galván, J.D., Büntgen, U., Ginzler, C., Grudd, H., Gutiérrez, E., Labuhn, I., Camarero, J.J., 2015. Drought-induced weakening of growth–temperature associations in high-elevation Iberian pines. *Global and Planetary Change* **124**, 95-106.

19. García González, I., 2000. Estudio dendroecológico de Quercus robur L. en el Norte de Galicia. Tesis Doctoral Universidad de Santiago de Compostela.

20. García-Cervigón Morales, A.I., Olano Mendoza, J.M., Gozalbo, M.E., Camarero Martínez, J.J., 2012. Arboreal and prostrate conifers coexisting in Mediterranean high mountains differ in their climatic responses. *Dendrochronologia* **30(4)**, 279-286.

21. Gea-Izquierdo G, Cherubini P, Cañellas I., 2011. Tree-rings reflect the impact of climate change on Quercus ilex L. along a temperature gradient in Spain over the last 100 years. *Forest Ecology and Management* **262**, 1807-1816. doi: 10.1016/j.foreco.2011.07.025

22. Gea-Izquierdo G, Fonti P, Cherubini P, Martín-Benito D, Chaar H, Cañellas I., 2012. Xylem hydraulic adjustment and growth response of Quercus canariensis Willd. to climatic variability. *Tree Physiology* **32**, 401-413. doi:10.1093/treephys/tps026

23. Gea-Izquierdo, G., Martin-Benito, D., Cherubini, P., Canellas, C., 2009. Climate-growth variability in Quercus ilex L. west Iberian open woodlands of different stand density. *Annals of Forest Science* **66(8)**, Art. No. 802.

24. Gea-Izquierdo, G., Viguera, B., Cabrera, M., Cañellas, I., 2014. Drought induced decline could portend widespread pine mortality. *Forest Ecology and Management* **320**, 70-82.

25. Génova Fuster, M., 1998. Estudio de los anillos de crecimiento y su relación con las variables meteorológicas en el pinar de Lillo (León). *Ecología* **12**, 237-250.

26. Genova, M., Fernandez, A., Creus, J., 1993. Diez series medias de anillos de crecimiento en los sistemas Carpetano e Iberico. *Investigacion Agraria INIA* **2(2)**, 136-149.

27. Génova, M., Martínez-Morillas, D., 2002. Estudio dendroecológico de Pinus nigra en Checa (Guadalajara). *Ecologia* **16**, 83-95.

28. Genova, M., Moya, P., 2012. Dendroecological analysis of relict pine forests in the centre of the Iberian Peninsula. *Biodiversity and Conservation* **21**, 2949-2965.

29. Génova, R., 1990. Comparación de tres series dendrocronológicas del Valle de Conangles (Pirineo Central). *Orsis*, 105-119.

30. Gonzalez, I.G., Eckstein, D., 2003. Climatic signal of earlywood vessels of oak on a maritime site. *Tree Physiology* **23(7)**, 497-504.

31. González-González, B.D., Rozas, V., García-González, I., 2014. Earlywood vessels of the sub-Mediterranean oak Quercus pyrenaica have greater plasticity and sensitivity than those of the temperate Q. petraea at the Atlantic–Mediterranean boundary. *Trees* **28(1)**, 237-252.

32. Lamas, S., Rozas, V., 2007. Radial growth of the main tree species in the Cortegada island (Parque Nacional de las Islas Atlanticas) as a consequence of history and climate. *Investigacion Agraria-Sistemas y Recursos Forestales* **16(1)**, 3-14.

33. Linares, J.C., Camarero, J.J., 2012. Growth patterns and sensitivity to climate predict silver fir decline in the Spanish Pyrenees. *European Journal of Forest Research* **131(4)**, 1001-1012, doi:10.1007/s10342-011-0572-7.

34. Linares, J.C., Tíscar, P.A., 2010. Climate change impacts and vulnerability of the southern populations of Pinus nigra subsp. salzmannii. *Tree Physiology* **30**, 795–806.

35. Macias, M., Andreu, L., Bosch, O., Camarero, J.J., Gutierrez, E., 2006. Increasing aridity is enhancing silver fir (Abies alba Mill.) water stress in its south-western distribution limit. *Climatic Change* **79(3-4)**, 289-313.

36. Martin-Benito, D., Kint, V., del Rio, M., Muys, B., Canellas, I., 2011. Growth responses of West-Mediterranean Pinus nigra to climate change are modulated by competition and productivity: Past trends and future perspectives. *Forest Ecology and Management* **262(6)**, 1030-1040, doi:10.1016/j.foreco.2011.05.038.

37. Nayling, N., Susperregi, J., 2014. Iberian Dendrochronology and the Newport Medieval Ship. *Int J Nautical Archaeology* **43(2)**, 279-291.

38. Olano, J.M., Rozas, V., Bartolome, D., Sanz, D., 2008. Effects of changes in traditional management on height and radial growth patterns in a Juniperus thurifera L. woodland. *Forest Ecology and Management* **255(3-4)**, 506-512.

39. Olivar, J., Bogino, S., Spiecker, H., Bravo, F., 2012. Climate impact on growth dynamic and intra-annual density fluctuations in Aleppo pine (Pinus halepensis) trees of different crown classes. *Dendrochronologia* **30(1)**, 35-47.

40. Pasho, E., Camarero, J.J., De Luis, M., Vicente-Serrano, S.M., 2011. Spatial variability in large-scale and regional atmospheric drivers of Pinus. *Agricultural and Forest Meteorology* **151(8)**, 1106–1119.

41. Penuelas, J., Hunt, J.M., Ogaya, R., Jump, A.S., 2008. Twentieth century changes of tree-ring delta C-13 at the southern range-edge of Fagus sylvatica: increasing water-use efficiency does not avoid the growth decline induced by warming at low altitudes. *Global Change Biology* **14(5)**, 1076-1088.

42. Pérez Antelo, A., 1993. Análisis de una cronología de Castanea sativa Mill. obtenida en la finca de Val de Fernando (Lalín-Pontevedra). *Ponencias y Comunicaciones del I Congreso Forestal Español*. Lourizán, Pontevedra. Tomo I: 111-116.

43. Planells, O., Gutierrez, E., Helle, G., Schleser, G., 2009. A forced response to twentieth century climate conditions of two Spanish forests inferred from widths and stable isotopes of tree rings. *Climatic Change* 9**7(1-2)**, 229-252.

44. Raventos, J., De Luis, M., Gras, M.J., Cufar, K., Gonzalez-Hidalgo, J.C., Bonet, A., Sanchez, J.R., 2001. Growth of Pinus pinea and Pinus halepensis as affected by dryness, marine spray and land use changes in a Mediterranean semiarid ecosystem. *Dendrochronologia* **19(2)**: 211-220.

45. Richter, K., Eckstein, D., Holmes, R.L., 1991. The dendrochronological signal of pine trees (Pinus spp.) in Spain. *Tree-Ring Bulletin* **51**, 1-13.

46. Rozas, V., 2001. Detecting the impact of climate and disturbances on tree-rings of Fagus sylvatica L. and Quercus robur L. in a lowland forest in Cantabria, Northern Spain. *Annals of Forest Science* **58(3)**, 237-251.

47. Rozas, V., Camarero, J.J., Sangüesa-Barreda, G., Souto, M., García-González, I., 2014. Summer drought and ENSO-related cloudiness distinctly drive Fagus. *Agricultural and Forest Meteorology* **201**, 153-164.

48. Rozas, V., Garcia-Gonzalez, I., 2012. Non-stationary influence of El Nino-Southern Oscillation and winter temperature on oak latewood growth in NW Iberian Peninsula. *International Journal of Biometeorology* **56(5)**, 787-800, doi:10.1007/s00484-011-0479-5.

49. Rozas, V., Olano, J.M., DeSoto, L., Bartolome, D., 2008. Large-scale structural variation and long-term growth dynamics of Juniperus thurifera trees in a managed woodland in Soria, central Spain. *Annals of Forest Science* **65(8), Art. No. 809.**

50. Ruiz-Flano, P., 1988. Dendroclimatic series of Pinus uncinata R. in the central Pyrenees and in the Iberian system, Spain: A comparative study. *Pirineos* **132**, 49-64.

51. Solla, A., Sanchez-Miranda, A., Camarero, J.S.J., 2006. Radial-growth and wood anatomical changes in Abies alba infected by Melampsorella caryophyllacearum: A dendroecological assessment of fungal damage. *Annals of Forest Science* **63(3)**, 293-300.

52. Vieira, J., Campelo, F., Nabais, C., 2009. Age-dependent responses of tree-ring growth and intra-annual density fluctuations of Pinus pinaster to Mediterranean climate. *Trees-Structure and Function* **23(2)**, 257-265.

53. De Luis, M., Novak, K., Raventós, J., Gričar, J., Prislan, P., Čufar, K., 2011. Climate factors promoting intra-annual density fluctuations in Aleppo pine (Pinus halepensis) from semiarid sites. *Dendrochronologia* **29(3)**, 163-169.

54. Campelo, F., Nabais, C., Garcia-Gonzalez, I., Cherubini, P., Gutierrez, E., Freitas, H, 2009. Dendrochronology of Quercus ilex L. and its potential use for climate reconstruction in the Mediterranean region. *Canadian Journal of Forest Research* **39(12)**, 2486-2493.

55. Rozas, V., Zas, R., Garcia-Gonzalez, I., 2011. Contrasting effects of water availability on Pinus pinaster radial growth near the transition between the Atlantic and Mediterranean biogeographical regions in NW Spain. *European Journal of Forest Research* **130(6)**, 959-970, doi:10.1007/s10342-011-0494-4.

ARTICLE 2

Radial growth variations of black pine along an elevation gradient in the Cazorla Mountains (South of Spain) and their relevance for historical and environmental studies.

Domínguez-Delmás, M., Alejano-Monge, R, Wazny, T., García-González, I., 2013.

European Journal of Forest Research 132(4), 635-652.

Black pines at the site Poyos de la Mesa (photo: M. Domínguez Delmás.

RADIAL GROWTH VARIATIONS OF BLACK PINE ALONG AN ELEVATION GRADIENT IN THE CAZORLA MOUNTAINS (SOUTH OF SPAIN) AND THEIR RELEVANCE FOR HISTORICAL AND ENVIRONMENTAL STUDIES

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Abstract

In southern Spain, the Cazorla Mountains (500-2,100 m a.s.l.) have supplied construction timber from black pine (*Pinus nigra* Arn.) for buildings and ships since at least the Middle Ages. To establish the age and provenance of wooden cultural heritage originating from this area, well replicated long-span chronologies are needed. Old-living trees occur at high elevations, whereas many historical timbers originated from lower altitudes, hence crossdating possibilities were questionable. To assess the potential of this species for the development of a multi-millennia tree-ring dataset with living trees and historical timbers for the western Mediterranean, we developed four ring-width chronologies along the circa 1,000 m altitudinal range of black pine in these mountains, and examined crossdating patterns and climate-growth responses along with altitude and through time. Teleconnections with other Iberian and Mediterranean tree-ring data were also tested. A well replicated chronology spanning AD 1331-2009 was obtained at the upper site, while lower elevations delivered shorter chronologies. Similarity among chronologies and responses to climate were dependent on elevation. Tree-ring width was negatively related to temperature in previous late summer and positively to February-March, whereas precipitation had an opposite effect; some negative influence of early summer temperature was also observed. However, growth responses were rather unstable throughout the 20th century. These chronologies showed good tele- and heteroconnections with conifer chronologies from Iberia, northern Morocco and Turkey, evidencing the existence of a common macroclimatic signal, which also varied along with elevation. The relevance of these results for dendro-historical studies is discussed.

Keywords

Dendrochronology, *Pinus nigra*, tree-ring width, radial growth responses, teleconnections, cultural heritage

1. INTRODUCTION

Radial tree-growth is the result of several endogenous and exogenous factors (Fritts, 1976; Cook, 1990). Among these, the climate-related environmental signal is assumed to be always present in tree-ring series to a greater or lesser extent, depending on the limiting effects of climatic variables such as temperature and water availability (Fritts, 1976; Kozlowsky and Pallardy, 1997). Annual differences in temperature and precipitation induce year-to-year (i.e. high-frequency) growth variations. These variations are the keystone for crossdating tree-ring series (i.e. matching them in their exact position) from trees of the same or different species that have grown under similar environmental conditions during specific periods of time, as they are likely to have synchronous patterns (Fritts, 1976). In central and northern Europe, tree-ring patterns of oak (*Quercus robur* L. and *Q. petraea* Matuschka Liebl.) and different conifer species show highly significant correlations (i.e. tele- and heteroconnections) over large areas for the Holocene (e.g. Leuschner et al., 2002; Eckstein et al., 2008, 2010), and from the Roman times to the Modern Period (e.g. Baillie, 1982; Briffa et al., 1992; Büntgen et al., 2011a,b).

Such tele- and heteroconnections, which are the result of macro-climatic signals prevailing across large territories (Fritts, 1976), allowed the construction of ultra-long supra-regional chronologies that served, e.g., to reconstruct former (and predict future) environmental conditions (Briffa et al., 1992; Leuschner et al., 2002; Büntgen et al., 2005, 2011a,b), to calibrate the radiocarbon curve for the northern hemisphere (see for an overview Kromer 2009 and references therein), and to absolutely date (pre)historical constructions, artifacts and vegetation-remains from the cultural and natural heritage (e.g. Jansma, 1996; Kuniholm, 1996; Haneca et al., 2009 and references therein).

At regional levels, however, the spatio-temporal behavior of tree-growth response to climate still remains intriguing, as it has been observed to have a dynamic character (e.g. Mäkinen et al., 2002; Carrer and Urbinati, 2006; Andreu et al., 2007; Büntgen et al., 2012). In practice, climate-induced high growth-variability within small geographic areas (along elevation gradients for example) may hamper crossdating of tree-ring series (Wilson and Hopfmueller, 2001), therefore limiting the retrospective extension of chronologies with local wood from (pre)historical sources originating from different elevations.

The south of Spain, influenced by Mediterranean climate, but also by Atlantic weather conditions, represents the southern and/or western distribution limit for several species, therefore is a critical spot for ecological and climatological studies (e.g. Linares and Tíscar, 2011 and references therein). Furthermore, its strategic position along historical trade routes, and the abundance of cultural heritage in and originating from the region (De Aranda y Antón, 1999; Rodríguez Trobajo, 2008), makes it a highly interesting area for dendro-historical and archaeological research. Within this area, the Cazorla Mountains have supplied construction timber for buildings and ships since at least the Middle Ages (e.g. Córdoba de la Llave, 1990; De Aranda y Anton, 1990; De la Cruz Aguilar, 1994; Araque Jiménez, 2007), especially from black pine (*Pinus nigra* Arnold subsp. *salzmannii* (Dunal) Franco). This species was highly appreciated for the quality of its wood for construction purposes (Fernández-Golfín et al., 2001). Consequently, black pine from the Cazorla Mountains can be found nowadays in a

great number of historical buildings in the western Mediterranean, and in shipwrecks all over the world, offering an invaluable source of tree-ring data for environmental, timber-trade and historical studies.

Black pines of the Cazorla Mountains represent relic forests growing at the south-western distribution limit of this subspecies (Alejano and Martínez, 1996) and, despite centuries of intensive logging in most areas of the mountain range, trees reaching 1,000 years of age had been reported at the highest elevations close to 2,000 m a.s.l. (Creus, 1998). Those trees are living archives of past climate, and they could also provide a much needed millennium-long tree-ring chronology for dating cultural heritage in the region. Such chronology could be in turn improved and extended retrospectively with local wood from historical sources. However, the possibility to crossdate historical timbers of this species that may have originated from low elevations with a chronology derived from the millennium-old black pines from the upper part of the mountains remained questionable. In the Bavarian region (south of Germany), heterogeneous tree-growth responses to climate along an elevation gradient make dendrochronological dating of timbers from historical buildings remarkably difficult (Wilson and Hopfmueller, 2001; Dittmar et al., 2012). In the Cazorla mountains, studies including black pine tree-ring records are abundant (e.g. Richter et al., 1991; Andreu et al., 2007; Martín-Benito et al., 2008; Linares and Tíscar 2010, 2011; Dorado Liñán et al., 2012), but are exclusively focused on ecological or climatological questions. Consequently, the ring-width chronologies developed so far in this region are either too short to be suitable for dendro-historical studies (Martín-Benito et al., 2008; Linares and Tíscar, 2010, 2011) or include only trees from the highest elevations (Richter et al., 1991; Andreu et al., 2007; Dorado Liñán et al., 2012). A well replicated long-span dataset of black pine covering the ca. 1,000 m elevation gradient in the Cazorla Mountains was therefore needed. Understanding radial-growth responses to climate along the elevation gradient of this species in southern Spain would help defining appropriate strategies towards compilation of (historical) tree-ring data and chronology building for dating cultural heritage, and as historical and environmental archive. Therefore, the objectives of this study were the following:

- To develop long-span tree-ring chronologies along the whole elevation gradient (ca. 1,000 m) of black pine in the Cazorla Mountains;
- To analyze the climatic variables that regulate radial tree-growth at different elevations;
- To assess the evolution of radial-growth responses to those climatic variables through time;
- To study the tele- and heteroconnections of the created chronologies with existing chronologies of black pine and other conifer species from Iberia and the Mediterranean basin.

2. MATERIAL AND METHODS

2.1. Study area

The Cazorla Mountains (Fig. 1a) are included within the Cazorla, Segura and Las Villas Natural Park, a mountain woodland spreading north-east to south-west at the eastern corner of the Baetic System in the Andalusian region (southeast of the Iberian Peninsula). It is the largest protected area in Spain, covering 209,921 ha, and constitutes a very important hydrological area, where the river Guadalquivir,

flowing west to the Atlantic Ocean, and the Segura River, flowing east to the Mediterranean Sea, originate (Fig. 1c).

The climate regime is typically Mediterranean (Fig. 1b) characterized by a hard summer drought, changing precipitation between and within years, and strong differences among maximum and minimum temperatures along the year, sometimes even within a day (Tíscar, 2004). Average rainfall is about 1,100 mm/year (ranging from 400 to 1,900 mm), November and April being the wettest months, and July and August the driest (Fig. 1b). Average temperature is 11.7ºC, with minima in January (4ºC) and maxima in August (21ºC), but weather is very variable with altitude and topography.

Lithology consists mainly of limestone and dolomites, the latter restricting the development of many tree species. A craggy topography characterizes these mountains, with altitudes ranging from 500 to 2,107 m a.s.l. at the highest point (*Empanadas* peak).

The most important coniferous species in the Cazorla Mountains are pines (*Pinus halepensis* Mill., *P. pinaster* Ait., and *P. nigra* subsp. *salzmannii*), which distribute in slopes and valleys according to edaphic conditions and elevation. Common hardwood species are *Quercus ilex* L. *and Q. faginea* Lam., which grow at lower altitudes, and are often mixed with maples (*Acer* spp.), aspens (*Populus* spp.), rowans (*Sorbus* spp.) and ashes (*Fraxinus* spp.). Black pine is the most abundant pine species, covering 60,000 ha between 1,000 and 2,000 m a.s.l. (Tíscar, 2004). This pine is adapted to poor and shallow soils, steep slopes, and rocky areas, where other more demanding species cannot survive (Alejano, 1997).

2.2. Site selection and sampling strategy

In April and September 2010, we selected and sampled four sites in the Cazorla Mountains along an elevation transect of ca. 1,000 m (Fig. 1c), covering the whole altitudinal range of black pine in the southeast of Spain. Cabañas (CBS, 1,755-1,953), lay at the altitudinal limit of the species in this mountain range; Navanoguera (NAV, 1,582-1,702), at mid-elevation, represented an open valley with low smooth slopes located in the divide between the Atlantic and the Mediterranean aspects of the Cazorla Mountains; Poyos de la Mesa (PMB, 1,500-1,619), still mid-elevation site but slightly lower than NAV, was located on a high-elevation plain descending towards a southern slope; finally, Linarejos (LIN, 1,079-1,177 m a.s.l.), the site at the lowest altitude, represented a mixed forest of *P. nigra* and *P. pinaster* growing on a narrow valley.

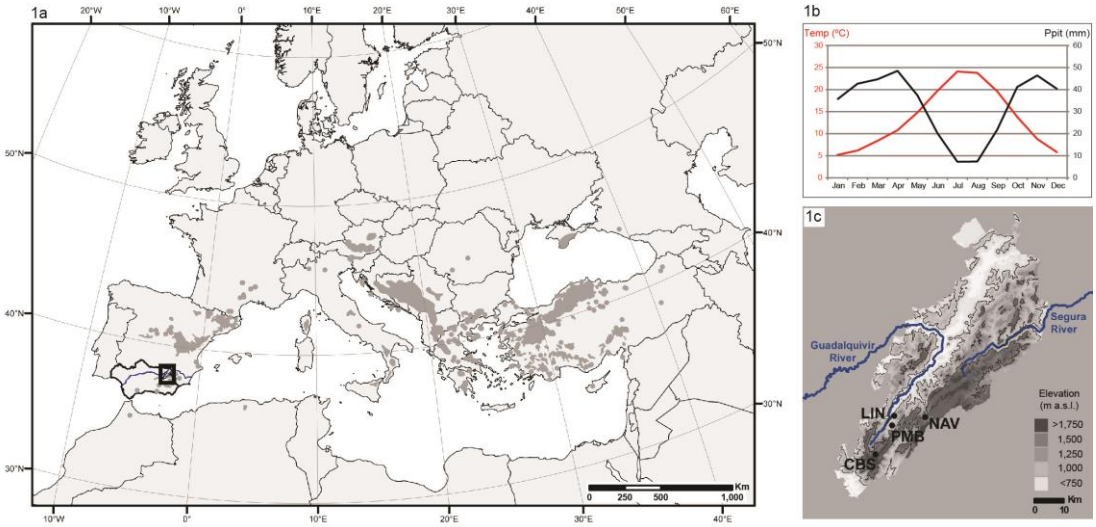

Figure 1. a) Distribution of *Pinus nigra* (source: EUFORGEN 2009, www.euforgen.org) and location of the Cazorla Mountains in the southeast of Spain (square); **b)** Climatic diagram of the study area calculated for the period 1901-2009, using temperature (ºC) and precipitation (mm) data from the Climate Research Unit (CRU), University of East Anglia, UK, available at http://climexp.knmi.nl; **c)** Location of the selected sites in the Cazorla Mountains.

To ensure a high replication of the chronologies, we selected a minimum of 19 trees (LIN) of different diameters and appearance at each location, trying to include most age classes. At the mid-elevation sites we sampled 20 (PMB) and 21 (NAV) trees, and at the high-elevation site (CBS) up to 55 trees were selected, to ensure that some of the samples would have a continuous series where others could contain absent rings. For each selected tree, we extracted between two and five cores at breast height using 60 cm long increment borers (5 mm diameter). The final dataset comprised 270 cores. We recorded coordinates and elevation, as well as the most relevant characteristics of each individual (height, diameter, and apparent anomalies) and its environment (soil appearance, slope, and exposition).

2.3. Acquisition of tree-ring data

Cores were glued onto wooden supports with the tracheids placed vertically to allow the preparation of the transversal surface. A Stanley knife was used to facilitate the visualization of the rings, and chalk powder was applied to the cleaned surface to enhance the contrast between tree-ring boundaries. Ring widths were measured to the nearest 0.01 mm using a TimeTable measuring device (VIAS, University of Vienna) coupled with the PAST4 v.4.3 program (B. Knibbe, SCIEM).

Crossdating of series from the same site was done by statistical and visual comparison of tree-ring series using PAST4. During this step, numerous missing or locally absent rings were identified. Once the exact position of an absent ring was located in the sample, a ring with a low value was inserted on the measurement to allow the continuity of the series, and yet register an anomaly for that year. Parts of the tree-ring series where absent rings were too numerous to allow an accurate insertion of rings were excluded from further analysis. The insertion of the rings and the quality of the crossdating among the series was verified with the software COFECHA (Holmes, 1983; Grissino-Mayer, 2001).

2.4. Computation and quality assessment of the Cazorla chronologies

After crossdating the individual tree-ring series, site standard (STD) and residual (RES) chronologies were computed with the program ARSTAN (Cook and Holmes, 1986) using a single average series per tree. The purpose of standardization is to remove non-desired signal imbibed on raw ring-width series and caused e.g. by natural age-trends, successional changes in the forest stand, human-induced signals, etc. (Fritts, 1976; Schweingruber, 1996). As many series showed variations that could be due to forest dynamics and human interventions, and given the length of the series (>100 years), we filtered them using a 100-year cubic smoothing spline and 50% variance reduction. This spline length was found to maximize the signal-to-noise ratio (Wigley et al., 1984) of the chronologies, while removing age trend and other non-common variance (Cook and Peters, 1981). The resulting dimensionless ring-width indices (RWI) were averaged with a biweight robust mean, which reduces the influence of outliers, into a STD chronology for each site. RES series were obtained after removing autocorrelation (i.e. previous year's influence on current year's growth) from the standardized series by first applying an autoregressive modeling (order 1) to the RWI, and then averaging the residuals with a robust mean. We used the RES chronologies to compute climate-growth analyses.

The quality of both STD and RES chronologies was assessed with the mean correlation between trees (rbar) (Briffa and Jones, 1990) and the Expressed Population Signal (EPS) (Wigley et al., 1984). Rbar indicates the strength of the signal between trees (Fritts, 1976) and EPS indicates the extent to which the sample size is representative of a theoretical infinite population for a given site. Intervals of a chronology attaining a value higher than 0.85 are commonly considered to have a high statistical quality (Wigley et al., 1984; Briffa, 1995).

2.5. Analysis of the common signal between the Cazorla chronologies

The four standard chronologies were compared to each other for their common interval attaining an EPS>0.85 (namely 1840-2009) using Pearson's correlation coefficient with its associated Student's *t*-value (*t*), and the percentage of parallel agreement (*GL*), along with the statistical significance of the latter (P_{GL}). To observe the variability of the correlations between the chronologies through time, we calculated moving correlations between the chronologies, using 50-year segments lagged one year for the same period.

To assess the differences between the standard chronologies we calculated principal components (PC), and used their loadings on the first and second PCs following a varimax rotation to study the ordination of the sites along the altitudinal gradient. This emphasizes the differences among sites, because each rotated PC tends to be associated to only some chronologies, so that the others do not bear any high positive loadings on the corresponding PC. These analyses were carried out in R (R Development Core Team, 2012).

2.6. Evaluation of radial growth response to climate and its spatiotemporal variability

In order to obtain climate-growth relationships, we used climatic gridded data (mean monthly temperature and total monthly precipitation) for the region, obtained from the Climate Research Unit

(CRU), University of East Anglia, UK, publicly available at the website of the Royal Netherlands Meteorological Institute (http://climexp.knmi.nl/).

We calculated correlation and response functions using the RES chronologies and the available climate data. As temperature and precipitation series covered the span 1901-2009, climate-growth relationships were calculated for a 16-month window (previous July to current October) along the period 1902-2009; in addition, climate data were seasonalized to cover previous late summer (August-October), and current late winter-early spring (February-March). We first computed Pearsons' correlations and achieved their confidence intervals out of 10,000 bootstrap iterations applying the corrections proposed by Mason and Mimmack (1992), using a routine written in Embarcadero® Delphi® XE2. Response function analysis was also performed on the same data, by means of the program DendroClim2002 (Biondi and Waikul, 2004), which calculates bootstrapped multiple regression on principal components. The functions were calculated for 1,000 iterations, and the significance of the regression coefficients was considered at $P<0.05$. Afterwards, to observe the variability of the climate-growth relationships obtained during the studied period and along the elevation transect, we computed moving correlation functions (Biondi, 1997) covering 50-year periods and consecutively shifted one year.

2.7. Tele- and heteroconnections

The STD chronologies from Cazorla were compared with STD tree-ring reference chronologies of *P. nigra*, and other conifer species from Iberia and the Mediterranean basin to assess their similarities and the geographical extent of their common signal. A selection of 106 reference chronologies were downloaded from the International Tree-Ring Data Bank (ITRDB; website hosted by the NOAA Paleoclimatology Program and World Data Center for Paleoclimatology, http://www.ncdc.noaa.gov/paleo/treering.html), after having verified their quality (Table 1). We calculated Pearson's correlation coefficients, Student's *t*-value, *GL* and P_{GL}:

- for the whole length of the chronologies (considering for the Cazorla chronologies the interval with EPS higher than 0.85);
- for an interval common to all (Cazorla and reference) chronologies (1840-1974).

We tested if the differences among the chronologies from Cazorla Mountains along the elevation gradient followed a pattern when compared to the dataset from the Mediterranean region. For this, we calculated Pearson's correlation (*r*) and *GL* on a matrix in which the sites from Cazorla served as variables, and the values of crossdating to each of the Mediterranean chronologies as cases. The analysis was performed for the common period to all chronologies (1840-1974, 135 years). Afterwards, both matrices entered a factor analysis with Varimax rotation, and the loadings on the two first principal components were used to understand the ordination of the site chronologies. These analyses were also performed in R.

Table 1 Standard chronologies from the International Tree-ring Data Bank used for the analyses of teleconnections (for coordinates, species codes and authors see http://www.ncdc.noaa.gov/paleo/ treering.html). Sp: species; Elev: elevation; (-): unknown.

ITRDB code	Sp	Elev (m a.s.l.)	Begin year	End year	ITRDB code	Sp	Elev (m a.s.l.)	Begin year	End year
FRAN021	PIMU	1750	1659	1977	SPAI018	PINI	1500	1687	1989
FRAN023	PIMU	2100	1769	1977	SPAI019	PINI	1600	1523	1988
FRAN027	PINI	1400	1518	1980	SPAI020	PISY	1650	1763	1991
GREE001	PILE	1750	1673	1981	SPAI021	PISY	1650	1715	1988
GREE002	PINI	1450	1825	1981	SPAI022	PIPI	1225	1821	1985
GREE003	ABBO	1350	1812	1981	SPAI024	PISY	1275	1696	1985
GREE005	PILE	2250	1583	1981	SPAI029	PINI	1385	1711	1983
GREE008	PINI	1500	1751	1978	SPAI030	PISY	1400	1809	1983
GREE009	PINI	1400	1657	1999	SPAI031	PINI	1225	1728	1984
GREE011	PINI	1320	1706	1979	SPAI032	PINI	1440	1794	1983
ITAL001	PINI	1550	1750	1987	SPAI033	PISY	1465	1813	1985
ITAL004	PCAB	1650	1836	1988	SPAI034	PISY	1470	1769	1985
ITAL007	PCAB	1900	1660	1975	SPAI035	PISY	1550	1726	1983
ITAL008	ABAL	1450	1827	1980	SPAI036	PISY	1800	1749	1983
ITAL011	ABAL	1720	1800	1980	SPAI037	PISY	1950	1661	1985
ITAL012	ABAL	1700	1654	1980	SPAI038	PISY	1850	1599	1984
ITAL013	PINI	1800	1773	1980	SPAI039	PINI	1450	1681	1984
ITAL014	PCAB	1650	1840	1980	SPAI041	PINI	1475	1681	1985
LEBA001	CDLI	1775	1829	2002	SPAI043	PINI	1500	1829	1985
LEBA002	ABCI	1175	1722	2001	SPAI044	PISP	1625	1605	1985
LEBA003	CDLI	1640	1809	2001	SPAI045	PINI	1385	1638	1985
LEBA004	CDLI	1900	1382	2002	SPAI046	PINI	1440	1644	1985
LEBA005	CDLI	1780	1778	2002	SPAI047	PISY	1750	1567	1983
LEBA006	CDLI	1720	1730	2002	SPAI048	PISY	1840	1671	1983
MORC001	CDAT	2200	1253	1984	SPAI049	PISY	1840	1593	1985
MORC002	CDAT	1700	1632	1984	SPAI050	PISY	1750	1681	1983
MORC003	CDAT	2200	1728	1984	SPAI051	PISY	1920	1752	1985
MORC004	CDAT	2000	1296	1987	SPAI052	PISY	880	1802	1985
MORC005	CDAT	2000	1283	1987	SPAI053	PIUN	2000	1811	1996
MORC006	CDAT	2000	1210	1987	TURK003	PCOR	1300	1686	1989
MORC007	CDAT	2500	1408	1987	TURK004	PISY	1300	1717	1988
MORC008	CDAT	2200	1366	1987	TURK012	CDLI	1400	1551	1998
MORC009	CDAT	2150	1300	1987	TURK013	PINI	1601	1772	2000
MORC010	CDAT	2200	1281	1987	TURK014	JUEX	1862	1246	2000
MORC011	CDAT	1900	1549	1984	TURK015	PIBR	1156	1730	2000
MORC012	CDAT	1700	1748	1984	TURK016	JUEX	1853	1332	2000
MORC014	CDAT	2200	984	1984	TURK017	CDLI	1853	1449	2000
SPAI001	PIMU	1870	1609	1977	TURK018	JUEX	1047	1152	2000
SPAI002	PISY	2050	1663	1977	TURK019	CDLI	1469	1693	2000
SPAI003	PIMU	2100	1793	1977	TURK020	PINI	1633	1586	2000
SPAI004	PIMU	1760	1808	1977	TURK021	CDLI	1723	1628	2000
SPAI005	PIMU	1960	1820	1977	TURK030	PINI	1600	1771	2002
SPAI007	ABPN	1650	1728	1982	TURK031	PINI	1500	1475	2001
SPAI008	PINI	1750	1610	1988	TURK032	PIBR	700	1738	2001
SPAI009	PINI	1250	1688	1988	TURK033	PINI	1500	1567	1995
SPAI010	PINI	1350	1615	1988	TURK035	JUEX	-	1017	2001
SPAI011	PINI	1500	1485	1988	TURK036	PIBR	1047	1694	2000
SPAI012	PISY	1950	1527	1988	TURK037	PINI	1650	1794	2002
SPAI013	PISY	1900	1685	1992	TURK038	PINI	1650	1771	2002
SPAI014	PISY	1630	1787	1992	TURK039	PINI	1480	1792	2004
SPAI015	PISY	1525	1791	1992	TURK040	JUEX	1800	1330	2001
SPAI016	PINI	1450	1667	1988	TURK041	JUEX	1790	1350	2001
SPAI017	PINI	1350	1760	1991	TURK042	JUEX	1725	1235	2001

3. RESULTS

3.1. Common signal of site chronologies

The obtained dataset comprised a total of 270 black pine tree-ring series from 114 trees located at elevations between 1,079 and 1,953 m a.s.l. Some attributes of the sampled trees (height, diameter, number of rings, ring-width and number of missing rings) are presented per site on Table 2. The chronologies developed showed a high statistical quality for dendrochronological purposes (Fig. 2). They shared the common period 1840-2009, restricted by the lowest elevation site (LIN) where the youngest trees were found. In contrast, the chronology from the highest elevation (CBS), which included five trees older than 700 years, reached back to AD 1331 with a high quality (EPS>0.85). The chronologies at intermediate altitudes, PMB and NAV, provided a high statistical quality for intervals of variable length (1544-2009 and 1698-2009 respectively). The common signal of the chronologies, expressed as the mean correlation between trees (rbar), was very high for all four sites, ranging between 0.642 (LIN) and 0.708 (NAV) (Fig. 2). An EPS>0.85 was attained with seven trees at LIN, NAV, and CBS, and with eight trees at PMB.

The sites located at the upper (CBS) and lower (LIN) bounds of the elevation gradient showed the lowest similarity (r=0.45, t =5.61, GL=67.5% and P_{GL} <0.001) (Table 3). Accordingly, the best statistical match was provided by the sites located at a similar elevation, namely NAV and PMB (r=0.77, t =13.35, GL=84.3 and P_{GL} <0.0001).

These relative correlation patterns remained rather stable over the common period 1840-2009 (Fig. 3). Interestingly, the variations of the correlations became highly synchronous towards the second half of the 20th century, adopting an upward trend in the last decades of the compared period (specially the CBS-LIN correlation), indicating an increase in the strength of the common signal.

Rotated PCA analysis clearly showed that elevation is the main factor explaining the differences among sites (Fig. 4), as the ordination of the loadings of the chronologies both two first PCs, which explained up to 90% of the total variance, followed the distribution of the sites along the altitudinal gradient.

Table 2. Attributes of the sampled trees and number of measured and missing rings (mean ± SD).

Sites	DBH trees (cm)	Height trees (m)	Rings present in samples	Missing rings in sample	% missing rings
CBS	89.8 ± 23.2	10.6 ± 2.4	452.0 ± 157.4	3.4 ± 4.8	0.83
NAV	103.5 ±23.7	14.6 ± 3.1	280.8 ± 94.6	0.6 ± 1.1	0.21
PMB	96.1 ± 21.6	15.1 ± 4.2	386.0 ± 109.0	1.4 ± 2.0	0.46
LIN	81.0 ± 28.6	19.9 ± 4.6	183.8 ± 59.9	0.4 ± 0.7	0.22

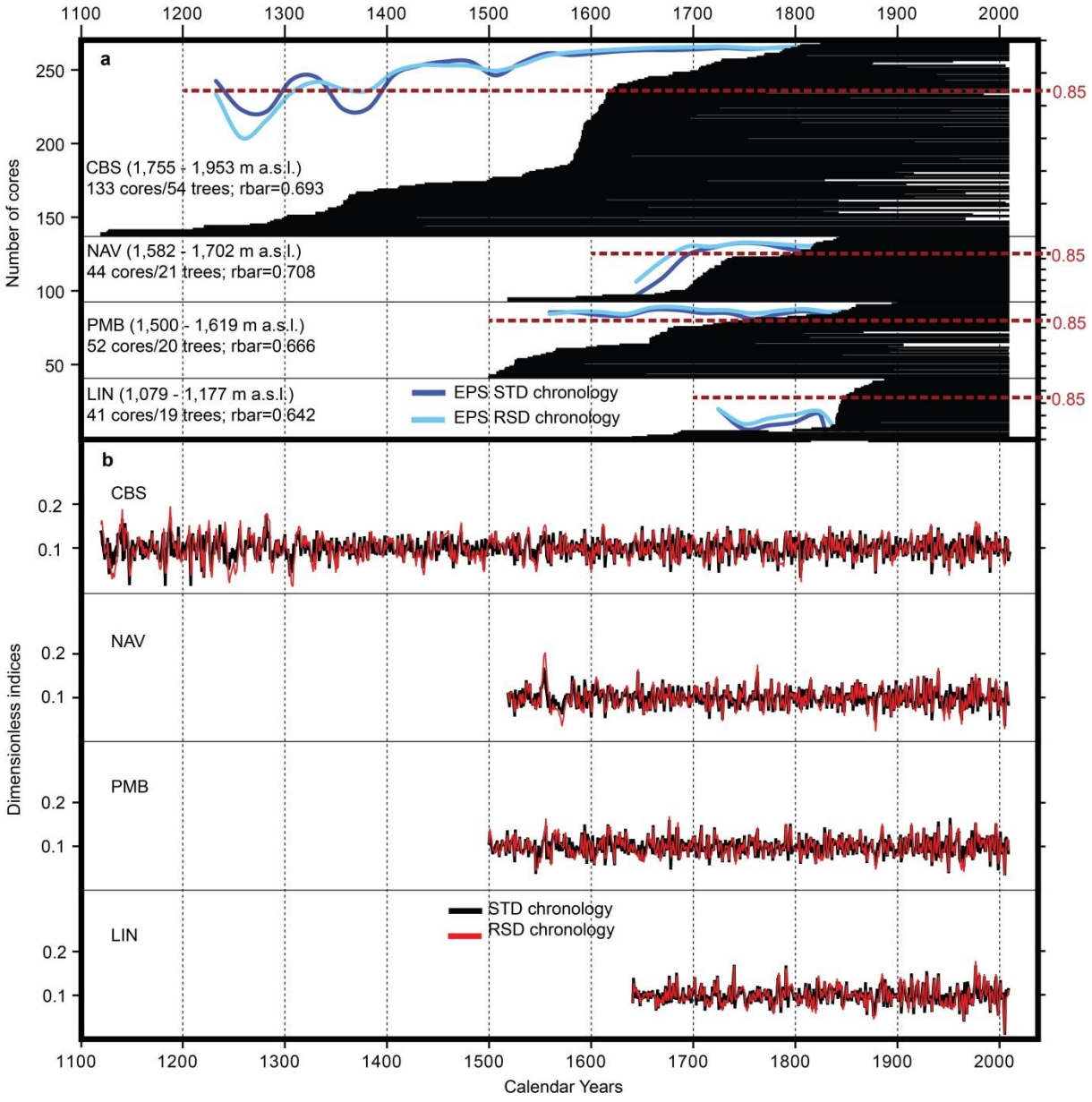

Figure 2. a) Time-span and number of individual cores collected at each site; rbar: intra-site tree correlation; EPS from standard (STD) and residual (RSD) chronology computed by ARSTAN; **b**) STD and RSD chronologies computed for each site.

Cazorla site chronologies	CBS (highest site)	NAV	PMB
NAV	*r*: 0.67 *t*: 10.00 *GL*: 77.5% P_{GI} <0.0001		
PMB	*r*: 0.62 *t*: 8.75 *GL*: 77.8% P_{GI} <0.0001	*r*: 0.77 *t*: 13.35 *GL*: 84.3% P_{GI} <0.0001	
LIN (lowest site)	*r*: 0.45 *t*: 5.61 *GL*: 67.5% P_{GI} <0.001	*r*: 0.66 *t*: 9.77 *GL*: 77.5% P_{GI} <0.0001	*r*: 0.72 *t*: 11.55 *GL*: 80.2% P_{GI} <0.0001

Table 3. Statistical comparison of chronologies for the common interval attaining EPS>0.85 (1840-2009); *r*: Pearson's correlation; *t*: Student's *t*-value; *GL*: % parallel variation; P_{GI}: signification level of GL.

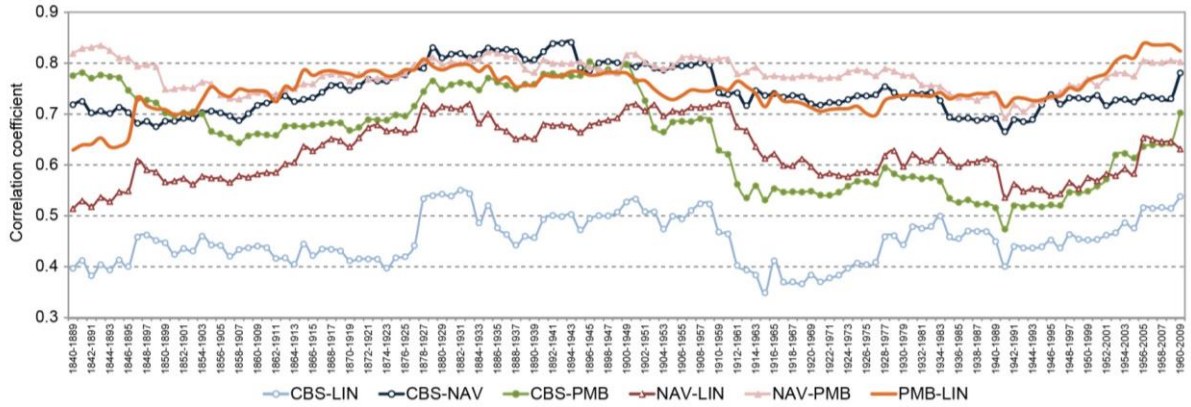

Figure 3. Temporal variation of the correlation between the computed Cazorla chronologies for the common period 1840-2009.

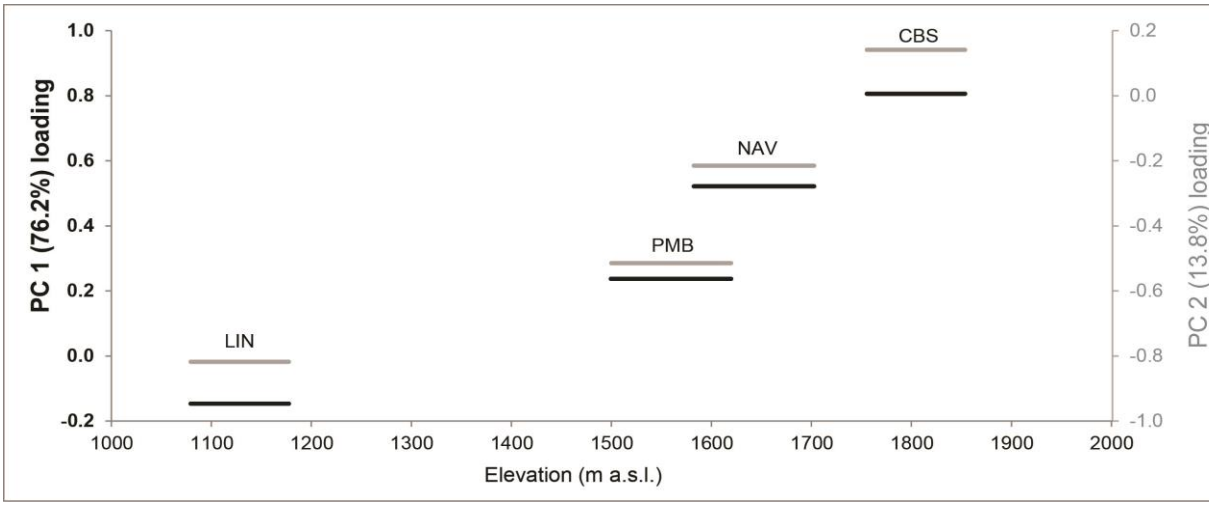

Figure 4. Loadings of each chronology on the first and second varimax-rotated PCs in relation to elevation. Horizontal lines indicate the elevation ranges for all trees sampled at each site.

3.2. Radial growth response to climate

In general, simple correlations revealed more relationships than the response functions (Fig. 5), although both analyses showed a stronger influence of temperature than precipitation on radial growth, and clear differences among sites with elevation.

Temperature at the end of previous summer/early fall (previous August to October) was closely related to tree growth at all elevations, as inferred from the results of the correlation functions. However, response functions identified this effect only for previous September to October at the highest site (CBS), and for previous September at the mid-elevation site NAV, whereas PMB and the lowest site LIN did not appear to respond to this factor. Correlation to mean temperature for the whole period from previous August to October was highly significant at the mid-elevations and the upper site (P<0.0001), and weaker at LIN (P<0.01). Growth response to late winter/early spring temperature (February-March current year) was strong and highly significant at all sites (P<0.001 for mid-elevation sites and P<0.0001 for the highest and the lowest site). Highly significant correlations

(P<0.0001) and response function coefficients were found for February at all sites; this relationship was also maintained for March, except for the lowest site (LIN) where correlation became insignificant, and was stronger at mid-elevations, with significant response function coefficients for both NAV and PMB. The other responses observed were not shared by all sites, but showed variations along the gradient. High temperature in current June-July appears to be negative for growth, but its effect on growth seems to be weaker than the role of temperature in late winter/early spring and previous late summer; response function analysis identified this factor only for LIN in May, and simple correlations, though significant at all sites, yield a low significance level (P<0.05 to P<0.01).

Growth response to precipitation was not as clear as to temperature. In general, relationships appeared to be weaker and more diffuse along the gradient. Correlation functions showed that precipitation had a significant effect at all elevations only in previous September (positive) and March (negative, especially significant at NAV, where P<0.0001). But response functions only indicated the positive relationship at CBS and PMB in previous September and at LIN in May, and the negative response at NAV in March. The lowest elevation site (LIN) seemed to be the most sensitive one to precipitation, as significant positive correlations (P<0.05 to P<0.001) appeared for previous October and current January, May and July as well. Positive relationships also showed up at PMB in previous January and May, whereas at the high elevation site (CBS), this factor has a significant positive effect in previous July (P<0.05) and current June (P<0.01).

3.3. Spatio-temporal variability of climate-growth relationships

Moving correlation functions showed a predominant response to temperatures than to precipitation (Fig. 6), although this trend has been changing since halfway the 20th century mid and high elevations, where response to February-March precipitation has been taking increasing relevance. We observed negative correlations to previous August to October temperatures, which remained significant along the whole century at the mid- and high-elevation sites, whereas the response to this variable was not as strong at LIN. CBS presented a quite stable pattern in the response to temperatures throughout the 20th century, showing a stronger response to previous August-October temperatures than to current February-March. At NAV and PMB, the response to previous August to October temperatures increased during the first half of the century, turning into a steady decrease during the second half of the century. The positive correlation to late winter temperature (February-March) followed a similar pattern at mid-elevation, becoming less significant towards the third quarter of the century, but increasing in the last decades. At the lowest site, response to temperature was less intense than elsewhere, but the pattern for current February-March temperatures was similar; this site seemed more sensitive to current June-July and, particularly, previous August-October temperatures. At mid and high elevations, negative correlations to June-July temperatures became non-significant by the second quarter of the 20th century, and so remained until present.

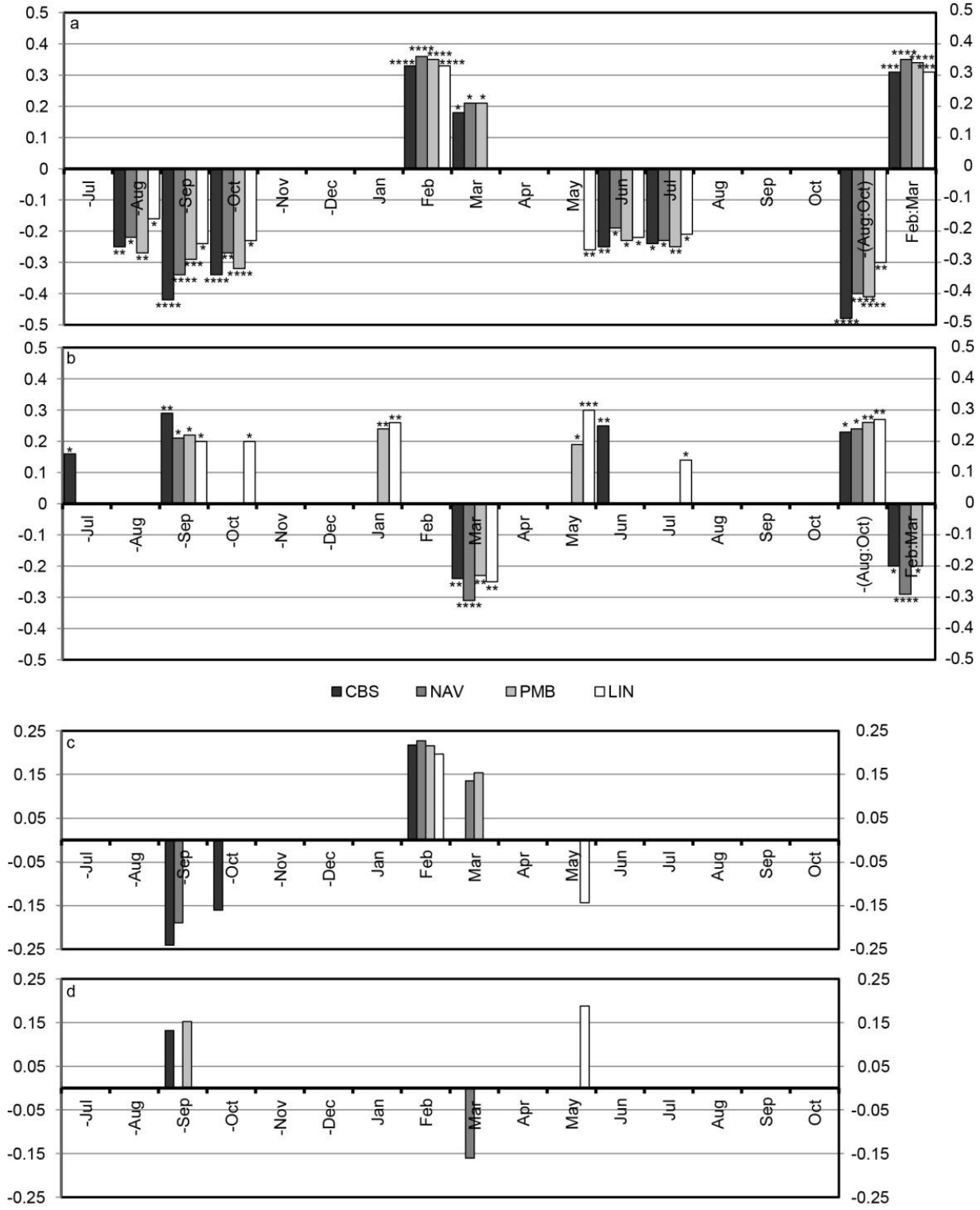

Figure 5. Bootstrapped correlation functions between the residual chronologies and monthly temperature (**a**) and precipitation (**b**), for the period 1902-2009; and response functions for temperature (**c**) and precipitation (**d**) for the same period. All calculations were performed for a 16-month window (July previous year to October current year); correlation functions also include calculations for the intervals August-October previous year and February-March current year. Only significant results are shown (*: $P<0.05$, **: $P<0.01$, ***: $P<0.001$, ****: $P<0.0001$).

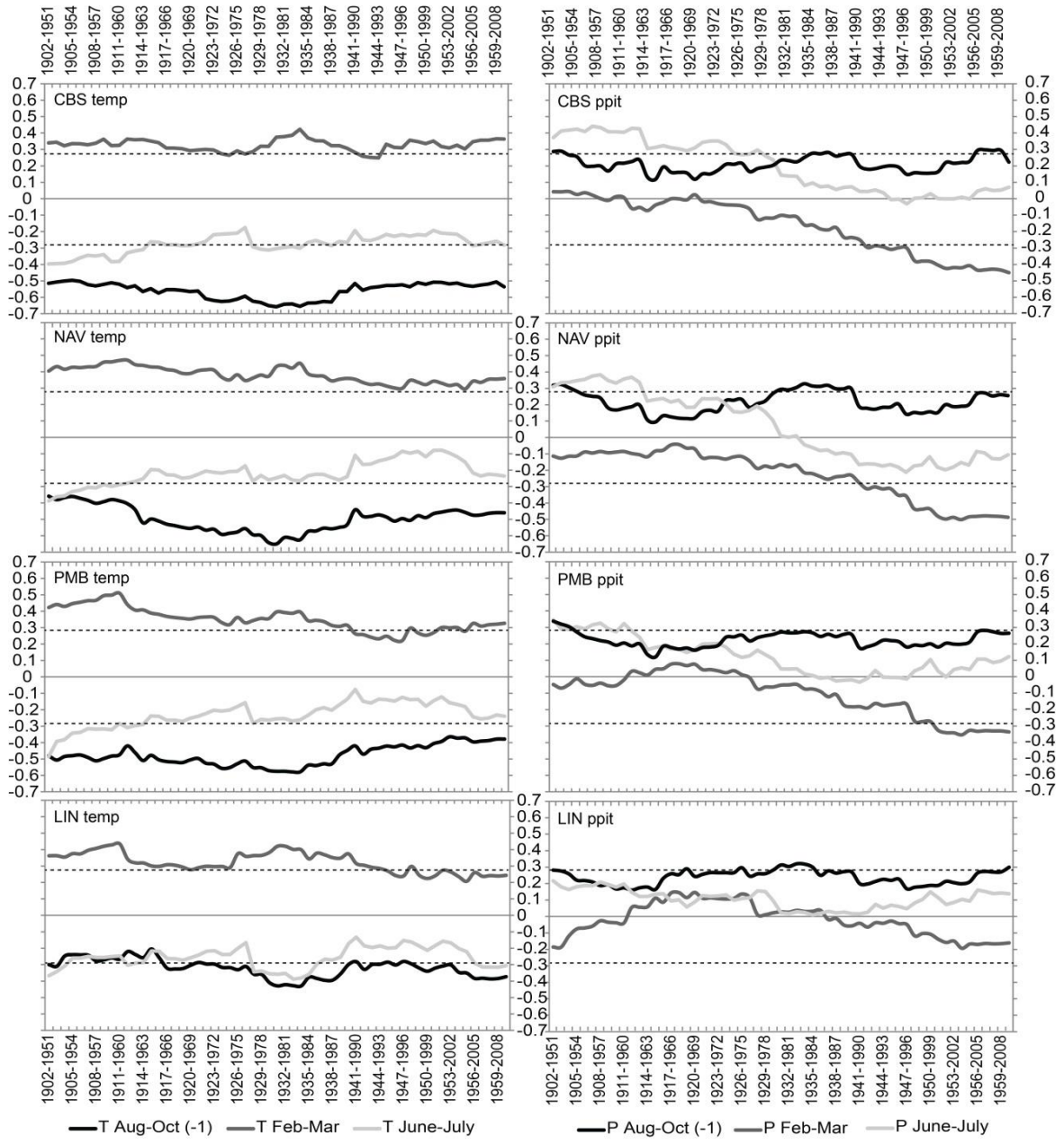

Figure 6. Evolution of growth responses to temperature and precipitation at the four study sites of the Cazorla Mountains for the period 1902-2009, calculated by moving correlation functions (50-year period shifted one year). Dashed horizontal lines indicate a significance level of $P<0.05$.

The role of precipitation on tree growth was very unstable through time (Fig. 6). At LIN, we found no clear response to precipitation. At the mid- and high elevation sites, the response to current June-July precipitation became non-significant already in the first half of the 20th century. More remarkably, the response to February-March precipitation increased steadily, reaching highly significant negative correlations towards the last quarter of the 20th century. This response reached the highest values at NAV, although it seemed to stabilize in the last two decades at both mid-elevation sites, whereas it still followed an upward trend at CBS for the end of the studied period. Response to previous August-October precipitation was very similar at all elevations, fluctuating slightly along the boundary of positive significant correlations during the 20th century.

3.4. Teleconnections

When considering the whole length of the Cazorla chronologies attaining an EPS>0.85, the highest similarities were found between the mid-altitude chronology NAV and black pine chronologies from the centre and east of Spain (*t*-values higher than 8) (Fig. 7). Lower, although still highly significant similarities also existed with chronologies of this species located further away (including a black pine chronology from Corsica) and with other pine species (*P. sylvestris* L., *P. pinaster*, and *P. mugo* subsp. *uncinata* Ramond ex DC.). NAV also showed strong heteroconnections with a chronology of *Abies pinsapo* Boiss. from the south of Spain, and another chronology of *Cedrus atlantica* Manetti from Morocco. The other mid-altitude chronology (PMB) was also similar to a broad number of black pine chronologies. More remarkable are the heteroconnections obtained between this chronology and other pine species, as well as with the *A. pinsapo* chronology from Spain and with four *C. atlantica* chronologies from Morocco. CBS, the chronology from the altitudinal limit of the species in Iberia, provided highly significant agreements with a broad range of chronologies, including some from black pine, *P. sylvestris*, *P. pinaster*, and *P. mugo* subsp. *uncinata*, the *A. pinsapo* chronology from south of Spain, and two *C. atlantica* chronologies from Morocco, although the *t*-values were lower than the ones for the mid-elevation chronologies (most of the matches ranged between 3 and 4). The best teleconnections for CBS (*t*-value higher than 6) were found with three *P. nigra* chronologies from the centre of Spain, whereas the best heteroconnections (*t*-value between 5 and 6) were obtained with two *P. sylvestris* chronologies from Spain and a *C. atlantica* chronology from Morocco. The chronology from the lowest site (LIN) provided a very good match (*t*=6.9) with a *P. nigra* chronology from the centre of Spain, and lower, but still highly significant teleconnections with other Spanish chronologies of the same species. A high and significant agreement (*t*=5.22) was obtained with a *P. nigra* chronology from southern Turkey.

Tele- and heteroconnections for the common interval 1840-1974 (135 years) delivered similar results. In general, correlations were found with same chronologies, but the degree of similarity decreased in some cases (especially for the upper site) as the statistics calculated are dependent on the length of the compared period. The Cazorla chronologies from mid-elevation maintained high agreements with numerous chronologies of *P. nigra* and *P. sylvestris*. Surprisingly, matches were still found between LIN and NAV and *P. nigra* chronologies from Turkey, although the statistical matches were rather weak (*t*-value between 3.2 and 4.6). Similarities with *C. atlantica* chronologies from Morocco declined for all four Cazorla chronologies in the compared period (*t*-values between 3.0 and 3.6). However, the agreement of CBS with the *P. mugo* subsp. *uncinata* from the Pyrenees increased when considering the common interval (*t*=5.34), as also did the *A. pinsapo* chronology (*t*=5.2).

The multivariate analysis on the crossdating between Cazorla and the chronologies from the reference dataset clearly indicates the importance of altitude within the study area (Fig. 8), as the ordination along the two principal components corresponds to this variation. This analysis, which explains nearly 95% of variance, separates the low-elevation site (LIN) from the highest elevation (CBS), while both sites at mid-elevation remain intermediate, but considerably closer to CBS, regardless of the statistic used for the comparison (correlation coefficient or test of parallel agreement).

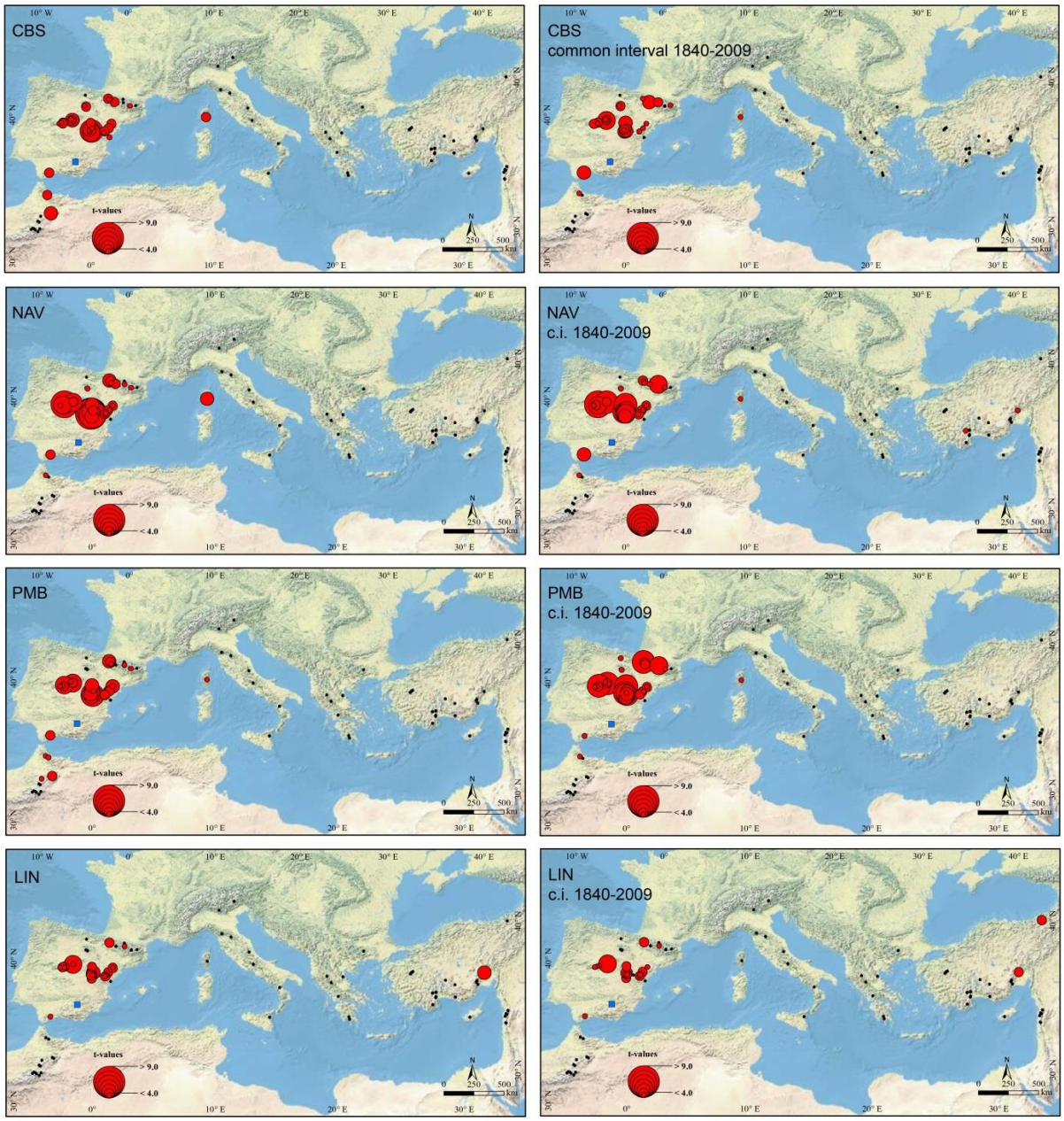

Figure 7. Maps presenting tele- and heteroconnections between the Cazorla chronologies and a selection of chronologies from the Mediterranean basin, for the period with EPS>0.85 (left graphs) and for the common interval 1840-1974 (right). Only *t*-values over 3.0, with a *GL* higher than 55.0% and *P*<0.01 are presented. Black dots indicate chronologies used in the comparison that did not produce results above those values.

4. DISCUSSION

In this contribution, we developed four well replicated chronologies along an almost 1,000 m elevation gradient to understand crossdating potential and radial growth responses to climatic factors of black pine, and their variability through time, as well as the connections between the black pine from the Cazorla Mountains and other conifer species in Iberia and the Mediterranean basin. Black pine in the Cazorla Mountains occurs within an elevation range from ca. 1,000 up to almost 2,000 m a.s.l., hence differences, both in age of the trees (due to different access possibilities for logging) as well as in

growth responses to climatic factors, were expected along the gradient. Such differences have been confirmed by our results.

4.1. Chronology quality and inter-site variability

The developed ring-width chronologies considerably differed in their time span, with trees several centuries older at the upper site. Although the variation of site factors has been reported to affect lifespan of trees as inversely related to growth rates (Di Filippo et al., 2012), we cannot assess this relationship, given the human impact on both stand structure and history at our sites. In fact, age structure appears to reflect the history of intense logging activities carried out well up to the 19th century in the most accessible lower part of the mountains (De Aranda y Antón, 1990, 1999; Araque Jiménez, 2007; Ruiz García, 2010). At the upper part, a well replicated chronology reaching back to AD 1331 was obtained, followed by a chronology of considerable length (466 years) at the mid elevation site PMB, but a long chronology was not possible at the lowest altitude as a result of such activities. However, trees at each site showed a strong common response despite the differences in age classes, as demonstrated by the rbar values and the low number of trees needed to achieve an EPS>0.85. This indicates a high quality of the collected material for not only for ecological research (Briffa, 1995) but also for dendro-archaeological purposes, as it shows a high potential to crossdate series from single trees (as opposed to object tree-ring mean curves representing several trees) with chronologies from the same elevation. Such situation can be of great importance if the construction of a well-replicated mean curve from historical material is not possible due to limited sampling options (e.g., when investigating historical wooden artefacts such as furniture, sculptures, or string instruments).

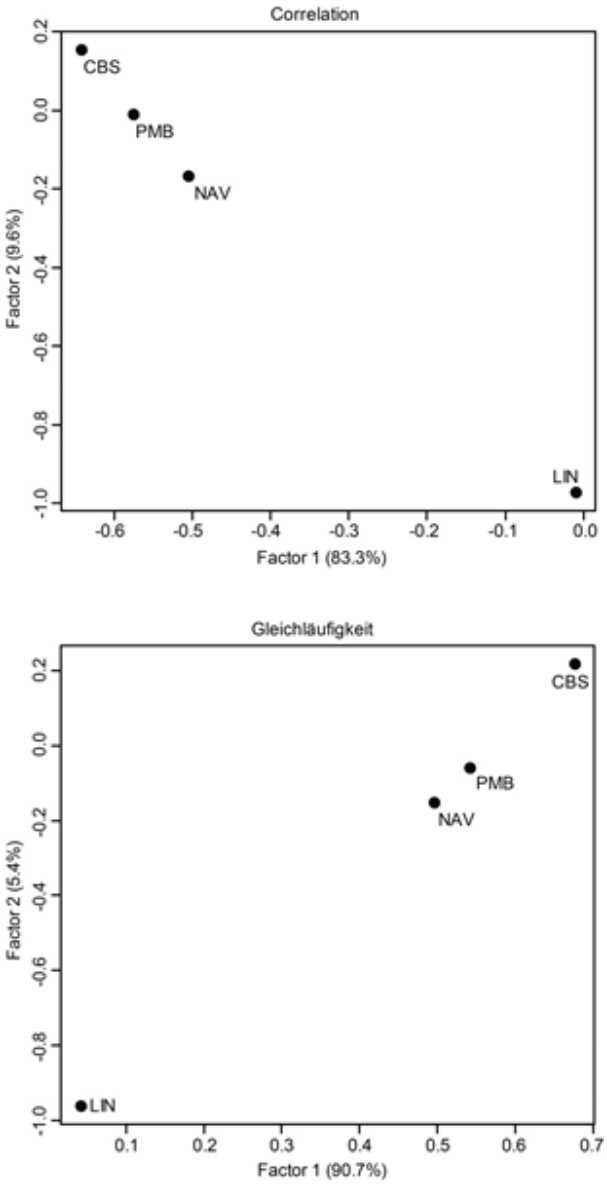

Figure 8. Principal component analysis of the comparison between the Cazorla chronologies and their crossdating to other Mediterranean STD chronologies, considering correlation coefficients and percentage of parallel variation.

Crossdating patterns among different chronologies can vary through time due to changing sample size or variations in the conditions that constraint growth (Briffa and Jones, 1990; Wilson and Elling, 2004; Andreu et al., 2007), and consequently it is important to compare them in different time periods. In this study, moving correlations among chronologies through the common interval

1840-2009 showed in general a high degree of analogy. The similarity among site chronologies was mainly determined by the elevation pattern, but several periods were more synchronous than others, especially from the 1970s onwards (synchronous upward trend). Since common variance in tree-growth is most likely caused by climate (Fritts, 1976), such synchronous patterns seemed to point at periods of increased common signal within sites, and also along the gradient, hence suggesting that climate became more limiting at all elevations in a similar way, particularly for the last four decades. These results agree with those reported by Andreu et al. (2007) for several pine species on sites at different elevations in the eastern half of Spain.

Despite the existence of a common pattern to all sites, our results also indicate that the affinity among the created chronologies is clearly dependent on elevation. The strong statistical results found between the lower and the upper sites are restricted to 1840-2009, a period with a high sample depth for all chronologies, but they cannot assure whether they could be extrapolated to previous periods. Using the CBS chronology (upper site) to date low-replicated object mean curves from 15^{th} to 17^{th} century artifacts or structures, made of wood from the lower part of the mountains, does not guarantee to yield any satisfactory results. Consequently, dendrochronological dating of historical wood from the Cazorla Mountains may result as challenging as dating *Picea abies* or *Abies alba* from different elevations happened to be in the south of Germany (e.g. Wilson and Hopfmueller, 2001; Dittmar et al., 2012). Therefore, sampling strategies for the development of long-span reference chronologies should focus on the acquisition of a dense tree-ring dataset from different elevations before trying to systematically date historical objects.

4.2. Radial-growth responses to climate

As climate is the main driving force that determines year-to-year variation of tree-rings (Fritts, 1976), tree-ring responses to climate should explain the main sources of variation for the crossdating among sites. In the present work, despite the existence of a common pattern to all sites, growth responses to climatic factors also differed along the studied elevation gradient, as has been observed in other studies along gradients (e.g. Di Filippo et al., 2007; Wilson and Hopfmueller, 2001; Dittmar et al., 2012). Overall, the developed dataset contains a strong temperature signal, with trees from the mid and upper sites having a very strong inverse relationship to temperature in previous late summer, and weaker to current year summer, as well as a mild positive response to current year February. These results are consistent with those found by Dorado Liñán et al. (2012) for adult and old black pines in the same area, which should be expected, as their PN-S site overlaps with our upper site (CBS). However, Dorado Liñán and others used climatological data from local stations, whereas we used CRU data. This demonstrates that both sources of data lead to the same results regarding growth responses in this area.

The negative effect of previous year August-September temperature coupled with the positive effect of precipitation has also been reported by other studies on conifers growing at mid and high elevations in eastern and north-eastern Spain (Richter et al., 1991; Andreu et al., 2007), as well as in the Alps (e.g. Büntgen et al., 2006). As suggested by Andreu et al. (2007), conditions in previous late summer would probably modulate the amount of carbohydrates available for the following season, so that a

prolonged growing period in the previous year would lead to a narrower ring in the current year, as a result of the consumption of the available photosynthates instead of their storage.

Relationships (negative to precipitation and positive to temperature) were also strong at the end of winter, i.e., the quiescent period when winter rest can be broken if environmental factors are favourable. Therefore, such responses appear to be related to the resumption of growth, i.e., moist and cold conditions prolong winter dormancy and thus result in a narrower ring.

Some responses were also observed during the current early summer, namely tree rings negatively related to temperature. Under such Mediterranean climate, summer precipitation is greatly reduced, and soil water reserves from winter and spring should be fundamental for summer growth, so that we hypothesize that temperature is probably modulating water loss by evapotranspiration. In fact, our results indicate that tree growth mostly occurs during spring, and the responses obtained determine the available reserves within the tree (previous summer), and the extension of the growing season by anticipating its beginning (warm late winter) or prolonging spring growth (mild early summer).

At the lowest site, differences were more remarkable than among the three other sites; among these, we found a response to water availability in spring (negative to May precipitation, positive to temperature), which is probably related to the anticipation of the summer drought characteristic to Mediterranean environments. According to Fritts (1976), tree-growth is more susceptible to variations for species living at their ecological limits. This could explain the differences between LIN and the upper sites, which are exposed to different prevailing limiting factors. In addition, LIN is made out of considerably younger trees, which may retain a different climatic signal than the older trees from the upper sites (Fritts, 1976; Briffa and Jones, 1990). Dorado Liñán et al. (2012) found homogeneous growth responses to climate among adult and old black pines in the upper part of the Cazorla Mountains, concluding that age did not affect climate-growth responses. However, given the considerable young age of the trees from our low-elevation site (not more than 170 years) those results cannot be extrapolated. For dendro-historical studies, the observed variations in climate-growth responses between the upper and lower sites could be limiting for crossdating, but the mid-elevation chronologies, which attain a longer span, may serve as bridge, helping dating historical timbers from lower sites.

4.3. Dynamic growth-responses through time

The strong responses found at the mid and upper elevation sites to temperature imply important consequences for the historical and climatological usefulness of these series, since they should greatly facilitate crossdating ring-width series from historical timbers from the same altitude. Similarly, a composite chronology developed from living trees and historical timbers from the mid and high elevation sites, should serve as a high resolution proxy for the study of past environmental conditions in the western Mediterranean (see results of Richter and Eckstein, 1990). However, our results also show that these growth responses are dynamic, presenting a marked shift in the strength of the response to previous year late summer temperatures towards the mid-20th century at the mid and high elevation sites, as well as an increasing effect (negative correlation) of precipitation from current February-March as the century progressed, becoming highly significant after the 1970s. At the lower site, response to current February-March temperature had practically lost significance since the 1970s,

whereas response to previous August-October precipitation seemed to have gained increasing relevance for the last two decades. This could be related to the considerable increase in February and March temperatures observed for the last decades in the climatic data used in this work (not shown).

Such shifts in growth-response to climatological variables are not easy to interpret, as they could be triggered by several factors (see Büntgen et al., 2012). However, the influence of changing climatic variables at a regional scale is a plausible explanation, as episodes of increased spring and winter temperatures, as well as fluctuating precipitation regimes in the late 19th century have been reported for the area, together with an increase of summer temperatures for the second half of the 20th century (Linares and Tíscar, 2011). Changes in radial-growth responses to climate have been reported not only in central Europe and Scandinavia (e.g. Mäkinen et al., 2002; Carrer and Urbinati, 2006; Büntgen et al., 2012), but also in the Mediterranean region, e.g. eastern Spain (Andreu et al., 2007) for different conifer species at various elevations, and using different standardization methods and meteorological records, hence supporting the non-stationary character of growth responses to regional climatic factors as suspected by Carrer and Urbinati (2006).

However, this considerable limitation for dendroclimatological research should not necessarily be a handicap for historical purposes, as long as the variations in the responses to climate along time are similar among sites. This seems to be the case for our study, since the trend of the changing responses to temperature and precipitation had a similar pattern among the sites regardless of the elevation.

4.4. Teleconnections and the supra-regional climatic signal

In general, drought is considered to be the most limiting factor for tree growth in the Mediterranean Basin (Specht, 1981), being dry summers and a high inter-annual precipitation variability unfavorable factors for plant growth (Mitrakos, 1980). Therefore, tree-growth response of conifers is expected to be homogeneous over large areas in the south-east of the Iberian Peninsula Richter et al. (1991). But our results indicate that this macro-climatic signal is not constant through time, and also that variations in regional climatic factors may induce different responses along with elevation. Such situation can hamper crossdating of tree-ring series, which should be taken into consideration for dendro-historical studies.

The similarities we found between the Cazorla chronologies and other black pine chronologies from Spain are consistent with the results reported by Richter et al. (1991) and Andreu et al. (2007), who found that pines of different species growing at similar altitudes and exposures presented highly similar growth variations. As previously stated by those authors, this evidences the existence of a common climatic signal over the western Mediterranean, and encourages the development of a regional black pine master chronology for this area. Furthermore, the high similarities between these chronologies and some chronologies of *P. sylvestris* from the Iberian Peninsula would also justify the combination of both species into a regional master chronology, although the effects of such mixture of species on the statistical dating of historical timbers should be carefully evaluated. Likewise, high similarities between the mid-elevation Cazorla sites with the *A. pinsapo* and the *C. atlantica* chronologies from northern Morocco indicate that the common climatic signal is consistent along a latitudinal gradient (from northern Morocco to north-eastern Spain). However, the decreased agreement with the *C. atlantica* chronologies when restricting the compared period to a common

interval of 135 years could indicate that the signal captured by both species is a low-frequency (i.e. multi-decadal to multi-centennial) signal. If this is the case, the construction of hetero-chronologies including *C. atlantica* is not advisable, as the high-frequency signal needed for dating historical timbers would not be enhanced, but reduced.

Highly significant teleconnections with black pine chronologies from the eastern Mediterranean (especially between sites at mid and low elevations) could indicate the existence of a macro-climatic signal reaching both ends of the basin. Nevertheless, the underlying reason for these connections should be properly identified and described, as the western Mediterranean (unlike the eastern part) is strongly influenced by the North Atlantic Oscillation, which affects winter precipitation and may have an influence on growth responses to February precipitation (e.g. Zorita, 1992; Hurrel, 1995), whereas this effect diminishes towards the eastern part of the Mediterranean basin.

5. FUTURE PERSPECTIVES AND CONCLUDING REMARKS

The construction of well-replicated black pine ring-width chronologies along the ca. 1,000 m elevation gradient of this species in the Cazorla Mountains revealed significant differences in climate-growth relationships along the gradient and through time. Such differences seem to be triggered by regional climate fluctuations and adaptive responses of trees, and they may hamper crossdating of historical data derived from low-elevation trees with the long chronology obtained at the high elevation site. To overcome this obstacle, the chronologies from the mid elevation sites may act as crossdating bridges, as they show more similarities to the lower site than to the upper chronology.

To achieve a well replicated set of reference chronologies for dating cultural heritage originating from this geographical region, further strategies for tree-ring data compilation should be directed at sites along the elevation gradient, as well as across the latitudinal and longitudinal gradients of the Cazorla Mountains and the rest of the Baetic System, covering all possible niches of black pine in the south of Spain. To improve the replication of the earlier centuries and extend the chronologies back in time, sampling of roof structures from buildings is recommended, although their selection should be preceded by historical research, in order to acquire as much information *a priori* as possible in what regards the origin of the historical wood.

Our results indicate that tree growth is influenced by a combination of factors, which has multiple implications for environmental studies. Notwithstanding this, trees at mid-elevations seem to capture a stronger macro-climatic signal than trees at the upper site. The observed shifts in responses to climatic factors through time should be further explored, and potential age effects on the climatic signal should also be assessed. For the time being, the use of these ring-width chronologies for climatic reconstructions is not advisable; we recommend the assessment of the temporal dynamics of climate-growth responses before climatic interpretations and reconstructions are made.

The common signal found with chronologies of black pine and other conifer species in Iberia, northern Morocco and Turkey, especially among mid-elevation sites, indicates the existence of a macro-climatic signal in stands at similar elevations. This signal should be better understood, as it may lead to supra-regional chronologies for the Mediterranean basin, which could be used for historical and climatological purposes.

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References

Alejano, R., Martínez. E., 1996. Distribución de *Pinus nigra* Arn. ssp. *salzmannii* en las Sierras Béticas. *Ecologia* **10**, 231–241.

Alejano, R., 1997. Regeneración natural de *Pinus nigra* Arn. ssp. *salzmannii* en las Sierras Béticas. Dissertation, Universidad Politécnica de Madrid.

Andreu, L., Gutiérrez, E., Macias, M., Ribas, M., Bosch, O., Camarero, J.J., 2007. Climate increases regional tree-growth variability in Iberian pine forests. *Glob Change Biol* **13,** 1–12.

Araque Jiménez, E., 2007. Conducciones fluviales de madera desde las Sierras de segura y Cazorla (1849-1949). *Cuad Geogr* **40**, 81–105.

Baillie, M.G.L., 1982. *Tree-ring Dating and Archaeology*. University of Chicago Press, Chicago.

Biondi, F., 1997. Evolutionary and moving response functions in dendroclimatology. *Dendrochronologia* **15**,139–150.

Biondi, F., Waikul, K., 2004. DENDROCLIM2002: A C++ program for statistical calibration of climate signals in tree-ring chronologies. *Comput and Geosci* **30**,303–311.

Briffa, K.R., 1995. Interpreting high-resolution proxy climate data. The example of dendroclimatology, in Von Storch, H., Navarra, A. (Eds), *Analysis of climate variability. Applications of statistical techniques*, Proceedings Autumn School Commission of the European Community, Elba Oct 30-Nov 6 1993, Springer-Verlag Berlin Heidelberg, pp 77–94.

Briffa, K., Jones, P.D., 1990. Basic chronology statistics and assessment, in Cook, E.R., Kairiukstis, L.A. (Eds), *Methods of Dendrochronology - Applications in the Environmental Sciences*, Kluwer Academic Publishers and International Institute for Applied Systems Analysis, Dordrecht, pp 137–152.

Briffa, K.R., Jones, P.D., Bartholin, T.S., Eckstein, D., Schweingruber, F.H., Karlen, W., Zetterberg, P., Eronen, M., 1992. Fennoscandian summers from AD 500: temperature changes on short and long timescales. *Clim Dyn* **7**,111–119.

Büntgen, U., Esper, J., Frank, D.C., Nicolussi, K., Schmidhalter, M., 2005. A 1052-year tree-ring proxy for Alpine summer temperatures. *Clim Dyn* **25**,141–153.

Büntgen, U., Brázdil, R., Heussner, K.U., Hofmann, J., Kontic, R., Kyncl, T., Pfister, C., Chromá, K., Tegel, W., 2011a. Combined dendro-documentary evidence of Central European hydroclimatic springtime extremes over the last millennium. *Quat Sci Rev*. doi: 10.1016/j.quascirev.2011.10.010

Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J.O., Herzig, F., Heussner, K.U., Wanner, H., Luterbacher, J., Esper, J., 2011b. 2500 years of European climate variability and human susceptibility. *Science* **331**, 578–582.

Büntgen, U., Frank, D., Neuschwander, T., Esper, J., 2012. Fading temperature sensitivity of Alpine tree growth at its Mediterranean margin and associated effects on large-scale climate reconstructions. *Clim Change*, doi: 10.1007/s10584-012-0450-4

Carrer, M., Urbinati, C., 2006. Long-term change in the sensitivity of tree-ring growth to climate forcing of *Larix decidua*. *New Phytol* **170**, 861–872.

Cook, E., 1990. A conceptual linear aggregate model for tree rings, in Cook, E.R., Kairiukstis, L.A. (Eds), *Methods of Dendrochronology. Applications in the Environmental Sciences*, Kluwer, Dordrecht, pp 98–104.

Cook, E.R., Holmes, R.L., 1986. Guide for computer program ARSTAN, in Holmes, R.L., Adams, R.K., Fritts, H.C. (Eds), *Tree-Ring Chronologies of Western North America: California, eastern Oregon and northern Great Basin*, Laboratory of Tree Ring Research, University of Arizona, Tucson.

Cook, E.R., Peters, K., 1981. The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree Ring Bull* **41**, 45–53.

Córdoba de la Llave, R., 1990. *La industria Medieval de Córdoba*. Caja provincial de Ahorros de Córdoba, Córdoba.

Creus, J., 1998. A propósito de los árboles más viejos de la Península, los *Pinus nigra* Arn. ssp. *salzmannii* (Dunal) Franco de Puertollano-Cabañas, sierra de Cazorla, Jaén. *Montes* **54**, 68–76.

De Aranda y Antón, G., 1990. *Los Bosques Flotantes: historia de un roble del siglo XVIII*. Colección Técnica, Ministerio de Agricultura, Pesca y Alimentación, ICONA, Madrid.

De Aranda y Antón, G., 1999. Visión histórica de la selvicultura popular española, in Marín Pageo, F., Domingo Santos, J., Calzado Carretero, A. (Eds), *Los montes y su historia: una perspectiva política, económica y social*. I Jornadas Forestales: historia, socioeconomía y política forestal, Universidad de Huelva, Huelva, pp 9–31.

De la Cruz Aguilar, J., 1994. *La destrucción de los Montes*. Universidad Complutense de Madrid, Madrid.

Di Filippo, A., Biondi, F., Čufar, K., De Luis, M., Grabner, M., Maugeri, M., Presutti Saba, E., Schirone, B., Piovesan, G., 2007. Bioclimatology of beech (*Fagus sylvatica* L.) in the Eastern Alps: spatial and altitudinal climatic signals identified through a tree-ring network. *J Biogeogr* **34**, 1873–1892.

Di Filippo, A., Biondi, F., Maugeri, M., Schirone, B., Piovesan, G., 2012. Bioclimate and growth history affect beech lifespan in the Italian Alps and Appenines. *Glob Change Biol* **18**, 960–972.

Dittmar, C., Eissing, T., Rothe, A., 2012. Elevation-specific tree-ring chronologies of Norway spruce and Silver fir in Southern Germany. *Dendrochronologia*, doi: 10.1016/j.dendro.2011.01.013

Dorado Liñán, I., Gutiérrez, E., Heinrich, I., Andreu-Hayles, L., Muntán, E., Campelo, F., Helle, G., 2012. Age effects and climate response in trees: a multi-proxy tree-ring test in old-growth life stages. *Eur J Forest Res* **131**, 933–944.

Eckstein, J., Leuschner, H.H., Bauerochse, A., 2008. Dendroecological studies on subfossil pine and oak from ‘‘Totes Moor’’ near Hannover, Lower Saxony, Germany. *Tree Ring in Archaeology, Climate and Ecology* 6, pp 70–76.

Eckstein, J., Leuschner, H.H., Giesecke, T., Shumilovskikh, L., Bauerochse, A., 2010. Dendroecological investigations at Venner Moor (NW Germany) document climate-driven woodland dynamics and mire development in the period 2450-2050 BC. *Holocene* **20**, 231–244.

Fernández- Golfín, J.I., Díez, M.R., Baonza, M.V., Gutiérrez, A., Hermoso, E., Conde, M., Vanden, V., 2001. Caracterización de la calidad y propiedades de la madera de Pino laricio (*Pinus nigra* Arn. ssp. *salzmannii*). *Invest Agrar Sist Recur For* **10(2)**, 311–331.

Fritts, H.C., 1976. *Tree-rings and climate*. London, New York and San Francisco Academy Press.

Grissino-Mayer, H.D., 2001. Evaluating crossdating accuracy: A manual and tutorial for the computer program COFECHA. *Tree-Ring Res* **57(2)**, 205–221.

Haneca, K., Čufar, K., Beeckman, H., 2009. Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. *J Arch Sci* **36**, 1–11.

Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull* **43**, 69–78.

Jansma, E., 1996. An 1100-Year Tree-Ring Chronology of Oak for the Dutch Coastal Region, in Dean, J.S., Meko, D.M., Swetnam, T.W. (Eds), *Tree Rings, Environment, and Humanity*. Radiocarbon, Department of Geosciences, The University of Arizona, Tucson, pp 769–778.

Kozlowsky, T.T., Pallardy, S.G., 1997. *Growth control in woody plants*. Academic Press, San Diego.

Kromer, B., 2009. Radiocarbon and dendrochronology. *Dendrochronologia* **27**, 15–19.

Kuniholm, P.I., 1996. Long tree-ring chronologies for the Eastern Mediterranean, in Demirci Ş, Özer AM, Summers GD (Eds), *Archaeometry 1994: The Proceedings of the 29th International Symposium on Archaeometry*, Ankara, pp 401–409.

Leuschner, H.H., Sass-Klaassen, U., Jansma, E., Baillie, M.G.L., Spurk, M., 2002. Subfossil European bog oaks: population dynamics and long-term growth depressions as indicators of changes in the Holocene hydro-regime and climate. *Holocene* **12**, 695–706.

Linares, J.C., Tíscar, P.A., 2010. Climate change impacts and vulnerability of the southern populations of *Pinus nigra* subsp. *salzmannii*. *Tree Physiol* **30,** 795–806.

Linares, J.C., Tíscar, P.A., 2011. Buffered climate change effects in a Mediterranean pine species: range limit implications from a tree-ring study. *Oecologia* **167(3)**, 847-859.

Martín-Benito, D., Cherubini, P., Del Río, M., Cañellas, I., 2008. Growth response to climate and drought in *Pinus nigra* Arn. trees of different crown classes. *Trees* **22**, 363–373.

Mason, S.J., Mimmack, G.M., 1992. The use of bootstrap correlation coefficients in climatology. *Theor Appl Climatol* **45**, 229–233.

Mäkinen, H., Nö dj, P., Kahle, H.P., Neumann, U., Tveite, B., Mielikäinen, K., Röhle, H., Spiecker, H., 2002. Radial growth variation of Norway spruce (*Picea abies* (L.) Karst.) across latitudinal and altitudinal gradients in central and northern Europe. *For Ecol Manag* **171**, 243–259.

Mitrakos, K.A., 1980. A theory for Mediterranean plant life. *Acta oecol* **1**, 245–252.

R Development Core Team, 2012. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna.

Richter, K., Eckstein, D., 1990. A proxy summer rainfall record for southeast Spain derived from living and historic pine trees. *Dendrochronologia* **8**, 67–82.

Richter, K., Eckstein, D., Holmes, R.L., 1991. The dendrochronological signal of pine trees (*Pinus* spp.) in Spain. *Tree Ring Bull* **51**, 1–13.

Rodríguez Trobajo, E., 2008. Procedencia y uso de madera de pino silvestre y pino laricio en edificios históricos de Castilla y Andalucía. *Arqueol Arquit* **5**, 33–53.

Ruiz García, V., 2010. *De Segura a Trafalgar*. El Olivo de Papel, Jaén.

Schweingruber, F.H., 1996. *Tree rings and Environment. Dendroecology*. Paul Haupt Verlag, Berne.

Specht, R.I., 1981. Primary production in Mediterranean climate ecosystems regenerating after fire, in Di castri, F., Goodall, D.W., Specht, R.I. (Eds), *Mediterranean type shrublands*, Elsevier, Amsterdam.

Tíscar, P.A., 2004. Estructura, regeneración y crecimiento de Pinus nigra en el área de Reserva Navahondona-Guadahornillos (Sierra de Cazorla, Jaén). Dissertation, Universidad Politécnica de Madrid.

Wigley, T.M.L., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *J Clim Appl Meteorol* **23**, 201–213.

Wilson, R., Elling, W., 2004. Temporal instability in tree-growth/climate response in the Lower Bavarian Forest region: implications for dendroclimatic reconstruction. *Trees* **18**, 19–28.

Wilson, R.J.S., Hopfmueller, M., 2001. Dendrochronological investigations of Norway spruce along an elevational transect in the Bavarian Forest, Germany. *Dendrochronologia* **19(1)**, 67–7.

ARTICLE 3

Dendroarchaeological research on roof structures from architectural heritage in Andalusia (Spain): case studies of the Jaen catedral and the *Colegial del Salvador* church in Seville

Domínguez-Delmás, M., Alejano-Monge, R., Wazny, T., *en prep*.

Detail of the roof structure of the nave at *Colegial del Salvador* church (photo: M. Domínguez Delmás).

DENDROARCHAEOLOGICAL RESEARCH ON ROOF STRUCTURES FROM ARCHITECTURAL HERITAGE IN ANDALUSIA (SPAIN): CASE STUDIES OF THE JAEN CATEDRAL AND THE *COLEGIAL DEL SALVADOR* CHURCH IN SEVILLE

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Abstract

We present the results of dendroarchaeological investigations carried out on roof structures from two historic buildings in the Andalusian region (south of Spain). Both the Jaen cathedral and the *Colegial del Salvador* church, in Seville, were built on the sites of medieval mosques after centuries of using the Islamic buildings for Christian worship. Jaen cathedral contains roof structures dating from the 16th, 17th and 18th centuries, whereas those of the *Colegial del Salvador* were completed between AD 1703 and 1709. Historical sources report that wood from the Cazorla and Segura mountains, located in the east of Andalusia, was used in the construction of both buildings. Therefore they represent excellent case studies to investigate the supply of timber for construction purposes in different centuries, including aspects such as wood provenance, transport of timber, and the evolution of wood-working techniques throughout the centuries.

During the inspection of the roof structures, we found different assembly marks at the 16th century roof of Jaen cathedral, and distinct tool marks in all researched structures. Furthermore, at the *Colegial del Salvador* church we found reused timbers and material evidence for historical rafting of timbers in the Guadalquivir River. We discuss these finds and compare them with parallels of other Spanish and European regions. Additionally, the research resulted in the successful dating of all construction phases of Jaen cathedral, confirming the historical information, and the dating potential of recently developed chronologies of black pine from the Cazorla and Segura mountains. At the *Colegial del Salvador* church only two timbers could be dated, demonstrating the complexity of the organisation of timber supply for this building at the turn of the 17th century, and the need to continue developing reference chronologies at different elevations throughout Andalusian mountains.

Keywords

Tree-ring dating, building history, timber frame roofs, wood supply, rafting joints, tools, assembly marks, Iberian Peninsula

1. INTRODUCTION

The potential of dendrochronology to provide absolute dates for wooden objects makes it a very attractive science for the study of Cultural Heritage. In the particular case of historic buildings, felling dates of structural elements such as ceiling and roof timbers contribute to the understanding of the building's history and can provide an exact chronology for different construction phases and later repairs (e.g. Wazny and Kloda, 2003; Haneca and Debonne, 2012; Brun and Tegel, 2007). Such information supports the historical value of a building, and serves to make well-informed assessments towards future renovations and conservation strategies. Furthermore, conducting a full dendroarchaeological research on the timber structures of a building (i.e. observing and decoding tool and carpenter's marks, as well as identifying rafting features) can increase our understanding about ancient wood-working techniques, timber-quality requirements and the organization of timber supply in specific time periods (i.e. Wrobel et al., 1993; Crone and Mills, 2002; Miles, 2006).

The region of Andalusia, in the south of Spain (Fig. 1), hosts an important amount of cultural and natural heritage. The architectural heritage in particular is especially noteworthy, as numerous buildings and architectural ensembles are representative of different periods, styles and cultures (e.g. Islamic, Gothic, Renaissance or Baroque). Proof of the relevance and uniqueness of the architecture in this region is the inclusion of several architectural ensembles in UNESCO's World Heritage List, such as the Historic centre of Cordoba (including the Great Mosque), the architectural ensemble of the *Alhambra, Generalife and Albaycin* in Granada, the Renaissance monumental ensembles of Ubeda and Baeza, and the architectural ensemble of the *Cathedral, Alcazar and Archivo de Indias* in the centre of Seville (UNESCO World Heritage List, last accessed 14 July 2015).

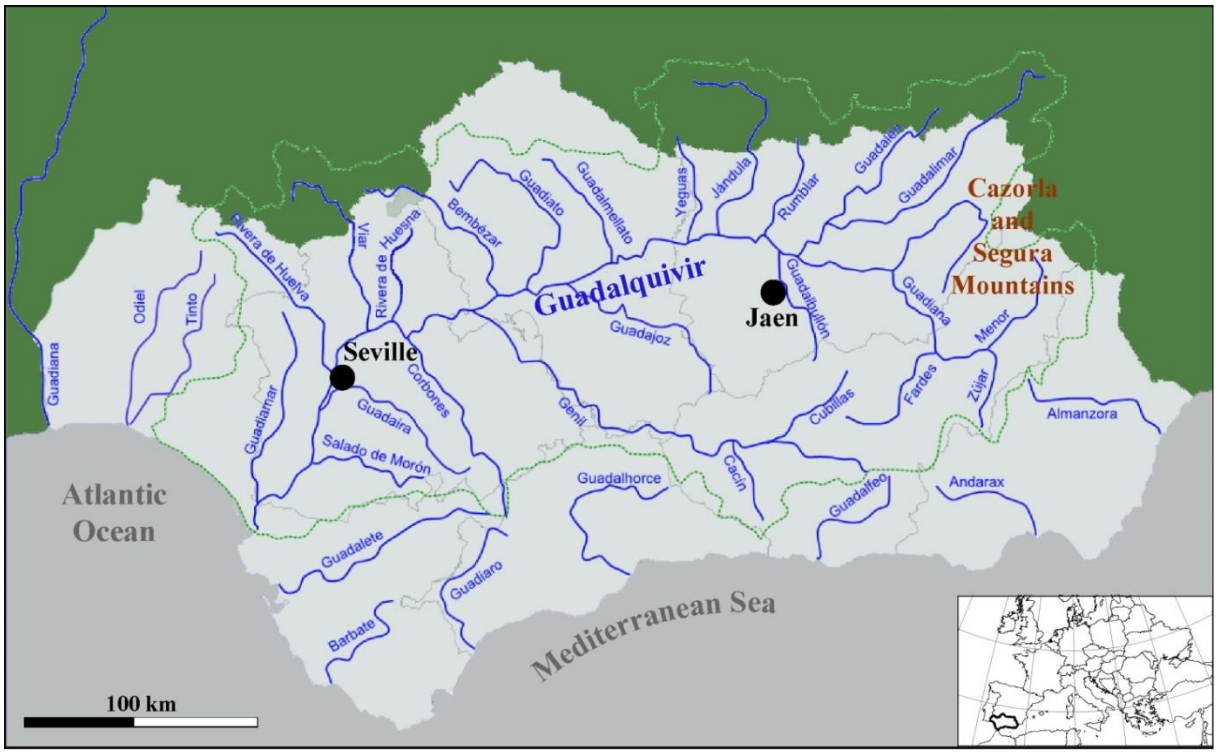

Figure 1. Region of Andalusia, located in the south of Spain. The dashed green line encloses the Guadalquivir River watershed, which covers most of the region. The Cazorla and Segura Mountains are located in the eastern border.

Wood was an essential material in the region for the construction and decoration of religious temples, palaces and vernacular buildings (Córdoba de la Llave, 1990; Martínez Ruiz , 1999). Its use was not restricted to roofs. Coffered ceilings, stairs, floors, doors, windows, as well as scaffolding, lifting cranes and other devices necessary to handle construction materials such as stone were also made of wood (Higueras Maldonado, 2009; Albendea Ruz, 2011). Timbers from roof structures of religious buildings in Andalusia have a particular interest for dendroarchaeology, as numerous Christian churches and cathedrals were erected on the sites where medieval Islamic Mosques had been standing (Mendoza, 2008). From the 13th century onwards, Christians used the existing mosques for catholic worship until the dioceses gathered enough economic resources to demolish and replace them by Christian temples. This situation could last several centuries, as in the case of Jaen cathedral and the *Colegial del Divino Salvador* church in Seville for example. Therefore, roof structures from catholic buildings may contain reused timbers from the medieval mosques.

Black pine (*Pinus nigra* subsp. *salzmannii*) was and still is very abundant in the Cazorla and Segura Mountains (eastern Andalusia), where it grows naturally from 1,000 m a.s.l. up to almost 2,000 m. Recently, a set of tree-ring chronologies of black pine from these mountains has been developed along this elevation gradient to provide a tool for dating and provenancing cultural heritage (Domínguez-Delmás et al., 2013). The full length of the chronology from the upper part of the mountains reaches back to AD 1120. Since this species has high quality for construction purposes, it is likely that black pine from these mountains was used in buildings since medieval times. To increase our knowledge about the wood procurement for the construction of Jaen cathedral and the *Colegial del Salvador* church in different centuries, we carried out the inspection and sampling of timbers of roof structures in both buildings following a dendroarchaeological approach.

2. MATERIAL AND METHODS

2.1 Jaen cathedral

The cathedral of Jaen has a very well documented building history (Table 1), being the earliest catholic temple built on the site of a former mosque in the Andalusian region. Following the conquest of Jaen in AD 1246 by the Christians, the Great Mosque was consecrated to the Virgin of the Assumption to be used for Christian worship. Between AD 1368 and 1382, the Islamic building was demolished and replaced by a Christian cathedral (Mendoza, 2008). However, the available financial resources must have been a limiting factor when purchasing materials, as the newly built Gothic cathedral had to be demolished by the late 15th century, and the one that followed, built in the same architectural style, was about to collapse in AD 1525, and again had to be demolished. In AD 1551, the construction of a new cathedral based on a Renaissance design by Andres de Vandelvira was launched with the support of newly collected funds. The sacristy was completed in AD 1577. Construction works were interrupted at the end of the 16th century due to an economic crisis, but were resumed again in AD 1635 thanks to an annual allowance granted to the diocese. The architect Juan de Aranda Salazar concluded the transept and the dome, and in AD 1660 the temple was consecrated. The facade was concluded in AD 1688. The choir was made in the 18th century reusing the 16th-century stalls, and its dome was completed in AD 1726. The tabernacle was built between AD 1764 and 1801.

According to Higueras Maldonado (2009), wood from the Cazorla and Segura Mountains was purchased for the roof structures of the cathedral in AD 1650, 1651 and 1652, and "old timbers" were used in scaffoldings. This historian also reports that old wood that could not be reused was sold in AD 1652 and 1653 to pay for new wood for the roof structures, and in AD 1734 to invest in the making of confessionals.

Currently, the cathedral awaits its inclusion in the UNESCO World Heritage Site list by extension of the Renaissance monumental ensemble of Ubeda and Baeza to Jaen, as it is a highly representative building of Spanish Renaissance style, which has served as model for cathedrals in south America (http://whc.unesco.org/en/tentativelists/5667/ last accessed 22 July 2015).

Table 1. Most relevant historical and construction events of both buildings.

Jaen cathedral (from **Higueras Maldonado, 2009**)	
AD 1246	Great Mosque of Jaen consecrated to the Virgin of the Assumption
AD 1368-1382	Demolition of the Great Mosque followed by the construction of a Gothic cathedral at the same site
Late 15th century	Demolition of the Gothic cathedral due to structural instability; construction of a second cathedral with the same stile
AD 1525	Demolition of the second Gothic cathedral due to structural instability
AD 1551	Construction of a new Renaissance cathedral begin, based on designs of architect Andrés de Vandelvira
AD 1577	Sacristy is concluded
Late 16th century	Construction works are paralysed due to economic crisis
AD 1635	Construction works are resumed again
AD 1650, 1651, 1652	Purchase of wood from the Cazorla and Segura mountains to be used in roof structures
AD 1660	Transept and dome completed, cathedral consecrated in this year
AD 1668	Façade completed
AD 1726	Dome above the choir completed
AD 1764-1801	Construction of tabernacle
Colegial del Salvador church (from **Mendoza, 2008**)	
AD 829-830	Construction of Ibn Adabbas, Great Mosque of Seville
AD 1182	A new Great Mosque is built on the current site of Seville cathedral; Adabbas mosque continues serving for Islamic worship
AD 1248	Christians take control of Seville and Adabbas is consecrated as collegiate to The Divine Saviour (*El Salvador*)
AD 1671	Adabbas mosque is demolished; construction works of a new Baroque collegiate church begin
AD 1679	Completion and collapse of the new building in the same year
AD 1679-1712	Construction of the second baroque church
AD 1696-1711	Final constructive phase of upper structures designed by Leonardo de Figueroa
AD 1703-1709	Construction of roof structures (pyramids above transept vaults and roof above the central nave)

2.2 The *Colegial del Salvador* church in Sevilla

Just as at Jaen cathedral, the *Colegial del Salvador* church was built on the site of what was *Ibn Adabbas*, the Great Mosque of Seville from the 9th to the 12th century (Mendoza, 2008). The architectural history of this site dates back to Roman times, as indicated by the finds of remains of capitals, columns and honorary epigraphs from that time during different archaeological excavations carried out at the site. Although there are different hypothesis about the type of Roman building(s) that must have preceded the mosque of Ibn Adabbas (e.g. Blanco Freijeiro, 1984; Campos, 1986; Ordoñez Agulla, 2002), it is likely that it must have been a building of great importance, as the persistence of

places of worship across civilizations has been observed in many parts of the old continent (Mendoza, 2008).

Archaeological evidence also has indicated that *Ibn Adabbas* was established as the great mosque of Seville in AD 829-830, and it was used as such until a new mosque was built on the site of the current cathedral in AD 1182 (Mendoza, 2008) (**Table 1**). After the conquest of Seville by the Christians in AD1248, *Adabbas* mosque was consecrated to the Divine Savior of the World (*El Salvador*), with the title of Collegiate Church, and was devoted to Christian worship for over four centuries without being substantially modified. In AD 1671, the building of *Adabbas* mosque was finally demolished to be replaced by a new Collegiate church. Construction works began that same year, but the new baroque building collapsed after its completion in AD 1679. The second one, built also in baroque style between 1679 and 1712, has remained until today. The architect Leonardo de Figueroa was in charge of the last construction phase of the building between AD 1696 and 1711, hence he was given the task to design the upper roofs. Going beyond the functional aspects, he conceived three pyramids above the ribbed vaults of the transept, and a pitched roof along the vaults of the central nave. These structures were built between 1703 and 1709.

In the years 1987, 1991 and 1997, emergency renovation works were carried out given the alarming situation of imminent collapse of some parts of the church. These works were followed by the complete restoration of the building (including the roofs) between 2003 and 2008. The original roof-structure of the lower sacristy was entirely replaced due the bad preservation state of the timber elements (Mendoza, 2008). This construction phase corresponded to the medieval mosque, so the replacement of the original timber elements constitutes an irreparable loss of historic and ecological wooden material. Fortunately, the structures of the upper roofs (the pyramids and the roof above the nave) remained virtually intact due to their good condition. Only the planking under damaged tiles was replaced, but tie-beams and roof trusses remained *in situ*.

2.3 Inspection, selection and sampling of roof timbers

At Jaen cathedral, three roof structures were selected for this research based on their assumed construction periods (Fig. 2): the 16th century roof above the sacristy (JCSAC), including ceiling timbers from the annexed chapter room; the 17th century roof structure above the altar (JCALT); and the 18th century roof structure above the choir (JCCHO). At the *Colegial del Salvador* church, all four original roof structures, i.e. the pyramids (south, CdSPS; east, CdSPE; and north, CdSPN) and the roof above the nave (CdSNA), were inspected and sampled (Fig. 3).

In the selected structures of both buildings, individual timbers were inspected in search for tool and , carpenter's annotations, as well as for transportation marks. Tool marks become clearly visible when placing a beam of raking light along the surface of the timbers, and they provide valuable technological and ethnographical information about the processing of wood in different periods. Carpenter's annotations may be related to the building sequence of a structure, and may provide clues about later repairs or the re-use of timbers when the sequence of marks is broken or different numbering systems are found. Transportation marks are often represented by holes of different shapes in the timbers, which correspond to rafting joints and indicate the transport of the wood in rafts (Eissing and Dittmar, 2011; Haneca and Debonne, 2012).

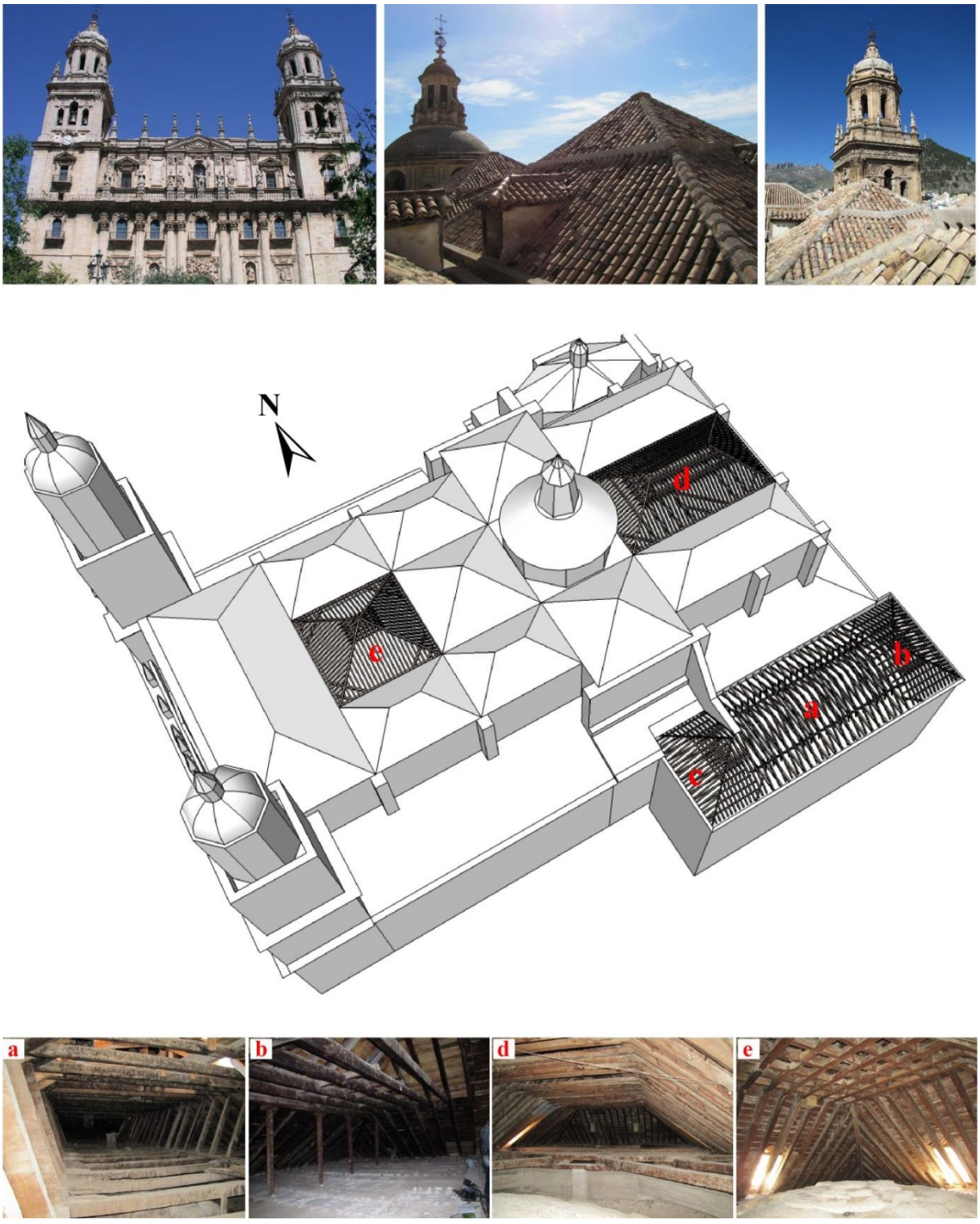

Figure 2. Jaen Cathedral. Top (left to right): fasade from the cathedral, and two views from the pyramid above the choir (JCCHO) (Photos: T. Wazny). Researched roof structures: (a) 16th century roof structure above the sacristy (JCSAC), covering the chapter room in the east-end (b), and the antechamber of the sacristy in the west-end (c); (d) 17th century roof structure above the altar (JCALT); (e) 18th century pyramidal roof covering the western dome above the choir (JCCHO). Photos: M. Domínguez-Delmás. Drawing: S. van Daalen and M. Domínguez-Delmás.

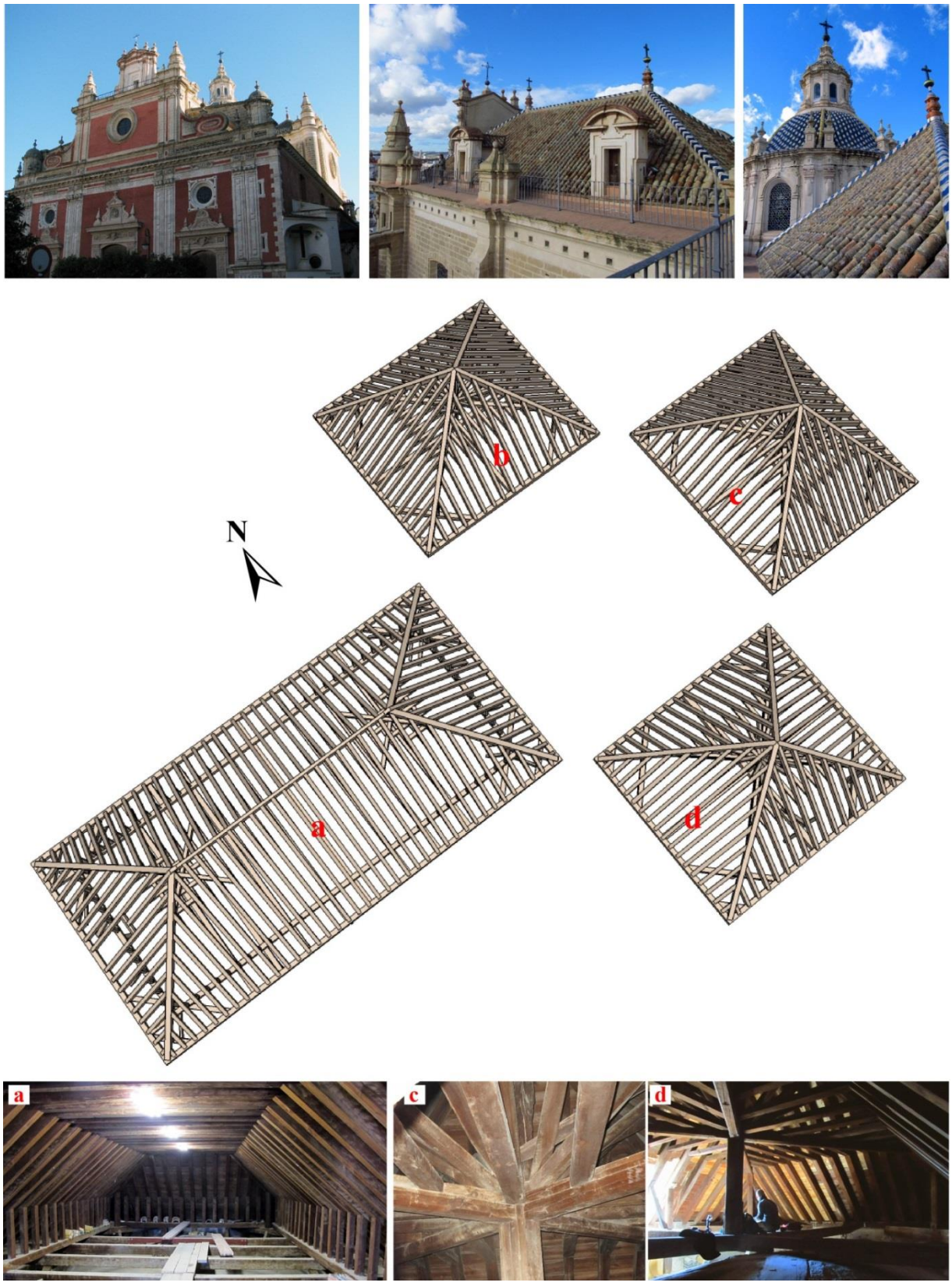

Figure 3. Colegial del Salvador church. Top (left to right): fasade, roof above the nave (CdSNA), and pyramid above the southern transept (CdSPS). Researched roof structures: (a) roof structure above the nave (CdSNA); (b) pyramid above the northern transept (CdSPN); (c) pyramid above the eastern transept (CdSPE); (d) pyramid above the eastern transept (CdSPS). Photos: M. Domínguez-Delmás. Drawing: S. van Daalen and M. Domínguez-Delmás.

When the objective of the dendroarchaeological research on a building is to date major construction phases, re-used timbers or timbers used for repairs should be avoided. However, considering our objectives, we paid special attention to timbers that may have been re-used from the old mosques. Keeping this in mind, we thoroughly inspected and selected timber elements suitable for dendrochronology, i.e. providing sufficient number of tree-rings, containing sapwood (i.e. outermost part of the stem) and/or the bark edge (i.e. last growth-ring formed before the felling of the tree).

One core was taken from selected elements using a dry-wood borer powered by an electric drill. Cork plugs were used to close the holes left by the borer. At Jaen cathedral, cross-sections were manually sawn from the protruding ends of the ceiling timbers from the chapter room.

2.4 Wood identification of historic timbers

The presence of different species in the same building may indicate different sources of timber and/or that the timber was purchased at a major wood market (De Vries, 1994). Therefore, prior to the dendrochronological analysis, species identification based on anatomical features of the wood structure was performed. Thin sections of the transverse, radial and tangential planes of each sample were manually cut with razor blades, mounted onto glass supports and observed under a transmitted-light microscope (Zeiss Axioscope40). A digital camera (Zeiss AxioCam MRc5) was used to visualize and photograph the key anatomical features of each sample. The wood anatomical features were compared with reference micro-slices and with the wood anatomical identification key by Schweingruber (1990).

2.5 Dendrochronological research

The surface of both cores and cross-sections was prepared with Stanley knives and/or surgical blades by cutting from the inner to the outermost ring along the transverse section. Chalk powder was applied to this surface to enhance the contrast between tree-ring boundaries. Ring-widths were measured to the nearest 0.01 mm using a TimeTable measuring device (VIAS, University of Viena) coupled with the program PAST4 v.4.3.1021 (Knibbe, SCIEM).

Tree-ring series from the same cross-section were statistically and visually compared (i.e. crossdated) to verify the quality of the measurements and identify potentially absent rings. Once in agreement, these series were averaged into one tree-ring series per sample (TSS). To try and identify timbers that may have originated from the same tree, these individual TSS were internally crossdated first with TSS from the same building phase, and then with TSS from other building phases in the same building. TSS thought to be from the same tree were averaged into series representing individual trees (TST). The TSTs and the remaining loose TSSs were standardised with ARSTAN (Cook, 1985) in two steps. Each series was first fitted to a negative exponential curve to eliminate the age trend, and then to a 32-year wave-length cubic spline, with a 50% cut-off variance, emulating the default standardisation settings from COFECHA (Holmes, 1983; Grissino-Mayer, 2001) to reduce the non-climatic noise contained in the series. To identify timbers with the same provenance, the standardised series were internally crossdated again, first within the same building and then also with the TSS and TST from the other building. Groups of matching series were averaged with a robust mean into ‘floating’ (i.e. not yet absolutely dated) standardised object chronologies (OCs). Finally, these floating chronologies and the remaining TSS and TST were crossdated against the absolutely dated master chronologies of

black pine from the Cazorla and Segura Mountains developed by Domínguez-Delmás et al. (2013). Statistical and visual crossdating was performed with PAST4 following standard dendrochronological procedures (e.g. Baillie, 1982).

3. RESULTS

3.1. Tool, carpenter's and transportation marks

3.1.1. Jaen cathedral

During the inspection of the 16th century JASAC we observed that, although some rafters and collar beams had been renovated, most of the timbers seemed to be original. Most timber elements had saw marks on two faces and adze marks on the other two (Fig. 4a-c). Such tool marks suggest that the logs were squared with adze (maybe in the same operation to remove the bark) before being sawn into quarters, hence all these timbers are most likely quarters of a stem. Additionally, we also found roman numerals in some elements of the central part of the roof (Fig. 5). On the southern part of the structure, the fifth strut counted from the East had a carved symbol that could be interpreted as a number five (IIII\) (Fig. 5a), which agrees with the position of this element. Two rafters on that southern side also had numbers that seemed to indicate that the sequence followed an East-West pattern. However, the numbering of the rafters did not commence from the easternmost one. On rafter 21 counted from the East, we found two symbols, a number four (IV) and a group of lines resembling a nine (IX) (Fig. 5b), whereas on rafter 25 we found a symbol representing an eight (IIX), which could also be read as an inverted 12 (Fig. 5c). Although the numbers four and eight agree with the relative sequence of those two rafters, their position towards the west end of the structure greatly hinders their interpretation. The lines that could represent the number nine appear a bit faded, indicating either that the timber was reused and this mark corresponded to the position in the previous structure, or that it is not an assembly mark. Finally, some collar beams also presented different marks that were difficult to read (Fig. 5d). They could be related to trade/property marks, assembly marks, etc., but their poor conservation suggests that those timbers could have been reused.

In the upper 17th and 18th century structures (respectively JCALT and JCCHO) we also observed saw marks in two faces of the timber elements and small adze marks in the other two. Numerals or other annotations marks were absent on these timbers, as well other marks that could point to their reuse, suggesting that these timbers are a more homogeneous group than the ones from the sacristy.

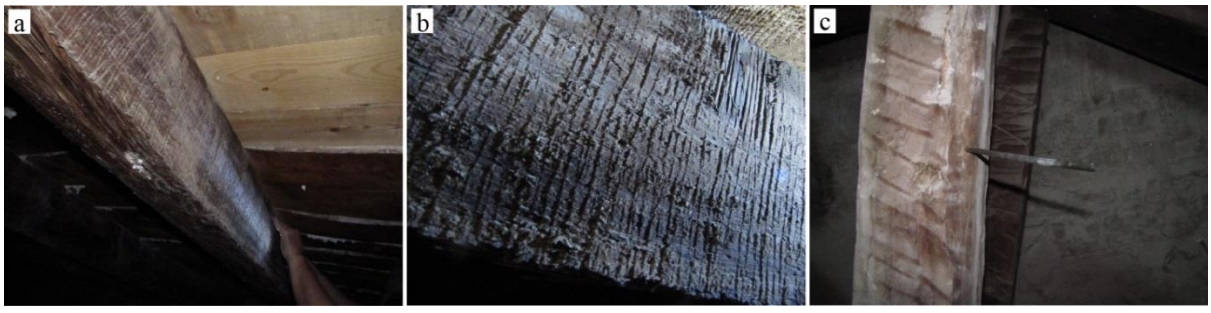

Figure 4. Tool marks in timbers from the JCSAC. Most of the timbers presented saw marks in two visible faces (a, b) and adze marks in the other faces (c). Photos: M. Domínguez-Delmás.

Figure 5. Carpenter marks in timbers from the JCSAC; (a) Mark resembling a five (IIII\) found in the fifth strut from the southern side of the structure; (b) double marking in the 21st rafter of the southern side (the red arrow points at the same rafter pointed at in (c)); (c) mark resembling an eight (IIX) in 25th rafter from the southern side, indicating a consecutive relative position with the mark IV in rafter 21; (d) different annotations in a collar beam that seem to indicate that this timber was reused. Photos: M. Domínguez-Delmás.

3.1.2. Colegial del Salvador church, Seville

Unlike at Jaen cathedral, the tool marks we found in the roof structures at the *Colegial del Salvador* church were more difficult to interpret. Throughout the inspected roof structures, the vast majority of timbers (rafters, struts, etc.) had adze marks on all visible faces (Fig. 6a-b), which would imply that the timbers had been split (with axes and wedges) and afterwards carved to the required size with an adze (Córdoba de la Llave, 1990). However, such method would result in more irregular edges, whereas numerous timber elements had sharp edges instead. A more thorough inspection revealed that in some elements, saw marks existed in the vicinity of the edges (Fig. 6c-e). This reveals that these timbers had been squared by sawing, to be slightly finished afterwards with an adze. Furthermore, some of the timbers seemed to be reused, as they presented notches that did not respond to their current structural function (Fig. 7). Numeral marks were absent on all the timbers.

Figure 6. Tool marks in timbers from different structures of the *Colegial del Salvador* church. Whereas most of the timbers presented adze marks in all faces (a, b), some had saw marks close to the edges, indicating that the logs had been sawn and then slightly smoothened with adzes (c-e). Photos: M. Domínguez-Delmás.

Interestingly, during the inspection of the roof structures in this building, we found on several timbers from the CdSPS wooden pegs and round holes randomly distributed along the timbers (Fig. 8a-d). The wooden pegs were fastened with thin twigs (Fig. 8e). After cleaning *in situ* the transverse surface of some wooden pegs with a Stanley knife, we could identify them as deciduous oak (*Quercus* subg. *quercus*) (Fig. 8f). Small fragments from some twigs were taken to the laboratory, where they were identified as willow (*Salix* sp.). Literature research confirmed that these finds were related to the construction of rafts (Pallaruelo, 2008; Eissing and Dittmar, 2011).

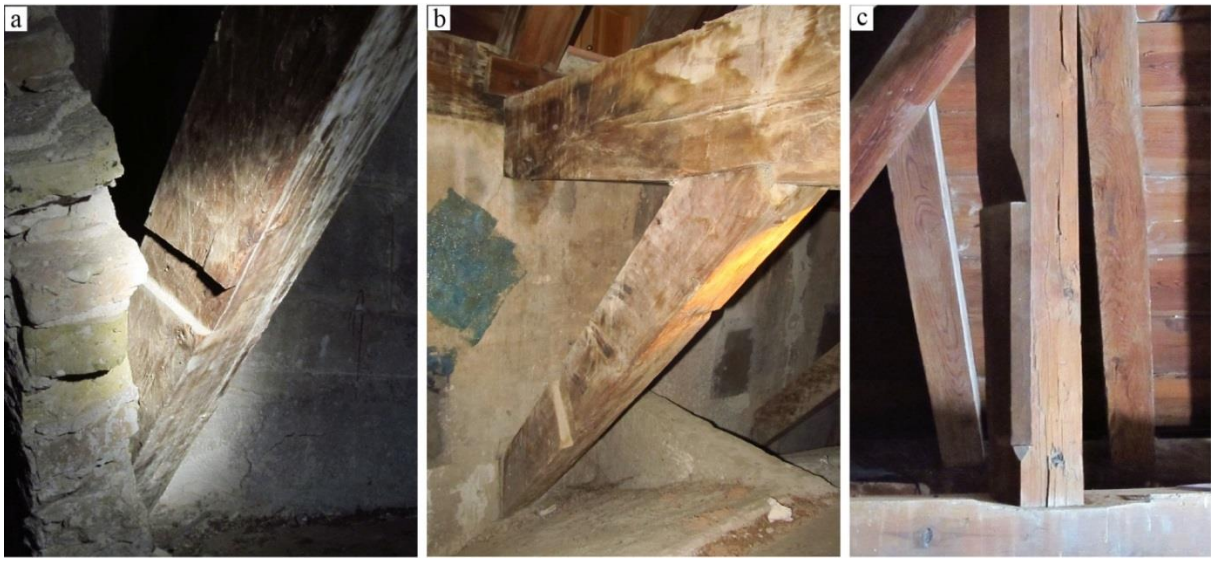

Figure 7. Notches in timbers from the CdSNA (a, b) and CdSPN (c) at the *Colegial del Salvador* church that point towards a previous use. Photos: M. Domínguez-Delmás.

Figure 8. Rafters from the pyramid roof structures of the transepts presenting wooden pegs related to timber rafting (a-d). The pegs are made of deciduous oak (*Quercus* subg. *quercus*) and are fastened with (or were used to fasten) willow (*Salix* sp.) twigs.

3.2. Dendrochronological results

3.2.1. Jaen cathedral

A total of 25 samples (21 cores and four cross-sections) were taken from the three roof structures inspected in this building (Table 2): 11 cores and four cross-sections were taken from the JCSAC; five cores were extracted from five timbers of the JCALT, and another five were obtained from five timbers of the JCCHO. The bark edge was present in seven samples of the JCSAC and three samples of the JCALT. All the samples were identified as *Pinus* sp., type *P. nigra*/*sylvestris*.

The synchronisation between the samples resulted, first of all, in the identification of two ceiling joists (dendro-codes JCS030 and JCS040) as quarters from the same tree (r = 0.69; *t*BP = 11.4; 80.9%*** for an overlap of 115 years). These tree-ring series were averaged into one single curve (JCS3_4T) and after standardisation of the series, an internal crossdating was run again. Good statistical and visual results were found between seven different series from the JCSAC that represented individual trees (JCS010, JCS3_4T, JCS060, JCS070, JCS081, JCS090 and JCS141). A 313-year long OC (JCSAC7Tstd) was built with those series. The five series derived from samples from the JCALT (JCS210, JCS220, JCS230, JCS240 and JCS250) could also be crossdated, and were averaged into the object chronology JCALT5T with a total of 110 rings. Finally, a third object chronology (JCCHO5T) was built with the series obtained from the five samples of the JCCHO (JCS160, JCS170, JCS180, JCS190 and JCS200). The last 34 rings of series JCS160 (i.e. most recent years) and the first 12 rings

of JCS200 could not be crossdated due to the occurrence of missing rings, hence we had to discard those segments, resulting in a OC with 187 rings.

Table 2. Sampled elements and tree-ring results from Jaen Cathedral. N: number of tree-rings; MRW (mm): mean ring-width; StdDev (mm): standard deviation MRW; Bark edge: +1ew, last ring incomplete (tree cut during the spring or early summer); lw, last ring complete (tree cut between the late summer and the winter).

Roof structure and sampled timber-element	Dendro-code	N	MRW (mm)	Std Dev (mm)	Bark edge	Date begin	Date end
Sacristy (JCSAC)							
Oblique beam above N wall (dividing wall between sacristy and chapter room)	JCS010	232	1.26	0.76	-	1262	1493
3rd ceilling joist chapter room	JCS020	118	1.20	1.06	-	-	-
5th ceilling joist chapter room	JCS030	127	1.26	0.59	-	1370	1496
9th ceilling joist chapter room	JCS040	115	1.37	0.72	-	1374	1488
Left top plate above dividing wall between sac. and chap. room)	JCS050	58	0.65	0.39	-	-	-
Rafter 19 N	JCS061	108	1.36	0.73	-	1447	1554
Rafter 11 N	JCS070	183	0.68	0.68	+1EW	1391	1573
Rafter 7 N	JCS081	158	0.86	0.75	+1EW	1416	1573
Rafter 4 N	JCS090	109	1.24	0.61	LW	1467	1574
Rafter 2 N	JCS100	53	0.64	0.18	-	-	-
Strut 10 N	JCS111	69	1.13	0.34	LW	-	-
Strut 9 N	JCS121	75	1.56	0.77	LW	-	-
Strut 2 N	JCS131	78	1.83	0.94	-	-	-
Tie-beam 3 left	JCS141	235	0.91	0.35	+1EW	1339	1573
Strut 5 S (marck with numeral III*I*) (lw)	JCS150	68	0.31	0.14	LW	-	-
Roof above altar (JCALT)							
1st horizontal left beam wall 1	JCS210	110	0.94	0.39	+1LW	1541	1650
Inner oblique beam between walls 1 and 2	JCS220	94	1.32	0.70	+1LW	1557	1650
Rafter 7 wall 1	JCS230	30	0.90	0.31	+2	1620	1649
Rafter 18 wall 2	JCS240	77	1.89	0.72	-	1570	1646
Purlin supported on inner oblique beam between walls 1 and 2	JCS250	77	1.55	0.91	-	1569	1645
Pyramid above choir (JCCHO)							
Rafter 12. wall 3	JCS160	131	1.12	0.93	?	1590	1720
Inner oblique beam between walls 2 and 3	JCS170	161	0.88	0.78	-	1558	1718
Rafter 12. wall 2	JCS180	181	0.67	0.46	-	1532	1714
Inner oblique beam between walls 1 and 2	JCS190	113	0.74	0.48	-	1604	1717
Rafter 10. Wall 4	JCS200	152	0.99	0.96	-	1563	1714

The crossdating of the object chronologies with the chronologies from living trees from the Cazorla and Segura mountains resulted in the absolute dating of the three of them (Table 3, Fig. 9). The felling dates obtained for the samples of the JCSAC lie between the spring and the summer of AD 1574, and the winter of AD 1574/75, whereas the felling date for the three samples from the JCALT containing bark edge was established in the spring of AD 1651. These dates are coherent with the historical information about the construction dates of these structures (Table 1), and imply that the trees were cut between 3 to 9 years earlier, probably to stockpile enough material and have time to process the wood. The presence of bark edge in the samples from the JCCHO could not be verified, although it cannot be

discarded that the last ring measured in sample JCS160 corresponds to the last ring under the bark. This is very plausible, as the JCCHO was concluded in AD 1726.

The statistical results obtained with the reference chronologies suggest that the dated wood from the JCSAC was obtained from the upper part of the Cazorla Mountain, although the lack of overlap for the full span (313 years) with the mid-elevation chronologies NAVstd and PMBstd, and the lack of overlap with the low-elevation chronology (LINstd) hampers making a proper assessment regarding the high-resolution provenance of this group of timbers. In contrast, the OCs from JCALT and JCCHO do overlap entirely with CBSstd, NAVstd and PMBstd, and partially with the low-elevation chronology LINstd. The best chrossdating results are achieved with the mid-elevation chronology PMBstd. This could indicate that the trees used for those structures grew at some mid-elevation site on the western part of the Cazorla and Segura Mountains. Matches with the low-elevation chronology are not significant.

Table 3. Crossdating results of the chronologies obtained for each building phase of Jaen Cathedral with reference chronologies of black pine from the Cazorla and Segura Mountains. *r*, correlation coefficient; *t*BP, Student's *t*-value according to Baillie and Pilcher (1987); Gl, percentage of parallel variation; Ol, overlap; n.s., not significant; n.o., no overlap.

	CBSstd AD 1120-2010	**NAVstd AD 1519-2009**	**PMBstd AD 1500-2009**	**LINstd AD 1641-2009**
JCSAC7Tstd AD 1262-1574	***r* = 0.50** ***t*BP = 7.78** **Gl = 71.2***** **Ol = 313**	*r* = 0.38 *t*BP = 3.40 Gl = 65.2* Ol = 56	*r* = 0.50 *t*BP = 5.33 Gl = 63.3* Ol = 75	n.o.
JCALT5Tstd AD 1541-1650	*r* = 0.33 *t*BP = 3.23 Gl = 65.0*** Ol = 110	n.s.	***r* = 0.49** ***t*BP = 5.90** **Gl = 68.6***** **Ol = 110**	n.s.
JCCHO5Tstd AD 1532-1718	*r* = 0.36 *t*BP = 5.04 Gl = 58.3* Ol = 187	*r* = 0.34 *t*BP = 5.02 Gl = 57.8* Ol = 187	***r* = 0.48** ***t*BP = 8.23** **Gl = 67.4***** **Ol = 187**	n.s.

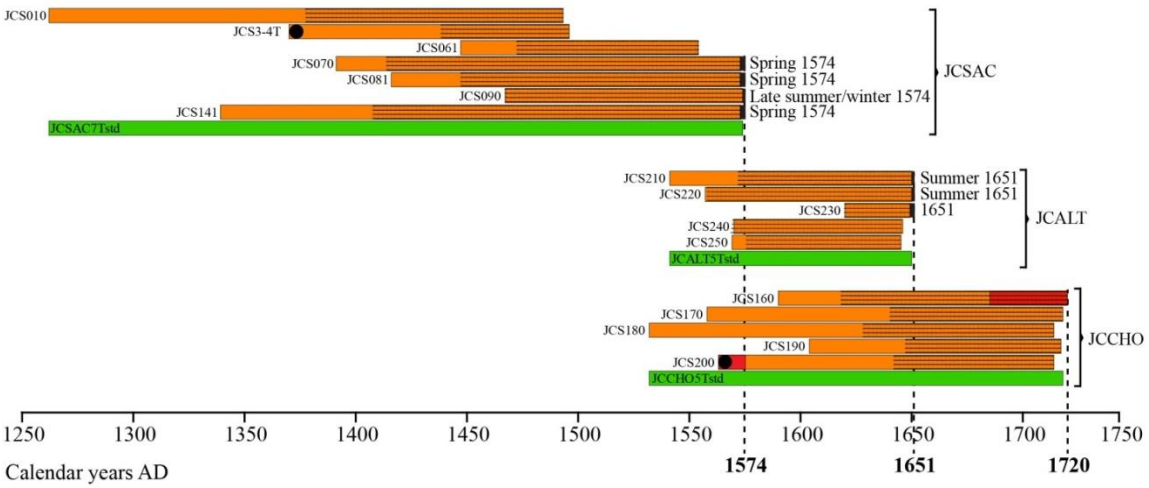

Figure 9. Bar graph indicating the felling dates and time span covered by the dated TRT of Jaen Cathedral, and the obtained object chronologies (green). The textured part of the bars represents the sapwood, and the black dot the presence of pith. The red part of bars from JCS160 and JCS200 indicates the portion of the series that could not be crossdated due to missing rings and has been disregarded for the OC.

3.2.2. Colegial del Salvador church, Seville

A total of 80 cores were obtained from 71 selected timbers in the roof structures of the *Colegial del Salvador* church, 30 from CdSNA, 19 from CdSPS,10 from CdSPE and 12 from CdSPN (**Table 4**). Nine timbers produced yellow saw dust whilst sampling, which could imply that they were from a different pine species than the rest. However, such conclusion could not be reached through the observation of the wood anatomy on those samples, hence all the samples were identified as *Pine* sp., type *P. nigra*/*sylvestris*.

Table 4. Sampled elements and tree-ring results from *Colegial del Salvador* church. N: number of tree-rings; MRW (mm): mean ring-width; StdDev (mm): standard deviation MRW; Bark edge: +1ew, last ring incomplete (tree cut during the spring or early summer); lw, last ring complete (tree cut between the late summer and the winter). Elements marked in bold had notches indicating reuse. Codes with an asterisk represent timbers with rafting joints.

Roof structure and sampled timber-element	Dendro-code	N	MRW (mm)	Std Dev (mm)	Bark edge	Date begin	Date end
Nave (CdSNA)							
1st tie-beam	SCS011	39	2.83	0.91	-	-	-
2nd tie-beam	SCS020	129	0.78	0.39	-	-	-
12th rafter North (=left) wall	SCS030	147	0.74	0.41	-	-	-
5th tie-beam	SCS040	192	0.85	0.37	-	-	-
15th rafter North (=left) wall	SCS051	108	1.49	0.90	-	-	-
6th tie-beam	SCS060	121	0.99	0.40	-	-	-
12th vertical beam right side	SCS071	181	0.80	0.53	-	-	-
12th rafter right side, WK	SCS081	142	1.15	0.46	LW	-	-
7th tie-beam	SCS091	80	1.48	0.47	-	-	-
1st strut left corner from the door	SCS101	98	1.43	0.51	-	-	-
1st strut right corner from door	SCS110	185	0.92	0.44	LW	-	-
2nd strut right corner from door	SCS121	184	0.81	0.41	-	-	-
Long diagonal beam right corner from door	SCS131	70	2.05	0.98	-	-	-
2nd strut left corner from door	SCS141	75	1.33	0.65	-	-	-
2nd long sleeper inner frame, right side; yellow saw-dust as tie-beam 7	SCS151	58	2.02	0.96	-	-	-
23rd rafter left (north) side	SCS161	140	0.84	0.38	-	-	-
7th strut left (N) side	SCS171	126	1.22	0.47	-	-	-
21st rafter right (S) side	SCS181	103	1.35	0.70	-	-	-
18th rafter right side	SCS191	164	0.86	0.36	-	-	-
26th rafter right side	SCS201	137	0.88	0.54	-	-	-
35th rafter left side	SCS211	66	2.33	0.91	-	-	-
3rd vertical support back (E) wall	SCS221	57	1.17	0.57	-	-	-
19th vertical beam right (South) side	SCS231	180	0.75	0.43	-	-	-
rafter 11 muro Este (al fondo)	SCS241	118	1.29	0.38	-	-	-
25th rafter right (S) side	SCS251	170	0.87	0.24	-	-	-
33rd vertical beam left (N) side	SCS261	154	0.85	0.44	-	-	-
sleeper on top of back (E) wall	SCS271	108	0.95	0.46	-	-	-
short diagonal tie-beam between E-S walls (back right corner)	SCS281	71	2.00	0.96	-	-	-
29th vertical beam left side	SCS291	135	0.84	0.56	-	-	-
18th rafter W Wall	SCS301	123	1.22	0.89	-	-	-

Pyramid South (CdSPS)							
2nd rafter E wall	SCS311	93	1.46	0.79	-	-	-
4th rafter E wall; holes from wooden pegs	SCS321*	90	1.80	0.91	-	-	-
Vertical support on top of diagonal beam between S-E wall (right from door)	SCS331	115	1.37	0.63	-	-	-
Tie-beam going from king post to S wall	SCS341	75	2.01	0.79	-	-	-
Long, diagonal beam between S-E wall	SCS350	189	0.65	0.28	-	-	-
Tie-beam from W wall to king post	SCS361	73	2.24	1.51	-	-	-
10th rafter W wall (with hole and an oak pen)	SCS371*	96	1.87	0.90	-	-	-
16th rafter W wall	SCS380	96	1.74	1.20	-	-	-
4th rafter S wall	SCS391	90	1.55	0.65	-	-	-
sleeper W wall	SCS401	88	1.51	0.48	-	-	-
14th rafter E wall	SCS411	94	1.75	0.83	-	-	-
Vertical beam on top of long diagonal beam running from E-N wall	SCS420	80	1.10	0.31	-	-	-
4th rafter N wall	SCS430	103	1.55	0.95	-	-	-
short diagonal beam between E-N wall	SCS440	160	1.08	0.62	-	-	-
Sleeper N wall	SCS450	128	1.05	0.51	-	1488	1616
15th rafter N wall	SCS461	86	1.63	0.96	-	-	-
short diagonal beam going from S-E wall (right from door)	SCS471	96	1.39	0.75	-	-	-
Short diagonal beam N-W wall	SCS480	84	1.10	0.37	-	-	-
Short diagonal beam S-W wall	SCS490	100	1.34	0.64	-	1540	1639
Pyramid East (CdSPE)							
6th rafter W-wall	SCS501	238	0.65	0.51	-	-	-
tie-beam from E-wall to centre	SCS511	69	2.21	0.99	-	-	-
sleeper E-wall	SCS521	184	1.05	0.79	-	-	-
11th rafter W-wall	SCS531	147	0.78	0.29	-	-	-
horizontal tie-beam from S-wall to centre	SCS541	87	1.49	0.69	-	-	-
14th rafter W-wall	SCS551	126	1.23	0.45	-	-	-
vertical beam on top of long diagonal beam that goes from S to W wall	SCS561	170	0.94	0.41	-	-	-
5th rafter S-wall	SCS571	101	1.15	0.47	-	-	-
4th rafter S-wall	SCS581	88	1.15	0.38	-	-	-
short diagonal beam going from W to S wall	SCS591	89	1.51	0.84	-	-	-
Pyramid East (CdSPE)							
7th rafter E wall	SCS601	171	0.67	0.24	-	-	-
Tie-beam going from centre to N wall	SCS610	83	2.13	0.90	-	-	-
11th rafter N wall	SCS621	168	0.83	0.44	-	-	-
14th rafter S wall	SCS631	71	1.54	0.60	-	-	-
13th rafter S wall	SCS641	170	0.80	0.45	-	-	-
16th rafter N wall	SCS651	259	0.69	0.39	-	-	-
7th rafter W wall	SCS661	81	1.64	0.59	-	-	-
13th rafter W wall	SCS671	90	1.59	0.59	-	-	-
Short diagonal horizontal beam going from S-E walls	SCS681	57	1.36	0.60	-	-	-
Vertical beam on top of long diagonal beam between S-E wall	SCS691	117	1.13	0.55	-	-	-
9th rafter S wall	SCS701	101	1.33	0.69	-	-	-
Short diagonal horizontal beam going from S-W walls	SCS711	113	1.22	0.54	-	-	-

Crossdating of the individual tree-ring series revealed that 20 timbers had been processed from eight trees (Table 5). Among them, four struts from the CdSNA, which have notches that indicate that they were reused, turned out to originate from the stems of two individual trees. Some of the other elements originating from the same trees were used in different roof structures, implying that the logs were first processed into specific timber elements, and then stock piled until those timber elements were required in the different roofs.

After averaging the different TRS into TRT, the dataset was reduced to 51 individual trees. Good matches were found between five TRT, three from the CdSNA (rafter SCS071, and struts SCS081 and SCS0T7), and two from the CdSPN (rafters SCS641 and SCS651), which were averaged into an OC spanning 259 years (CdS5MC) (Table 5). Another OC was made with the series SCS040 and SCS060 (CdS2MC). The remaining TRTs and the two OCs where compared with the Cazorla and Segura chronologies and with the OCs and TRT from Jaen cathedral. This resulted in the dating of two TRTs from CdSPS (SCS450 and SCS490), in the years AD 1616 and 1639 respectively. SCS450 achieves the best match with JCCHO5T (tBP = 5.44, Gl = 70%*** for 85 years overlap), and is replicated by a good match with CBS (tBP = 5.33, Gl = 65.9%*** for the full length of the series). SCS490 presents the best match by far also with JCCHO5T (tBP = 7.39, Gl = 72.5%*** for the full overlap of 100 rings). These series were averaged into the mean curve SCS45_49M. The best match for this mean curve was obtained with JCCHO5T (tBP=8.32, Gl=73.1%***, for 108 rings overlap), which was replicated with a much lower score by CBS (tBP = 4.55, Gl = 62.8%***, for 152 rings overlap). The rest of the TRTs and the OCs remained undated.

Table 5. Internal crossdating results from Colegial del Salvador samples, presenting individual tree-ring series (TRS) from timbers that derive from the same individual trees (TRT),and object chronologies (OC) obtained after the second internal crossdating. N: number of tree-rings.

TRS	TRT	N
SCS591 **SCS631** **SCS681** **SCS711**	**SCS0T1**	**124**
SCS661 **SCS671**	**SCS0T2**	**91**
SCS531 **SCS561**	**SCS0T3**	**180**
SCS111 **SCS121**	**SCS0T4**	**187**
SCS131 **SCS281**	**SCS0T5**	**75**
SCS371 **SCS431** **SCS461**	**SCS0T6**	**110**
SCS231 **SCS261** **SCS291**	**SCS0T7**	**180**
SCS101 **SCS141**	**SCS0T8**	**102**
TRT	OC	N
SCS071 **SCS081** **SCS0T7** **SCS641** **SCS651**	**CdS5MC**	**259**
SCS040 **SCS060**	**CdS2MC**	**192**

4. DISCUSSION

4.1. Historical rafting of timbers in the Guadalquivir river

The holes with oak pegs that we found in some timbers from the pyramids South and North at the *Colegial del Salvador* church (Fig. 8) demonstrate that wood was transported as rafts. Although the transport of loose logs from the forests high up in the Cazorla and Segura mountains down to the valley and along the river was well documented since at least the end of the 10th century up until the mid-20th century (Nieto Ojeda, 1998; Araque Jiménez, 2007), no detailed accounts or evidence of

transport as rafts along the broad valley had ever been provided. Given that these timbers remain undated and their exact provenance unknown, it is also possible that the wood originated from different mountains in the south or southeast of the region (e.g. La Sagra, Sierra Nevada), which connect with the Guadalquivir through tributary rivers. Rafts could have been assembled at some point down in the valley along the Guadalquivir river.

In Spain, the transport of wood in rafts is well documented for the river Tagus, and especially for the Ebro (largest river of Spain) and its Pyrenean tributaries (e.g. Krüger, 1997; Pallaruelo, 2008). In the Ebro, rafts were constructed by tying the logs together using willow (*Salix* sp.) twigs. These twigs were collected in spring, when sap flow had already started and the thin willow branches were easy to bend. To make them yet more flexible, they were fastened by one end with an oak branch or a piece of an oak stem into holes made with borers on some of the timbers (see Pallaruello, 2008: 128-129). The oak branch would be pressed deep into the hole to hold the twig-end and the rest of the twig would be wrapped around the oak branch to increase its suppleness. The holes found not only contained oak pegs, but also willow twigs (Fig. 8), which could be the leftovers from this process. Another possibility is that the willow twigs were used as rope, fastening them with two oak pegs as described by Eissing and Dittmar (2011: 141, Fig. 4). This could explain the presence of four pegs in some of the timbers (Fig. 8a, b). The fact that some of the beams were sawn right through the hole (Fig. 8) implies that the logs were processed into the individual timbers after the transport, probably at the construction site. This contrasts with the findings of Haneca and Debonne (2012) in the Low Countries, where oak timbers were floated as squared logs.

4.2. Tools and construction techniques

Assembly marks are commonly found in roof structures in north western Europe (e.g. De Vries, 1994; Hoffsummer, 2002; Haneca and Debonne, 2012), and have always been associated with the pre-design and assembly of the framing structure on the ground before lifting up each individual element to its final position in the roof. However, the numbers we found in the central part of the JCSAC only cover nine of the 26 rafters, and their position is central, which greatly hinders the interpretation of the structure as a whole. Some rafters of this consecutive series are recent repairs, as indicated by their lighter and vivid colour, but the lack of numerals in the rest of the rafters, which are apparently original, is confusing.

Assembly marks were absent at both the 17th and 18th century structures of Jaen cathedral, and at the structures of the *Colegial del Salvador* church. This seems to imply that the procedure of pre-fabricating the roof structure on the ground was abandoned by the 17th century, which could be related to improvements on the designs of roofs, and ways to process wood towards more standardised shapes. Timbers for specific elements (e.g. rafters, struts, etc.) would be made on the ground following standard dimensions, to be refined with adzes before placing them in their final position. At Jaen cathedral, timber elements in the 17th and 18th roofs looked very homogeneous in their dimensions, although they presented the same tool marks than the ones in the 16th century roof above the sacristy (i.e. saw marks in two faces and adze marks in the other two). These tool marks suggest that the timbers were quarters of logs: the logs were sawn first in halves and then in quarters, whereas the faces corresponding to the outer part of the stem were shaped with adzes. This was also confirmed during the sampling, as samples taken from what seemed to be the outermost corner towards the inner

part of the quarter-like elements, indeed contained the outer part of the stem and run towards the rings close to the pith.

At the *Colegial del Salvador* church timbers presented either only adze marks, which suggests that they represent full square logs, or both saw marks at the edges combined with adze marks along the faces. The later could be the result of sawing the logs into quarters, to refine them afterwards with the adze. Another explanation for the presence of different tool marks in the same face of the same timbers could be that the material had been reused and had to be slightly reduced with an adze to adapt them to their new position. If this was the case, the timbers should date in earlier periods than the documented time of construction of the roofs. However, the lack of dates for these timbers hampers the possibility to confirm this hypothesis.

4.3. Construction dates and supply of timber from the Cazorla and Segura mountains

At Jaen cathedral, 18 out of 25 timbers sampled could be dated, confirming the historical information about the construction dates of the different building phases. Excellent crossdating results with the Cazorla and Segura chronologies further supports the historical information regarding the provenance of the wood. Furthermore, our research indicates that the timber for the 17th and 18th century structures derived most likely from mid-elevation sites with a western aspect. The 16th century timbers, however, date best with the chronology from the upper part of the mountains, although the lack of full overlap with the mid-elevation chronologies impedes concluding that the wood originated from the upper part. The lack of wooden pegs and other leftovers from rafting in these timbers is not surprising, as Jaen is located at a short distance from the foothills of the Cazorla and Segura Mountains (Fig. 1). The wood was most likely transported first as loose logs from the mountains, using the upper course of the Guadalquivir and its tributaries, down to the valley, and then transported to Jaen over water up the Guadalbullon river, or by land.

Seville, however, is located further away from the mountains, hence the transport of wood by rafts over long distances in the Guadalquivir river seems the most practical option. Unfortunately, all except two from the 71 timbers sampled at the *Colegial del Salvador* church remain undated, including the timbers presenting rafting joints, which also hampers the possibility of assigning a provenance to the investigated wood, and by inference, to the rafting features. The sampled material is very heterogeneous in terms of growth patterns (mean ring widths of the samples range from 0.65 to 2.83 cm), suggesting that the wood was obtained from different sources, or that it corresponds to timbers from different periods. Another explanation for the lack of synchronisation of some samples could be that the tree-ring series contain missing rings that could not be identified. Mendoza (2008) explicitly mentions the use of wood from the Segura mountains to build the roofs, but the presence of reused timbers supports the hypothesis that the wood consists on a mixture of reused timber and newly cut trees from potentially different parts of the Cazorla and Segura mountains, or even that it originated from different mountains in the east and south of the Andalusia region. This heterogeneity is also evident by the differences in mean ring-width, which shows that different types of trees including fast-growth ones (either younger trees or trees that were grown in open sites), as well as slow-grown trees (older trees, or trees that have grown in less favourable conditions, possibly at higher elevations) were used for the construction of the roof structures of the *Colegial del Salvador* church. In the Netherlands, for example, wood from different sources is often found in roofs of large buildings such as cathedrals

or churches, which has been explained by the purchase of the wood in large timber markets (De Vries, 1994). In Andalusia, historical records described how wood was bought at the villages in the Cazorla and Segura Mountains, from where it would be transported downstream to Seville (Córdoba de la Llave, 1990). Therefore, wood from different locations could have mingled in the upper course of the Guadalquivir, or at the point where rafts were assembled.

5. CONCLUDING REMARKS

Dendroarchaeological investigations carried out on roof structures from Jaen cathedral and the *Colegial del Salvador* church in Seville have increased our knowledge about the timber supply for construction purposes from the 16th to the 18th centuries in Andalusia, south of Spain.

The presence of Roman numerals in timbers from the 16th century roof above the sacristy of Jaen cathedral suggests that the technique of preassembling roof structures in the ground before lifting the individual timbers to their final position in the building may have been employed up to the 16th century. The lack of such annotations in the 17th and 18th century roof structures investigated in both buildings implies that this technique may have been abandoned from the 17th century onwards. The improvement of tools and wood-processing techniques may have played an important role in this change.

This research provides the first material evidence for historical rafting of timbers in the Guadalquivir River, proving that rafts were assembled as it was done in the Ebro, or maybe even in rivers from the Bavaria region in the south of Germany, or the river Meuse in present-day Belgium. Since the timbers with rafting joints remain undated it is not yet possible to assign a specific period of time to this activity in the Guadalquivir River, nor to place the wood in a specific geographical area within Andalusia, but nonetheless, this find opens the door to questions to be pursued in the near future.

Our dating results confirm the historical information about construction dates, and dates of purchase of timber for Jaen cathedral. Furthermore, the statistical matches of the object chronologies obtained from each building phase with the reference chronologies from the Cazorla and Segura mountains are coherent with the conclusions reached by Domínguez-Delmás et al. (2013). Such results demonstrate that the ultra-long tree-ring chronology from the upper part of the mountains does not provide the most statistically-sound correlations with wood from mid- or lower elevations. This supports the need to continue developing reference chronologies at different elevations throughout the Andalusian mountains. In this manner, it may be possible to date in the near future all the timbers that have remained undated, and solve the questions that remain unanswered.

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References

Albendea Ruz, E., 2011. La carpintería de lo blanco de la Casa de Pilatos de Sevilla. Tesis Doctoral Universidad de Sevilla.

Araque Jiménez, E. 2007. Conducciones fluviales de madera desde las Sierras de segura y Cazorla (1849-1949). *Cuadernos Geográficos* **40(1)**, 81–105.

Baillie, M.G.L., 1982. *Tree-ring Dating and Archaeology*. University of Chicago Press, Chicago.

Blanco Freijeiro, A., 1984. *Historia de Sevilla*: *la ciudad antigua (de la Prehistoria a los Visigodos)*. Universidad de Sevilla, Sevilla.

Bridge, M., 2013. The Bailiff's cottage, St. Osyth's priory, Burn Road, St. Osyth, Essex. Tree-ring analysis oftimbers from the roof. Scientific dating report. English Heritage, Research Report Series 54.

Brun, O., Tegel, W., 2007. Premiers résultats des analyses dendrochronologiques relatives aux boulins de construction de la cathédrale de Reims. *Bulletin de la Société Archéologique Champenoise* 98e annee, n° 4 octobre-décembre 2005, Reims, 84–93.

Campos, J., 1986. *Excavaciones arqueológicas en la ciudad de Sevilla*. Monte de Piedad y caja de Ahorros de Sevilla, Sevilla.

Cook, E.R. 1985. A Time Series Approach to Tree-Ring Standardization. Unpublished PhD Dissertation. University of Arizona, Tucson, AZ, USA.

Córdoba de la Llave, R., 1990. *La industria Medieval de Córdoba*. Caja provincial de Ahorros de Córdoba, Córdoba.

Cramer, J., Eissing, T., 1996. 'Dächer in Thüringen', in *Arbeitshefte des Thüringischen Landesamtes für Denkmalpflege 2*, Verlag Ausbildung und Wissen, Bad Homburg and Leipzig.

Crone, A., Mills, C.M., 2002. Seeing the wood and the trees: dendrochronological studies in Scotland. *Antiquity* **76**(293), 788–794.

De Vries, D.J., 1994. *Bouwen in de late Middeleeuwen. Stedelijke architectuur in het voormalige Over- en Nedersticht*, PhD Thesis, University of Leiden.

Domínguez-Delmás, M., Alejano-Monge, R, Wazny, T., García-González, I., 2013. Radial growth variations of black pine along an elevation gradient in the Cazorla Mountains (South of Spain) and their relevance for historical and environmental studies. *European Journal of Forest Research* **132**(4), 635–652.

Eissing, T., Dittmar, C., 2011. Timber transport ad dendro-provenancing in Thuringia and Bavaria, in Fraiture, P. (Ed.), *Tree-Rings, Art and Archaeology*, proceedings, Brussels, Collection *Scientia Artis* **7**, 137–149.

Grissino-Mayer, H.D., 2001. Evaluating crossdating accuracy: A manual and tutorial for the computer program COFECHA. *Tree-Ring Res* **57**(2), 205–221.

Haneca, K., Debonne, V., 2012. Precise tree-ring dating of building activities despite the absence of bark: A case-study on medieval church roofs in Damme, Belgium. *Dendrochronologia* **30**(1), 23–34.

Higueras Maldonado, J., 2009. *La catedral de Jaén. Su construcción renacentista (s. XVII-XVIII)*. Universidad de Jaén, Jaén.

Hoffsummer, P., 2002. *Les charpentes du Xe au XIXe siecle, typologie et evolution en France du Nord et en Belgique,* Paris.

Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull* **43**, 69–78.

Krüger, F., 1997. Manufacturas caseras, indumentaria, industrias. Los Altos Pirineos v. IV, DGA, Diputación de Huesca, Garsineu Edicions, Lleida.

Miles, D., 2006. Refinements in the interpretation of tree-ring dates for oak building timbers in England and Wales. *Vernacular Architecture* **37**, 84–96.

Martínez Ruiz, E. 1999. Los montes en la cultura islámica. El bosque de al-Andalus desde el siglo VIII al XIII. En Marín Pageo, F., Domingo Santos, J. & Calzado Carretero, A. (eds.), Los montes y su historia: una perspectiva política, económica y social. *Collectanea* **27**, 63–87.

Mendoza, F., 2008. *La Iglesia del Salvador de Sevilla*. Biografía de una Colegiata, Sevilla.

Nieto Ojeda, R., 1998. *El aprovechamiento maderero en las sierras del parque natural de Cazorla, Segura y Las Villas.* Departamento Territorial "Alto Guadalquivir" de la FSP-UGT, Jaen.

Ordóñez Agulla, S., 2002. Sevilla romana, in Valor Piechota, M. (Coord. Ed.), Edades de Sevilla, Hispalis, Isbiliya, Sevilla. Ayuntamiento de Sevilla, 11–38.

Pallaruelo, S. 2008. *Navateros*. Prames, Zaragoza.

Schweingruber, F.H., 1990. *Anatomy of European woods*. Haupt Verlag, Bern, Stuttgart.

Wazny, T., Kloda, P., 2003. The wooden church at Tarnowo Pałuckie – science and conservation integrated, in Kozlowski, R. (ed.), *Cultural Heritage Research: a Pan-European Challenge*. Proceedings of the 5th EC Conference, Kraków, ICSC, 329–333.

Wrobel, S., Holst, J.C., Eckstein, D., 1993. Holz im Hausbau – Dendrochronologisch-bauhistorische Reihenuntersuchungen zum Hausbau des 13.–17. Jahrhunderts in Lübeck, in *Wege zur Erforschung städtischer Häuser und Höfe,* ed. R. HAMMEL-KIESOW, K. Wachholtz Verlag, Neumünster, 183–249.

ARTICLE 4

Swedish oak, planks and panels: dendroarchaeological investigations on the 16th century *Evangelistas* altarpiece at Seville Cathedral (Spain).

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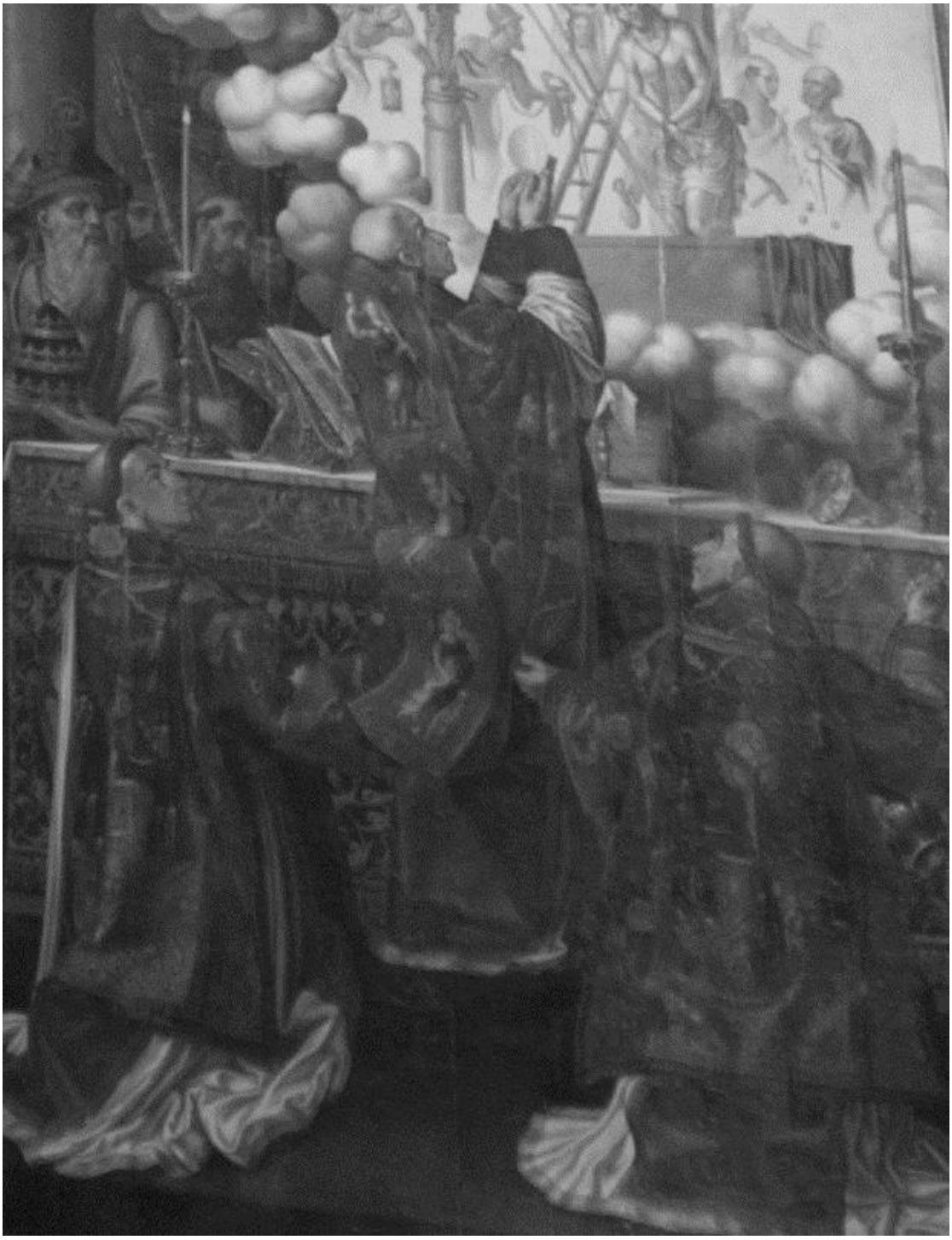

Detail of the *Evangelistas* altarpiece depicting the Mass of St. Gregory (original photo kindly provided by A. Jiménez Martín).

SWEDISH OAK, PLANKS AND PANELS: DENDROARCHAEOLOGICAL INVESTIGATIONS ON THE 16TH CENTURY *EVANGELISTAS* ALTARPIECE AT SEVILLE CATHEDRAL (SPAIN)

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Abstract

The results of the dendroarchaeological research carried out on the 16th century altarpiece from the *Evangelistas* chapel at Seville Cathedral (Spain) are presented. The altarpiece consists of nine panels and was commissioned from the Flemish artist Hernando de Esturmio in AD 1553, who signed the completed work in AD 1555. The research aimed at i) registering information about the processing of the wood and panel making, ii) verifying the AD 1555 construction date, and iii) finding out the provenance of the wood.

Five panels were selected for this research. The observed technological features allowed the reconstruction of the production process from *borne* (oak wainscots) to the final product and, based on that, two types of panels were described. Dendrochronological results showed that the wood employed in both types of panels represents a rather homogeneous group, implying that the raw material was probably transported to Seville in the same batch, and was prepared and assembled using slightly different methods to meet the requirements stipulated by the contract. Sapwood was identified in 12 of the 33 researched planks. The most recent tree-ring dates in AD 1549. Using a Bayesian approach, we obtained the combined *felling date range AD 1549 to 1554* for six of the trees with a *99.7%* confidence level. This would allow for a seasoning time of a couple of weeks up to four years, although we cannot discard that some of the other trees were likely cut earlier and had longer seasoning periods. Interestingly, our research provides evidence that the wood originated from the southwest of Sweden, representing an alternative source to the south-eastern Baltic oak commonly used for panel paintings in northern Europe in the 16th century. This is the first time that such procurement source is reported by dendrochronology in an altarpiece. Wood technological features of the planks and panels are compared to those of Baltic oak wainscots and to contemporary altarpieces in Spain and Portugal. Possible reasons for the use of this alternative procurement source are discussed.

Keywords

Tree-ring dating, panel painting, wainscots, *borne*, wood provenance, timber trade, Sweden

1. INTRODUCTION

Oak (*Quercus* spp.) timber from south-eastern Baltic countries, particularly modern day Poland and its hinterland, was highly appreciated for panel-painting and sculptures by Flemish and Dutch artists in the 16th century. This has become evident through the dendrochronological analysis of numerous art pieces carried out during the last decades (e.g. Fraiture, 2009 and references therein; Jansma et al., 2004). The preference for oak from this geographical area has been explained by the fine and regular grain of the wood, which conferred excellent quality for carving and the making of panels (Beeckman, 2005). Moreover, merchants from the Low Countries and Hanseatic traders facilitated the availability of this commodity in western markets (Brand, 2007; De Vries and Van der Woude, 1997). Consequently trade of Baltic wood towards the Low Countries is well documented in historical records such as the Sound toll-registers (e.g. Eckstein and Wrobel, 2007).

In the Iberian Peninsula, merchants and artists from the Low Countries had been established since the late Middle Ages (Gómez Bárcena, 2004). In the 16th century, the political bonds between Spain and the Low Countries contributed to tighten the trade relationships, and made Spain a yet more attractive destination for Flemish and Dutch wood carvers and painters. At that time, the most important Spanish trade hub was Seville, in the south of Spain (Fig. 1), with its inland harbour strategically located by the navigable Guadalquivir River, at barely 100 km from the Atlantic Ocean. From the late Middle Ages until the 18th century, the city played a crucial role as trade centre between the Atlantic and the Mediterranean commercial routes. Italian (mostly Genoese), English, German, Dutch and Flemish merchants settled in the city, ensuring Seville as a stop-over for ships departing from Mediterranean ports to the north of Europe (especially England and the Low Countries) and vice versa (Serradilla Avery, 2007).

The development of Seville as the main trade centre and harbour from south-western Europe carried along the expansion of the city, as well as an increasing demand for construction timber for buildings and ships. By the mid-16th century wood had become a scarce product in the vicinities of the city. This is reflected in the numerous documents at the Notarial Protocol Archive and the *Archivo de Indias* referring to the import of wood to the city from neighbouring regions, as well as from the north of Europe and America (Otte Sander, 2008; Palomero Páramo, 1983). For instance, *pino de Segura* (probably *Pinus nigra* Arn.) was imported from the Cazorla and Segura Mountains (Rodríguez Trobajo, 2008), located ca. 300 km east of the city up the Guadalquivir River, whereas Scots pine (*Pinus sylvestris* L.) was imported from Norway, former Prussia, Riga and also aboard ships loaded in the Low Countries, where this species would arrive from Scandinavia, Germany and eastern Europe (De Vries and Van der Woude, 1997); other species such as chestnut (*Castanea sativa*), beech (*Fagus sylvatica*), white poplar (*Populus alba*) and walnut (*Juglans regia*) were imported from neighboring regions and from the north of Spain; *çedro de Yndias* (probably *Cedrela odorata* L.) was imported from America via La Habana (Bruquetas Galán, 2002); and finally oak (*Quercus sp*.) was imported from the north of Spain, and from the markets in the Low Countries, Sweden, Germany and the Baltic region (Otte Sander, 2008; Bruquetas Galán, 2002). This oak imported from the north of Europe was known in Spain as *borne* and was traded in Seville by the Dutch, Flemish and German Hanseatic merchants settled in the city (Bruquetas Galán, 2002).

Figure 1. Location of Seville in the south of Spain and oil painting attributed to Alonso S_anchez Coello showing a partial view of the city in the late 16th century with the cathedral at the back. A timber market can be observed in the right part of the painting (source: Museo de América, Madrid).

In this context of bustling trade and urban development, the construction of Seville Cathedral, initiated in the 15th century (Jiménez Martín, 2006), was followed by the decoration of its interior. The altarpiece for the *Evangelistas* chapel, situated in the northern part of the temple, was commissioned from Hernando de Esturmio on 27 May of AD 1553 (Hernández Díaz, 1937; Magdaleno Granja et al., 2005). The Dutch painter, whose original name was Ferdinand Storm, was born around AD 1515 in Zierikzee (in the current Netherlands) and had moved to Seville in AD 1537. The altarpiece is signed by him in AD 1555, one year before his death.

Over the centuries, humidity and poor conservation conditions took their toll on the altarpiece, and restoration works were carried out in 2003–2004 by the *Instituto Andaluz de Patrimonio Histórico* (IAPH, Andalusian Institute for Cultural Heritage). To fully document it, an integral, multidisciplinary study was performed before the restoration. Dendrochronological research was carried out to verify the fabrication date of the altarpiece and to ascertain the provenance of the wood. Additionally, wood anatomical and technological features were thoroughly recorded, as they could increase our knowledge about the raw material used for 16th century wooden panels and the processing of the wood to the final product.

2. MATERIAL AND METHODS

2.1 The *Evangelistas* altarpiece

According to the commissioning contract, the *Evangelistas* altarpiece had to be composed of nine panels distributed in a bench or predella and two tiers of three blocks each (Hernández Díaz, 1937; Magdaleno Granja et al., 2005) (Fig. 2). The contract described in detail the scenes that had to be depicted on each panel, and provided detailed instructions about, among others, the exact dimensions of the panels, the wood that should be used to make them (seasoned *borne*), how the planks should be glued together with animal-skin glue (*engrudo de Flandes*) and how each panel should be reinforced with five or six crossbeams made of 'seasoned *borne*'. Those crossbeams would have to be attached to the planks by dovetail joints. Chestnut was required for (and limited to) the peripheral mouldings (Hernández Díaz, 1937).

During the preliminary assessment of the conservation state of the altarpiece it was established that six of the panels had to be restored (Magdaleno Granja et al., 2005). The altarpiece was then disassembled and the panels were transported to the facilities of the IAPH in Seville.

2.2 Inspection of the panels and selection of planks for dendrochronological research

The first step of the dendrochronological research consisted of the careful inspection of the back of the panels and their transverse ends, in order to identify planks with sapwood and to observe the tree-ring patterns. The borders of the planks conforming the edge of the panels had been thinned down to 0.3-0.7 cm, and several planks presented in their transverse end decayed or disrupted surfaces that would hamper the possibility to achieve a reliable and continuous tree-ring sequence. Therefore, in the selection of planks for dendrochronological research, preference was given to those presenting sapwood and/or the most number of rings in a smooth surface.

The planks of one panel (St. John) were too deteriorated at the edges to allow the observation of tree rings, hence this painting was excluded from the dendrochronological research. The research was performed in the two major central panels, Resurrection of Christ (390 cm high x203 cm wide) and Mass of St. Gregory (286x 204 cm), as well as in two panels from the tiers depicting apostle St. Matthew (right panel of the upper tier, with dimensions 266 x 160 cm) and apostle St. Mark (right panel of the lower tier, 287 x 160 cm) and the central panel of the predella, depicting Saints Sebastian, John the Baptist and Anthony (83 x 206 cm) (Fig. 2).

Characteristics such as the dimensions of the individual planks, presence of tool-marks, direction and quality of the grain and presence of knots were registered. These observations provide information about the homogeneity/heterogeneity of the material used in the panels and allow inferring the minimum size of the timber-product from which the planks derived, as well as the working techniques and tools used for the construction of the panels. Finally, the dendrochronological research was conducted on a total of 33 planks from the five panels selected.

2.3 Preparation of the wood and acquisition of tree-ring data

To make the tree-rings visible in the selected planks, a 2-5 mm wide line was cleaned and polished on the transverse ends at the edge of the panels, using 600-800 grit sandpaper (Fig. 3). This preparation method complies with the premise pointed out by other dendrochronologists of keeping the

intervention on art-pieces as non-intrusive as possible (e.g. Eckstein, 2005; Fraiture, 2009). Tree-ring sequences were photographed along overlapping segments using a Nikon camera with macro objective. The images were calibrated at a maximum resolution of 120 pixel/mm. We used the software CooRecorder (Larsson, 2011a) to measure ring-widths as series of coordinates and CDendro v. 7.4 (Larsson, 2011b) to convert the coordinates to millimetres.

Figure 2. *Evangelistas* altarpiece after the restoration (photo: A. Jiménez Martín). As specified in the contract, the altarpiece is composed of nine panels distributed in a predella and two tiers of three blocks each. The images depicted correspond to Saints Justa and Rufina (1), Saints Sebastian, John the Baptist and Anthony (2), Saints Catherine and Barbara (3), St. Luke (4), Mass of St. Gregory (5), St. Mark (6), St. John (7), the Resurrection (8), and St. Matthew (9). The dendrochronological research was carried out on the shaded panels (2, 5, 6, 8 and 9).

2.4 Dendrochronological dating, provenance of the wood and estimated felling dates

The statistical and visual comparison of the obtained tree-ring series between them (internal crossdating) and with the master chronologies (external crossdating) was performed using PAST4 v. 4.3.1021 (Knibbe, 2012). For statistical crossdating the Student's *t*-value adapted for tree-ring series by Baillie and Pilcher (1973) (*t*-BP) and the percentage of parallel variation or 'Gleichläufigkeit' (Gl) defined by Eckstein and Bauch (1969) were considered. Matching series were averaged into a raw (non-standardized) object chronology (OC). Non-matching series were visually scrutinized against the created OC in search for potential mistakes in the measurements, and the pictures were eventually re-

measured. Then, the final OC and the remaining loose series were compared to a set of reference chronologies representing well defined areas in Scandinavia, Germany and Poland, as well as to a set of chronologies derived from wood imported to Denmark, Great Britain and Scotland from Scandinavia, Germany and the south-eastern Baltic (Hillam and Tyers, 1995; Crone, pers. comm.; Daly, pers. comm.). All sound statistical matches were visually verified.

To estimate the felling date of planks retaining partial sapwood we used OxCal 4.1.2 (Bronk Ramsey, 2009), which allows to estimate the felling date range of a group of suspected coeval timbers within a defined confidence interval (C.I.) using Bayesian statistics (Millard, 2002; Miles, 2006; Tyers, 2008). To implement this approach a probability distribution function (PrDF) for the number of sapwood rings for the region of origin of the investigated wood must be available. Such a PrDF can be built up with ring counts of sapwood from living trees and/or historical samples with complete sapwood from the same region. After applying a lognormal transformation to the data, a sapwood model is produced by OxCal. The PrDF is defined by two parameters; a constant *a* and the residual standard deviation σ._This sapwood model can then be used in OxCal, together with the dates obtained for the heartwood/sapwood border of the examined samples retaining partial sapwood and the number of sapwood rings remaining in those samples. The OxCal-model will then calculate the felling date distribution of each sample and a combined felling date range for the group following a Bayesian approach, considering the highest probability density region of the distribution function (Millard, 2002). For the following analysis the probability level was set at 99.7% (3σ).

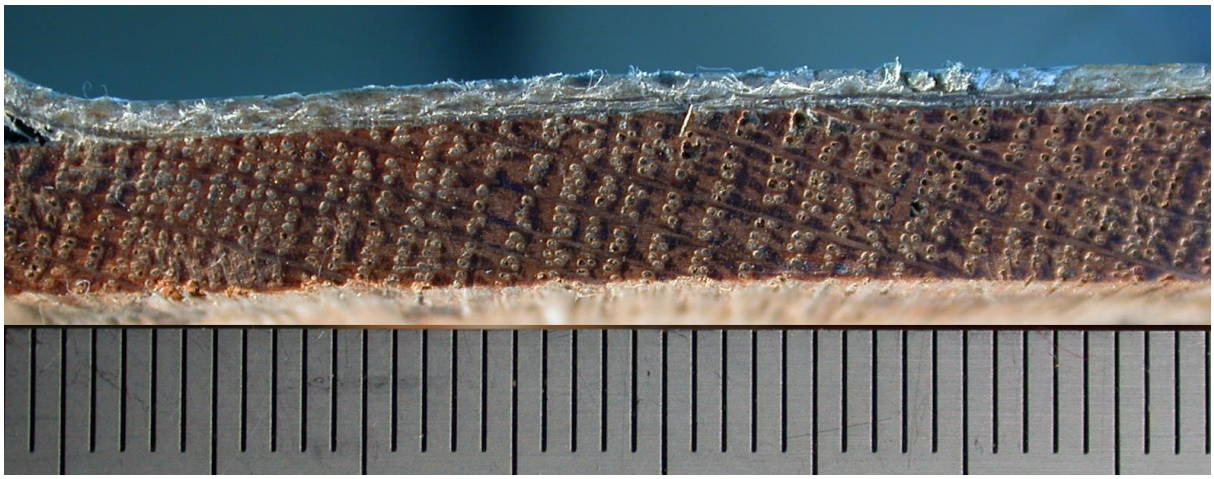

Figure 3. Surface of a plank polished with sandpaper 600-800 grit. Growth direction towards the right.

3. RESULTS

3.1 Wood technology and panel construction

The altarpiece presents two types of panels, which are differentiated by the sizes and disposition of the planks and by the construction process. The panel of the central predella is composed by five horizontal planks: four of them cover the entire horizontal length of the panel (206 cm), whereas the fifth plank is made out of two fragments of 165 and 41 cm long. The width of the longer planks ranges from 16 to 23 cm, whereas the fragments of the fifth plank have a width of only 7.5 cm (Table 1). All

of them are 2.3 cm thick. Two planks retain partial sapwood, and one of these presents also a sapwood inclusion and a knot (Fig. 4). The observed tool marks allowed the reconstruction of the process of panel making (Fig. 4): (1) cleaving of each plank and trimming to size; (2) joining of planks by rectangular dowels and gluing them together with animal-skin glue (*engrudo de Flandes*); (3) attaching transverse crossbeams by dovetail joints; (4) rabbeting a tongue on the edges of the panel using a chisel and/or a plane.

Table 1. Dendrochronological results of the researched planks. Measurement codes with an asterisk indicate curves that have been shortened. The numbers in brackets indicate the portion of the curve considered in the calculations.

Position in altarpiece	Plank code	Plank Width (cm)	Number of rings	Mean ring width (mm)	Standard deviation (mm)	Sap-wood rings	Year begin AD	Year End AD
Central panel predela (Saints Sebastian, John the Baptist and Anthony)	010	23	116	1.91	0.53	8	1425	1540
	02B	16	96	1.70	0.66	-	1427	1522
	03B	18.3	126	1.40	0.33	-	1399	1524
	04B	16.5	173	0.92	0.28	9	1366	1538
	05A	7.5	88	0.60	0.21	-	-	-
St. Mark, right register	06A	16.5	199	0.80	0.21	-	1321	1519
	07A	19	131	1.39	0.54	-	-	-
	08A	13	134	0.97	0.27	-	-	-
Mass of St. Gregory, central register	10A	13.4	76	1.66	0.50	3	1463	1538
	11A	16.8	105	1.60	0.76	-	1409	1513
	12A	11.8	150	0.78	0.19	23	1400	1549
	13A	11	99	1.11	0.48	-	1393	1491
	14A	15.4	60	2.21	0.78	-	1457	1516
	15A	16.9	161	0.79	0.41	-	1332	1492
St. Matthew, right register	16B*	12	66 (52)	1.53	0.60	2	1473	(1524) 1536
	17B*	14.8	155 (147)	0.86	0.26	8	1380 (1388)	1534
	18A	16.5	107	1.29	0.33	6	1427	1533
	19A	14.1	130	1.02	0.33	7	1406	1535
	20C	13.9	93	1.35	0.39	5	1450	1542
	21A	16.7	174	0.84	0.49	-	1356	1529
	22A	14.4	124	1.24	0.32	10	1418	1541
	23A	12.9	112	0.91	0.26	3	1420	1531
	24A	15.2	218	0.81	0.42	-	-	-
	25A	13.1	98	1.14	0.41	-	1418	1515
	26A	13.7	62	1.30	0.31	-	1457	1518
Resurrection, central register	30A*	14.3	121 (109)	1.15	0.36	-	1368	(1476) 1488
	31A	18.2	180	0.96	0.32	8	1356	1535
	32A	14.5	125	1.11	0.46	-	1385	1509
	33A	11.6	98	1.03	0.47	-	1408	1505
	34A	14.5	117	1.16	0.39	-	1410	1526
	35A	13.2	119	1.05	0.29	-	1409	1527
	36A	11.1	108	1.05	0.24	-	1413	1520
	37A	11.4	49	2.13	0.82	-	1465	1513

Figure 4. Back of the panel from the central predella. Sapwood was present in two planks. One plank also presented a sapwood inclusion. Cleaving marks are evident in all planks. The numbers indicate the process of panel making: (1) cleaving of each plank and trimming to size; (2) joining of planks using rectangular dowels and gluing them together with animal-skin glue; (3) attaching transverse crossbeams by dovetail joints; (4) rabbeting a tongue on the edges of the panel using a chisel and/or a plane.

The other type of panels is represented by the panels of the registers, which are made from planks arranged vertically. These planks are much longer than those of the predella but have generally a smaller width (11 to 18.2 cm) and thickness (1 to 1.5 cm) (Table 1). The grain of the wood is very straight and free of knots. The central panel from the upper register, representing the Resurrection, is made out of 15 long planks (Fig. 5). Most of them present lengths of about 300-320 cm, one of them reaching 376 cm. They all are extended to meet the total length of the panel (390 cm) with smaller fragments of different planks linked by Z-shaped joints. The other panels are shorter (287, 286, and 266 cm for St. Mark, Mass of St. Gregory and St. Matthew, respectively), and are made from planks that reach their entire length. The construction process of these panels (Fig. 6) also differs from that observed in the predella: (1) cleaving and trimming of each plank with axe and/or chisel (although the axe marks could belong to an earlier process to obtain planks from the tree trunks), (2) rabbeting with plane of the longitudinal thicker side of some planks, (3) joining of planks by rectangular dowels and gluing them together, (4) attachment of crossbeams by dovetail joints; (5) thinning towards the edges of some planks with chisel or small adze, and bevelling of the edges with a plane.

Figure 5. Front and back of the *Resurrection* panel. The deformation suffered by the planks over the centuries can be seen under the reflecting light in the upper part of the front of the painting. In the picture showing the back of the panel we have indicated with white lines the joints between different vertical planks. The two black vertical bars are part of the support used during the restoration works.

From the eight researched planks of the Resurrection panel only one retained sapwood (Table 1). Several sapwood rings were observed in two of the six planks researched from Mass of St. Gregory's panel, as well as in seven of the 11 planks selected from St. Matthew's panel. Sapwood was absent in the three planks selected from St. Marks panel.

3.2 Dating of the panels and wood provenance

From the 33 researched planks 29 could be internally crossdated (Fig. 7), with only four planks (Q415005A, 7A, 8A and 24A) remaining unsynchronised. Several series presented *t*-values higher than 7, although only the statistical and visual match between the planks 22A and 26A (*t*-BP= 9.21, Gl= 70.2, $p<0.005$ for an overlap of 62 rings) allows hypothesising that the wood may derive from the same tree. Given the uncertainty of this observation, these two series were treated individually in subsequent analyses. An OC (Q415029M) was built with the 29 relatively dated tree-ring series.

The comparison of the OC with the reference chronologies resulted in the date of the last ring in AD 1549. After shortening the OC to the interval with a minimum sample depth of four series (AD 1356-1540), the best matches were obtained with chronologies representing the southwest of Sweden and eastern Denmark, although excellent matches (*t*-BP>9 for overlaps higher than 100 rings) were also found with object chronologies from buildings in Scotland and chronologies obtained from different shipwrecks (Table 2, Fig. 8). The strongest match (*t*-BP= 17.1, Gl=78.6, $p<0.0001$ for an overlap of 185 rings) was obtained with the regional chronology QBRV400A representing the southwest of Sweden (Bräthen, 1982, 1983, corrected by Andersson and Axelson, and made available at http://www.cybis.se/wiki). Given the multi-regional provenance of the underlying tree-ring series included in that chronology, we decided to create two subchronologies based on the current regions where the wood was found: *Västergötland* (QBRV200B) and *Halland* (QHAG067A). The former contains series from wood found around Lodosë and in Hedared and Bälinge (Block 2 and 2B in Bräthen, 1982, 1983, corrected by T. Axelson), whereas the latter includes series of wood found in Lindberg and Halmstad (measurements from Bräthen corrected by A. Andersson). The result was a higher agreement of Q415029M with the *Halland* chronology (*t*-BP=14.4, Gl=79.5, $p<0.0001$ for an overlap of 185 rings) than with *Västergötland* (t-BP=11.3, Gl=75.1, $p<0.0001$ for the same overlap) (Table 2, Figs. 8 and 9). No sound matches were found with the Polish and the Baltic1 and 2 chronologies.

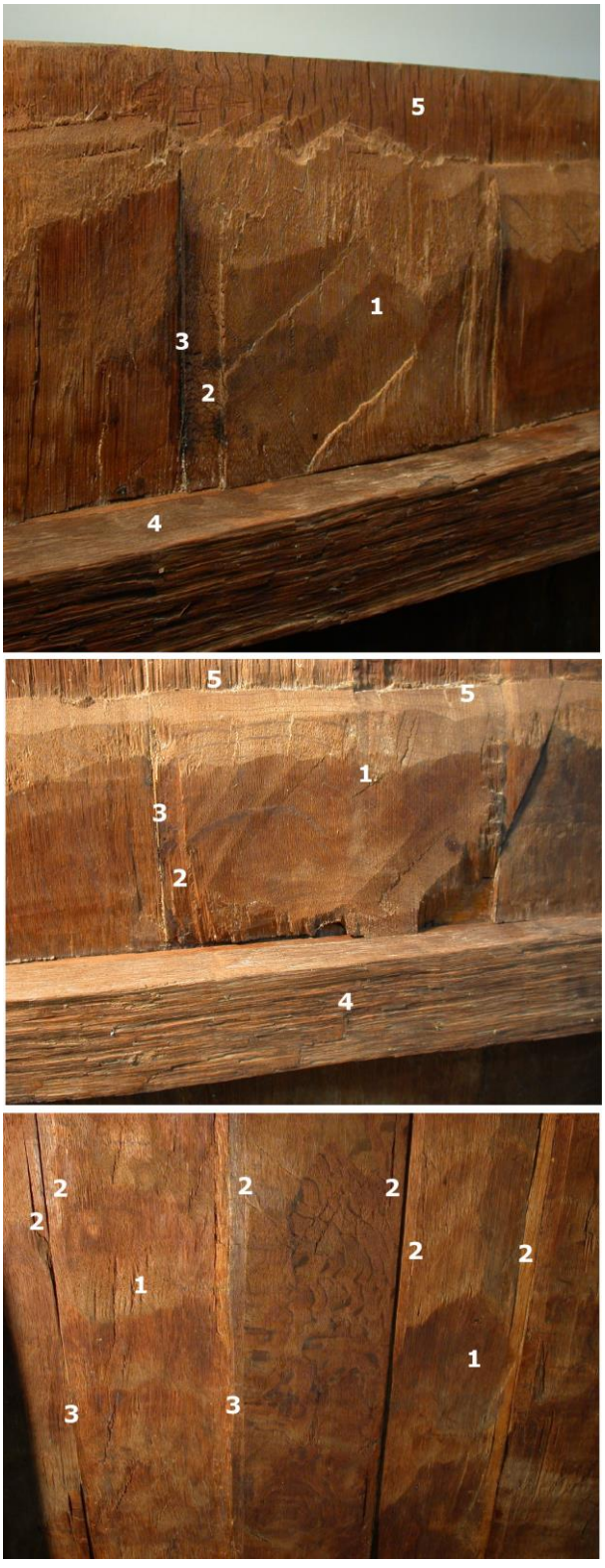

Figure 6. Back of St. Mark's panel. The tool marks indicate that the wood was worked with an axe, an adze and a plane. Saw marks are absent. The numbers indicate the process of panel making: (1) cleaving and trimming of each plank with axe and /or chisel, (2) rabbeting with plane of the longitudinal thicker side of some planks, (3) joining and gluing of planks, (4) attachment of crossbeams by dovetail joints; (5) thinning of the edges of planks with chisel or small adze, and bevelling of the edges with a plane.

3.3 Estimated felling dates

Given the provenance of the wood in the southwest of Sweden, we used sapwood information reported by Bräthen (1982) to define

the PrDF for sapwood counts. This sapwood dataset originates from trees of different ages and growth rates growing in the southwest of Sweden. The resulting PrDF is defined by a = 2.71194 and σ = 0.26701, and referred to as "Bräthen". The narrow dispersion of the heartwood/sapwood border of the 12 planks that contained partial sapwood (Fig. 10) suggests that all trees could have been felled in the same year or barely a few years from each other. Therefore we included all of them in a model to estimate their felling date range with the "Bräthen" PrDF, and to assess their combined agreement (A_{comb}). As a result, their combined *felling date range* was *AD 1549-1551* at the *99.7%* probability level (Fig. 11). However, the low A_{comb} value (28.4%) indicates that the model fails, as is demonstrated by six planks that were flagged for showing poor agreement (i.e. individual agreement indices (A) lower than 60%): 04B (A=57.4%), 17B (A=25.1%), 18A (A=33.9%), 19A (A=44.8%), 23A (A=44.8%) and 31A (A=33.7%) (Fig. 11). In the light of these results, and given that the use of more than nine samples for the Combine function in OxCal has been observed to produce a loss of accuracy in the estimation (i.e. too narrow felling date ranges) (Miles, 2006), we computed the estimation again excluding the six discordant series from the model. The resulting combined *felling date range* was *AD 1549-1554 (at 99.7% probability)* (Fig. 12), with individual agreement indices ranging from 79.6% (plank 22A) to 142.4% (plank 12A) and A_{comb}=148.6% (n=6, A_n=28.9%). This indicates that these planks can be considered a coherent group in terms of their felling date.

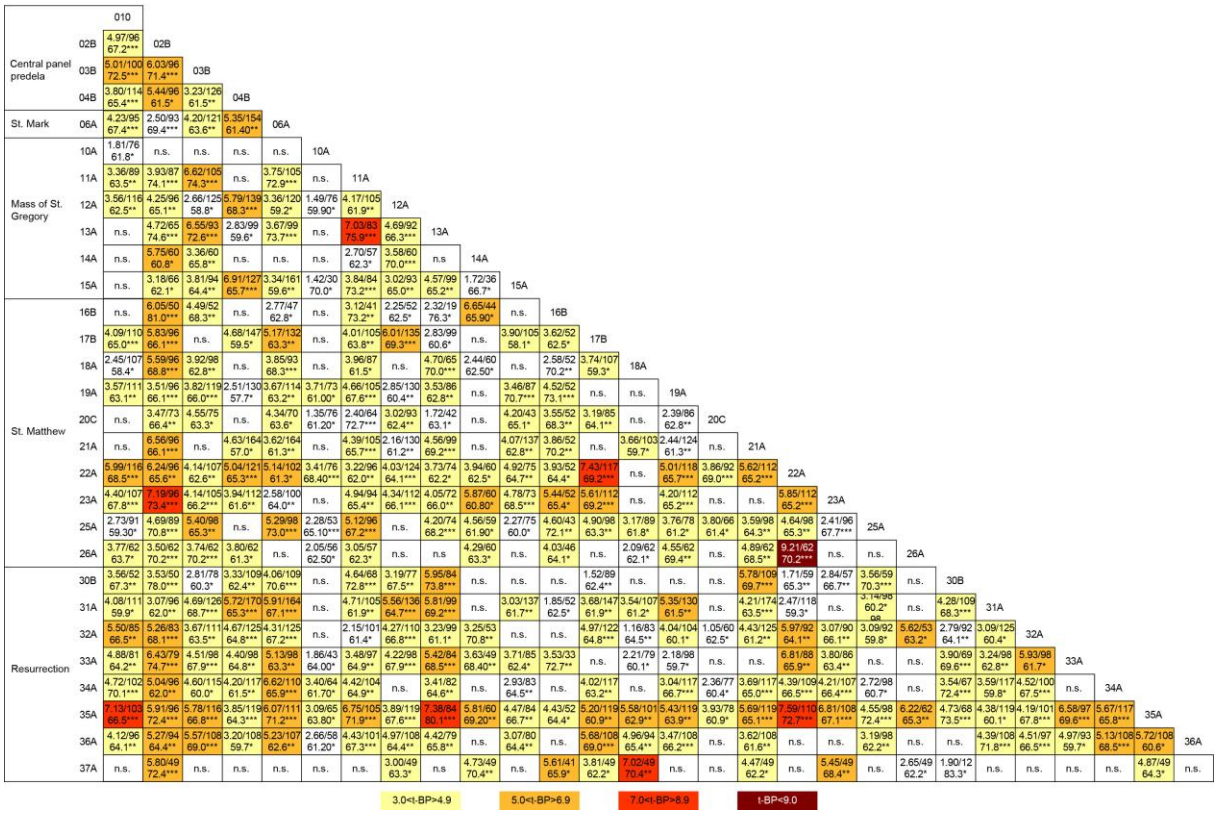

Figure 7. Matrix presenting the results from the internal crossdating: *t*-BP, overlap, Gl and its associated significance level; n.s.: not significant. Good correlations (*t*-BP>5) have been found between planks of different panels suggesting that this is a group of timbers with the same provenance. The highest match (*t*-BP=9.21) has been found between two planks from St. Matthew panel. These planks could originate from the same tree.

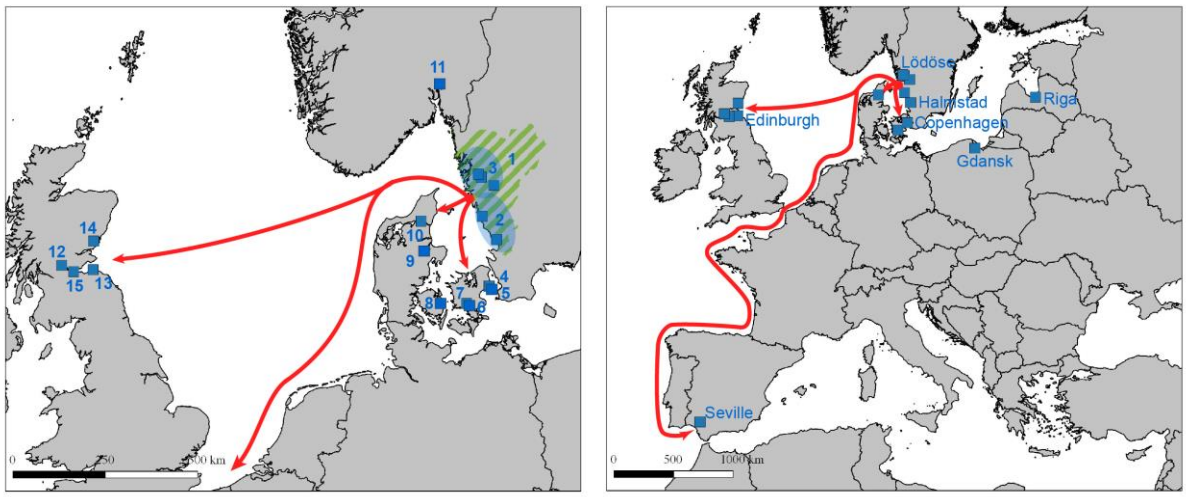

Figure 8. Area of provenance of the wood in south-western Sweden and places where some of the chronologies providing the best matches were developed: 1) Western Sweden (QBRV400A); 2) Halland; 3) Västergötland; 4) B&W shipwreck 2; 5) Amager Strand ship; 6) Suså Næstved; 7) Hammer Church; 8) Nyborg Castle; 9) Gåsehage ship; 10) Ålborg østerå & boulevarden; 11) Oslo Barcode ship 14; 12) Stirling Castle; 13) Fenton Tower; 14) Guthrie Castle; and 15) Midhope Castle. The arrows indicate suspected trade routes.

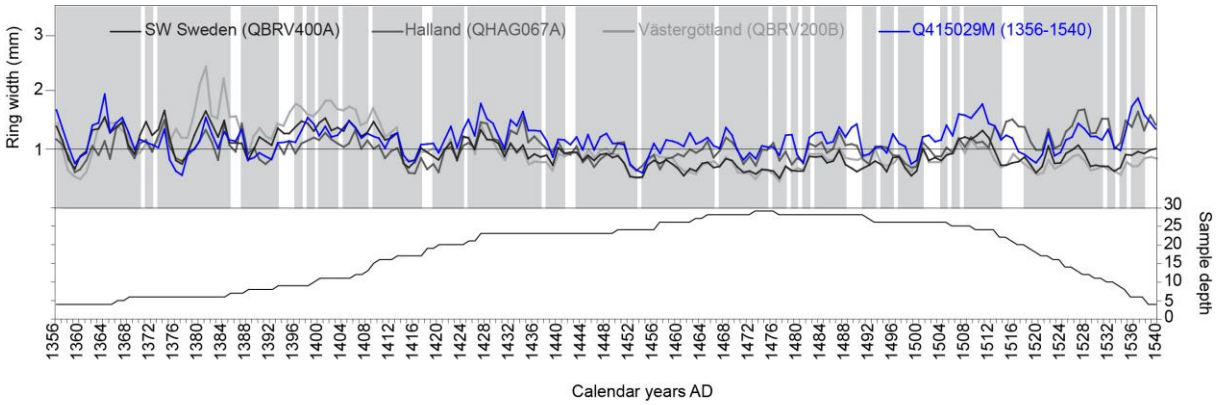

Figure 9. Visual match between the object chronology Q415029M (AD 1356–1540) and the reference chronologies from western Sweden (Bräthen, 1982). The shaded area indicates the synchronous parallel variation (Gl) between Q415029M and QBRV400A.

4. DISCUSSION

4.1 *Borne*: imported oak wainscots in Iberia

The fact that all planks were radial or almost radial without reaching the pith of the tree and lacked saw marks indicates that they were converted by radial splitting of primary timber products (e.g. Crone and Barber, 1981). The secondary products obtained by this conversion method often present three squared sides and a round one, which were associated in Spain with *borne* wood, as reflected by the artist Alonso Matías in AD 1614 (Llaguno, 1829). Matías described this wood as "melon slices: flat and thicker in one tangential end and angulated in the other", and reported approximate measures of 5.2 and 1.75 cm thick respectively, and about 334 cm long. These descriptive characteristics of the oak boards imported to Iberia from northern Europe indicate that the term *borne* was used in Spain to refer to secondary timber products known as *wainscots* in north-European markets. Wainscots were

high-quality oak boards, exported the early 17th century from the Baltic region (mostly from the Polish harbour of Gdansk, but also from Konigsberg, in current Lithuania), and are frequently mentioned in historical records such as the Sound toll-registers or the customs accounts of Gdansk's harbour (Zunde, 1999; Wazny, 2005).

In Seville, this imported *borne* was cheaper than other local species, as can be deduced from some contracts. For example, in the altarpiece dedicated to Saint Matthew in Lucena, dating from AD 1577, *borne* paid at 1 *ducado* was used for the structure, whereas the *pino de Segura* used for the sculptures was paid at 7 *ducados* (Carrassón López de Letona et al., 2003). This local pine was very abundant in the region and was commonly used for sculptures, reliefs and columns in altarpieces (Bruquetas Galán, 2002), but it was also very demanded for construction timber (Fernández-Golfín et al., 2001), which may explain its high price. The cheaper price of the *borne* must have been due to the abundance of this product in the city. This is confirmed by a letter from Fray Juan de Siruela, who was sent to Seville in AD 1615 to buy *borne* wood for the altarpiece of the *Real Monasterio de Guadalupe*, in the nearby province of Caceres. In his letter, the fray reports that *borne* wood was plentiful in the city and therefore he could buy it at a very good price (Andrés, 2001).

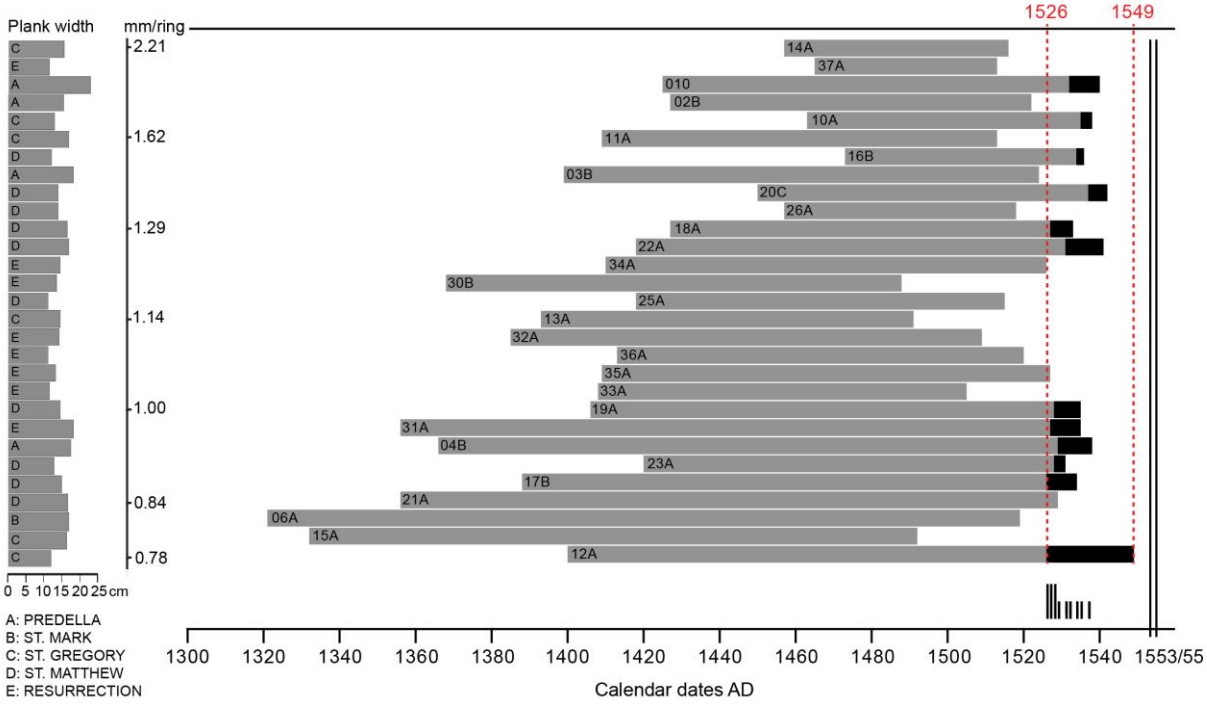

Figure 10. Bar diagram of the dated planks ordered by average ring width. The black portion of the bars indicates the sapwood. The frequency histogram represents heartwood/sapwood borders. Dash lines enclose the begin/end dates of the sapwood in plank 12A. The construction period AD 1553/55 is represented by vertical continuous lines. The width of each plank is presented on the left.

4.2 From *borne* to panels

Sixteenth century altarpieces were high quality technological products and as such, their production and technical specifications were regulated by the guilds (Bruquetas Galán, 2002). The guild

Ordinances stressed among others the importance of using slowly dried wood, and the need to remove the sapwood from oak planks. These specifications are very similar to those required, for example, by Flemish guilds such as the Saint-Luke Guild of Antwerpen (Beeckman, 2005), and they are the result of a very good knowledge of the physical properties of wood and technological know-how. However, the presence of sapwood in several planks of the *Evangelistas* altarpiece proves that the regulations were not always strictly followed. A close observation of the outer edge of each plank revealed that the wood had been removed on those sides in a somewhat irregular fashion. The use of an unsharpened tool could be an explanation for the lack of accuracy aligning the edges and removing the sapwood, but another explanation could be a purposeful intention to discard as little wood as possible if the width of the wainscots was already scant. This second explanation seems rather plausible when looking at the time spans of the dated planks (Fig. 10). The overlapping spans of the dated series demonstrate that none of the planks were obtained from consecutive pieces of a same, very wide wainscot. By observing the grain in some of the planks that deviated from a straight vertical plane, and considering a rough estimation of the thickness of the missing sapwood, we could infer a radial thickness of the stems between 15.4 cm (Q415012A) and 24.2 cm (Q415037A), with an average of ca. 19.5 cm. The length of the wainscots used in this altarpiece could have ranged between at least 320 and 376 cm, as indicated by the length of the planks from the Resurrection panel. Wainscots of these lengths could have been cut to obtain the shorter planks for the panels of St. Mark (287 cm long), St. Gregory (286 cm) and St. Matthew (265 cm), and the leftover bits of wood could have been used to elongate the planks from the Resurrection panel to the total length of 390 cm.

Although the dimensions of the planks from the *Evangelistas* altarpiece are consistent with those used in different 16th century Iberian altarpieces made of *borne*, some significant differences have been found with others. For instance, the central panel of the altarpiece of Mariscal Diego Caballero at Seville Cathedral, made by the Flemish artist Pedro de Campaña in AD 1556, has a dimension of 330 x 240 cm (height x width), but in this case, the 14 planks used to make the panel were arranged horizontally, hence they were cut at a length of 240 cm. We do not know if such arrangement of the planks was due to the lack of wainscots meeting the total vertical length required for the panel (330 cm), or if it was a personal preference of the artist, as more of his works present such horizontal disposition of the planks (Laguna Paul, pers. comm.). In the Convent of Christ in Tomar (Portugal), the panels of the main altarpiece, which was built in AD 1488-1499 with Baltic oak, are 240 cm wide by 400 cm high (Henriques et al., 2010). To meet the required length, vertical planks of 230 cm were extended with pieces of 170 cm. This implies that the Baltic wainscots available to make these altarpieces were shorter than 400 cm, and probably also much shorter than those purchased for the *Evangelistas* altarpiece. On the other hand, the planks of these two altarpieces were 4 cm thick, hence more than twice the thickness of the planks used in the panels of the registers of the *Evangelistas* altarpiece. The planks from the *Evangelistas* altarpiece must have derived from thinner boards that were thinned yet further during the preparation process. The lack of outstanding matches between the planks we researched suggests that they derive from different trees, proving that they were not obtained from splitting thicker wainscots in halves.

Table 2. Statistical results between the object chronology Q415029M shortened to a sample depth of four series (AD 1356–1540) and selected reference chronologies. The results are ordered by overlap and *t*-BP.

Geographically defined chronologies		**Start–End dates (AD)**	**Overlap**	***t*-BP**
QBRV400A	Västergötland-Halland, SW Sweden (Bräthen, 1982, corrected by T. Axelson and A. Andersson)	1300–1600	185	17.10
QHAG067A	Halland (Lindberg, Halmstad), SW Sweden	1312–1612	185	14.40
QBRV200B	Västergötland (Lodöse, Hedaret, Bälinge) SW Sweden	1337–1553	185	11.30
NLQNORW	SW Norway (Domínguez-Delmás, M., unpublished)	1354–1735	185	5.56
66STD6	East Pomeranian, NW Poland (Wazny, T., 1990)	996–1985	185	3.98
Danish object chronologies (may contain imports from Sweden)		**Start–End dates (AD)**	**Overlap**	***t*-BP**
ZEALAND0	Zealand island, Denmark (Daly, unp.)	452–1770	185	16.08
2121M002	Suså Næstved, SW Zealand, Denmark (Daly, 2001b)	1052–1596	185	14.87
8127M001	Ålborg østerå & boulevarden, N Denmark (Daly, 2000a & 2001a).	846–1771	185	14.34
4077M001	Nyborg Castle, E Funen Island, Denmark (Daly, 1999)	1310–1540	185	11.53
2117M001	Hammer Church, Zealand, Denmark (Daly, 1998a)	1316–1514	159	11.76
2M000006	Sjælland Churches, Denmark (Daly, unp.)	1318–1514	159	11.17
81M00004	Churches in Vendsyssel Denmark - W Sweden group (Daly, 1998b)	1350–1480	125	10.29
Scottish building and object chronologies (Swedish/Danish provenance)		**Start–End dates (AD)**	**Overlap**	***t*-BP**
EP3 1539	Stirling Castle, Scotland, UK (Crone, 2008a)	1361–1539	179	11.79
FTMAS1	Fenton Tower, E Lothian, Scotland, UK (Crone, 2013)	1366–1547	175	11.36
EP4 1592	Stirling Castle, Scotland, UK (Crone, 2008a)	1390–1592	151	11.41
MIDHOPE	Midhope Castle, West Lothian, Scotland, UK (Crone and Mills, 2012)	1265–1505	150	9.83
STPCMNX3	Barrel, Cowgate, Edinburgh, Scotland, UK (Crone, 2011)	1410–1552	131	9.58
GAROOF2	Guthrie Aisle, Angus, Scotland, UK (Crone and Mills, 2012)	1350–1458	103	9.58
Object chronologies from shipwrecks (undefined provenance)				
Z027M002	Amager Strand ship Denmark (Daly, 2008)	1313–1567	185	9.65
Z073m001	Oslo Barcode ship 14 (Daly, 2011)	1385–1574	156	11.55
Z040M001	Gåsehage ship Randers (Daly, 2009)	1386–1567	155	12.61
00652M02	B&W shipwreck 2, Copenhagen, E Denmark (Daly, 2000b)	1405–1607	136	13.68

4.3 Estimated cutting dates, seasoning of the wood and the artist signature

The presence of sapwood in several planks allowed estimating felling date ranges in OxCal using a Bayesian approach and applying the "Bräthen" sapwood model. The individual disagreement (A<60%) shown by six samples included in the model representing all the planks retaining partial sapwood could indicate that those trees were likely cut in earlier years than the apparent coeval group comprised by the planks 010, 10A, 12A, 16B, 20C and 22A. This would imply that those timbers were stock-piled in Sweden or that the wainscots had been stored in Seville for a couple of years. However, five of the discordant series have very low growth rates (0.01 cm/year or lower) and given the small

width of the planks (Table 1, Fig. 10), they are likely to derive from trees reaching 200 years. Generally, older slow-grown oaks contain a higher number of sapwood rings than younger, fast-grown ones (Haneca et al., 2009 and references therein; Sohar et al., 2012). In our dataset, the slowest growth-rates are shown by plank 12A, which is also the one containing the highest number of sapwood rings (Fig. 10). Given that the heartwood/sapwood borders of the planks showing statistical disagreement have the same or later dates than the one from plank 12A (AD 1526, Fig. 10), it cannot be discarded that those trees were cut at the same time than the ones from the coeval group. The sapwood model used here to estimate the felling date range does not take into account the growth rate (i.e. average ring width) of the trees, as this variable was not reported by Bräthen (1982). Hence the results regarding the low agreement of six planks could have been different if the average ring width of the trees would have been considered.

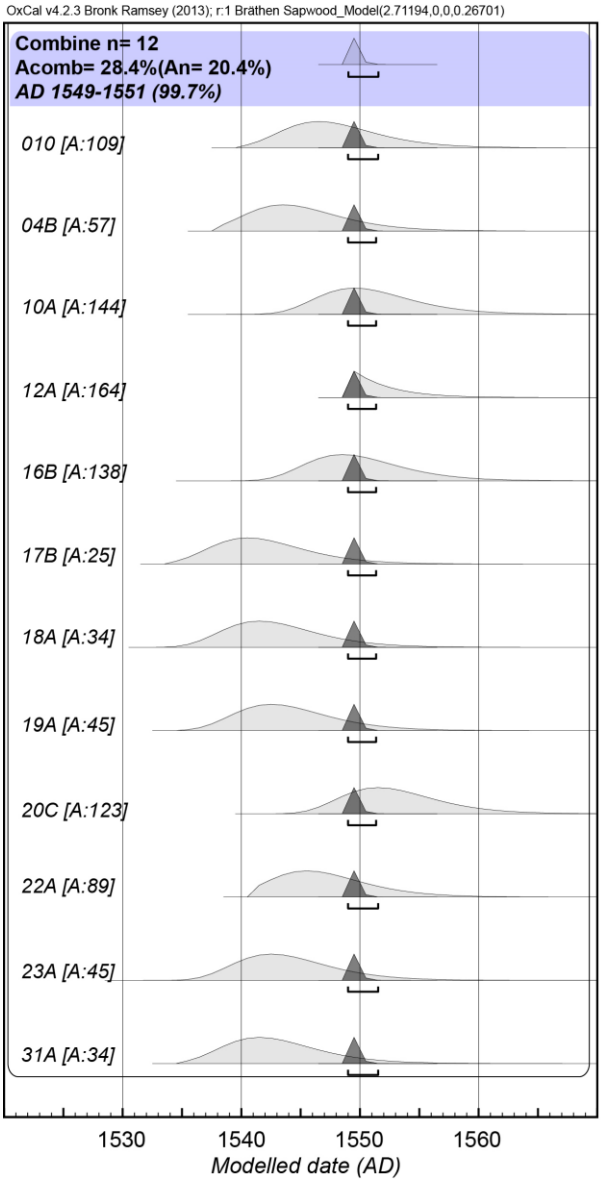

Figure 11. Estimated felling date ranges obtained with OxCal 4.2.3 for the 12 samples retaining partial sapwood. The light grey area presents the probability distributions for the individual samples. The darker area highlights the combined *felling date range* (highest probability density) for the interval *AD 1549–1551 (99.7% probability)*.

The combined felling date range for the coeval group of six planks is set at the interval *AD 1549-1554 (99.7% confidence level)*, with *AD 1549* as the year with the highest probability (Fig. 12). This year corresponds to the date of the last ring present in the plank 12A. Considering that the panels must have been fabricated soon after the commission of the work in May of AD 1553, and that it must have taken at least a couple of weeks to sail from the west of Sweden to Seville, it seems unlikely that the trees were cut after the commission date. A cutting date between 1549 and 1553 would allow for a maximum of four years down to a couple of months to season the wood. Klein (1996) reported a seasoning time between two and eight years for panels dating from the 16th and 17th century, hence our results are on the shorter side of that interval. However, these thinner Swedish wainscots may have needed shorter seasoning times than the thicker Baltic ones. Therefore it seems unlikely that a short drying time was the cause for the warping that had taken place across the width of the planks. The hygroscopic imbalance generated between the painted front and the untreated back of the planks, must have played a decisive role in the deformation of the wood.

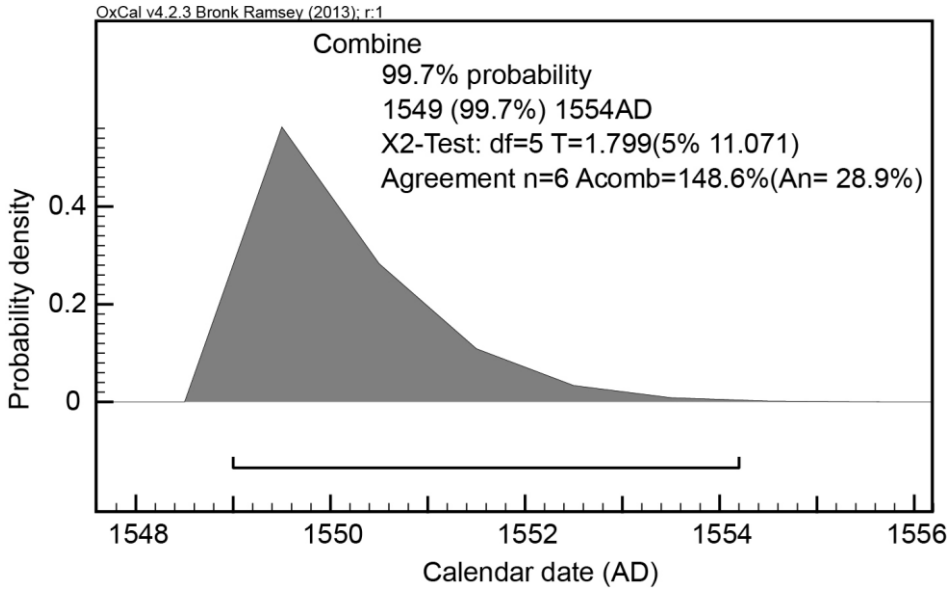

Figure 12. OxCal single plot showing the combined highest probability density for the planks 010, 10A, 12A, 16B, 20C and 22A with the bracket indicating the *99.7%* combined *felling date range AD 1549-1554*.

4.4 Swedish oak as an alternative to south-eastern Baltic procurement sources

The dendrochronological analysis has revealed that most of the researched planks derive from individual trees that probably grew in the same area. This implies that the two types of panels that we have described are only two constructive variants meant to comply with the requirements stipulated by the contract, i.e. wood from the same batch was processed and assembled in two slightly different ways.

Furthermore, the comparison of the obtained OC with the reference chronologies has shown distinctive high statistical scores of Q415029M with the master chronology from south-western Sweden and, in particular, with one of its subgroups (the Halland chronology), suggesting that the wood originates more likely from the Halland region (Fig. 8). The high correlations found with site chronologies in Denmark should not be misleading. Those site chronologies derive from historical timbers, and especially the ZEALAND0 chronology contains numerous tree-ring series obtained from historical/archaeological wood found all over Zealand, in Denmark (Daly, pers. comm.). However, in the 16th century, timber from western Sweden was exported to Denmark and southern Sweden, but not vice versa (Dow, 1969). The significantly lower statistical matches found with other master chronologies from nearby regions (e.g. southern Norway and north-western Poland) shows a clear division in the high-frequency (year-to-year) climatological signal contained in tree-ring series from those areas, validating further the described provenance of south-western Sweden.

Additionally, the high similarity found between the *Evangelistas* OC and timbers from Scottish castles such as Midhope and Stirling (Crone and Fawcett, 1998; Crone, 2008a,b) suggests a close proximity of the timber procurement sources. Crone and Fawcett (1998) and Crone (2008a) defined the

provenance of those timbers as Scandinavian, likely Swedish/Danish, but our results suggest that it would be useful to re-examine those datasets to refine the source area.

Wood trade from Sweden to Scotland in the 15th and 16th centuries is quite well documented (Dow, 1969; Paton, 1957). For example, in AD 1512, three shipments of timber from western Sweden were ordered to provide a total of 1,066 'Swidyn burdis' (Swedish boards) for shipbuilding in Scotland (Dow, 1969). In AD 1546, references to shipments of timber from Nya Lodöse, also in the south-west of Sweden, to Scotland have also been found in historical records (Paton, 1957). These dendrochronological and historical reports of Swedish timbers in Scotland represent either structural elements such as beams, boxed heart baulks, half- and quarter-baulks, and boards, whereas cleft planks were imported to Scotland mainly from the south-eastern Baltic regions (Crone and Mills, 2012; Crone, 2008b). Therefore, our research presents the first dendrochronological evidence of cleft oak wainscots from the southwest of Sweden used for panel paintings in western Europe, raising the question of its absence in the most important centres of art production in the Low Countries.

Dendrochronological studies carried out in the last decades have repeatedly reported the use of oak from the south-eastern Baltic in panel paintings dating from the 15th century up to the first decades of the 17th century (e.g. Klein and Esteve, 2001; Jansma et al. 2004; Fraiture, 2009 and references therein). The quality of the Swedish oak used in the *Evangelistas* altarpiece seems to be comparable to that described for the Baltic oak, i.e. straight grain, generally free of knots and with low growth rates that allowed a neat cleaving of the timbers to produce thin long planks (Wazny, 2005). For example, 76% of the planks from the *Evangelistas* altarpiece had growth rates below 1.4 mm per year (Table 1), a higher percentage than that reported by Fraiture (2009) for south-eastern Baltic oak from the same period (ca. 62% of planks). Furthermore, its price must have been cheaper than that of the Baltic oak, as the export of timber from the western coast of Sweden was exempt of payment of the Sound-toll taxes (Dow, 1969). Therefore, the lack of such high quality, cheaper product in the northern workshops is startling.

Interestingly, the use of Swedish oak in panel paintings in Spain has a coincident timeline with the use of Baltic oak in works of art produced in Flemish and Dutch workshops, but also in the south of Spain. South-eastern Baltic oak seems to have been available for art pieces in western markets, including Seville (Bruquetas Galán, 2002), until the early 17th century (Wazny, 2005). Swedish *borne* was available in Seville at least in the mid-16th century, as demonstrated by this research, and also in AD 1615, as recorded in the book accounts of the *Real Monasterio de Guadalupe*. In those accounts, the *borne* bought by Fray Juan de Siruela for the monastery's altarpiece was registered as "*borne* wood brought from Sweden by ship to Seville" (Monastery Archive, sign. C-III, 1617). Further historical research and dendrochronological analysis of other art pieces could shed light into the frequency and magnitude of the trade of Swedish *borne* in the Iberian Peninsula.

The absence of Swedish oak in works of art from the Low Countries and England could have different explanations. One could be, for example, the requirements set by guilds in the Low Countries. The Swedish *borne* employed in the *Evangelistas* altarpiece had smaller widths than the planks of Baltic oak reported by Fraiture (2009) for the same period, hence the smaller size of the Swedish wainscots could have led to their rejection by the very demanding guilds. Another reason might be related to shipbuilding. Daly (2007) reported oak from the south and southwest of Sweden in the B&W 1 Dutch

ship, dated to ca. AD 1584, proving that wood from that geographical source was employed in the Netherlands at that time for shipbuilding. The OC obtained from the *Evangelistas* altarpiece has also provided very high statistical matches with four shipwrecks dated to the late 16th and early 17th (Table 2). Therefore it is possible that the narrower Swedish wainscots were traded primarily as timber products for the shipbuilding industry.. However this hypothesis could only be verified through extensive historical and dendrochronological research on 16th and early 17th century Dutch and Spanish shipwrecks.

5. FUTURE PERSPECTIVES

Our results have demonstrated the potential of combining dendrochronology with wood technology to gain knowledge about the wood procurement and wood-working techniques for the production of a 16th century altarpiece. Furthermore, our research has provided an empirical description of the product known as *borne* in the Iberian Peninsula, and more importantly, has revealed the area of south-western Sweden as an alternative source of oak wainscots for altarpieces in the 16th century. This result poses numerous questions regarding the frequency and magnitude of the trade of Swedish *borne* in the Iberian Peninsula, and its applications. Dendroarchaeology can contribute providing a general definition of the technological features of this timber product in precise periods of time. International multidisciplinary research is the key to unravel such exciting questions. Efforts towards the combined study of documentary sources and comparative dendroarchaeological investigations of *borne*, Baltic and Scandinavian wood in different countries should be pursued.

Acknowledgments

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References

Andrés, P., 2001. *Guadalupe. Un centro histórico de desarrollo artístico y cultural*. Diputación de Cáceres, Institución Cultural El Broncense, Salamanca.

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

Beeckman, H., 2005. The impact of forest management on wood quality. The case of medieval oak, in Van de Velde, C., Beeckman, H., Van Acker, J., Verhaeghe, F. (Eds.), *ConstructingWooden*

Images: Proceedings of the Symposiumon the Organization of Labour and Working Practices of Late Gothic Carved Altarpieces in the Low Countries, Brussels 25–26 October 2002. VUB Press, Brussels, pp. 91–114.

Brand, H.,2007. Baltic Connections. Changing patterns in seaborne trade (c. 1450–1800), in L. Bes, E. Frankot en H. Brand (Eds.), *Baltic Connections Archival Guide to the Maritime Relations of the Countries around the Baltic Sea (including the Netherlands) 1450–1800*. Vol. I, Leiden, pp. 1–25. URL: www.balticconnections.net/index.cfm?article=Baltic+Sea+Trade, last accessed 19 June 2012.

Bräthen, A., 1982. *Dendrokronologisk serie från västra Sverige 831–1975*. Rapport RAÄ 1.

Bräthen, A., 1983. *The tree-ring chronology of Western Sweden 753–1720,* Dendrokronologiska Sällskapet, Meddelanden 6.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* **51**, 337–60.

Bruquetas Galán, R., 2002. *Técnicas y materiales de la pintura española en los Siglos de Oro*. Madrid, Fundación de Apoyo a la Historia del Arte Hispano.

Carrassón López de Letona, A., Gómez Espinosa, T., Gómez González, M., 2003. Retablo Mayor de la iglesia de San Mateo de Lucena (Córdoba). *Bienes culturales: revista del Instituto del Patrimonio Histórico Español* **2**, 149-164. URL: http://www.mcu.es/patrimonio/MC/ BienesCulturales/Capitulos.html

Crone, A., 2008a. Dendrochronological analysis of the oak and pine timbers, *Stirling Castle Palace. Archaeological and historical research*. http://sparc.scran.ac.uk

Crone, A., 2008b. *Stirling Castle Palace. Archaeological and Historical Research 2004–2008. Dendrochronological analysis of oak and pine timber*. Historic Scotland. Kirkdale Archaeology.

Crone, A., 2011. Coopered vessel, in Jones, E. (Ed.), Through the Cowgate: life in 15th-century Edinburgh as revealed by excavations at St Patrick's Church, *Scottish Archaeol Internet Rep* 42, 56–8.

Crone, A., 2013. Dendrochronology results, 48-54, *in* Cressey, M., Alexander, D., Hicks, K. & Suddaby, I. (Eds), Anatomy of a tower house: survey and excavation at Fenton Tower, *East Lothian Antiquarian and Field Naturalists' Society* 29, 33–57.

Crone, A., Barber, J., 1981. Analytical techniques for the investigation of non-artefactual wood from prehistoric and medieval sites. *Proc Soc Antiq Scot* **111**, 510–515.

Crone, A., Fawcett, R., 1998. Dendrochronology, documents and the timber trade: new evidence for the building history of Stirling Castle, Scotland. *Med Archaeol* XLII, 68–87.

Crone, B. A., Mills, C.M., 2012. Timber in Scottish buildings, 1450 - 1800; a dendrochronological perspective, *Proc Soc Antiq Scot* **142**, 329–69.

Daly, A., 1998a. Dendrokronologisk undersøgelse af tømmer fra Hammer kirke, Roskilde Amt. *Nationalmuseets Naturvidenskabelige Undersøgelser rapport nr*. 8, 1998. København.

Daly, A., 1998b. Kirker i Vendsyssel - alder og funktion. Dendrokronologisk del. *Nationalmuseets Naturvidenskabelige Undersøgelser rapport nr*. 36, 1998. København.

Daly, A., 1999. Dendrokronologisk undersøgelse af tømmer fra Nyborg slot, Fyns Amt. *Nationalmuseets Naturvidenskabelige Undersøgelse* rapport nr. 1999: 5. København.

Daly, A., 2000a. Dendrokronologisk Undersøgelse af tømmer fra Østerå, Aalborg. *Nationalmuseets Naturvidenskabelige Undersøgelser rapport nr*. 25, 2000. København.

Daly, A. 2000b. Dendrokronologisk undersøgelse af tømmer fra B&W grunden, Skibsvrag 2 og 5. *Nationalmuseets Naturvidenskabelige Undersøgelser rapport nr*. 26, 2000, København.

Daly, A., 2001a. Dendrokronologisk undersøgelse af tømmer fra Boulevarden, Aalborg. *Nationalmuseets Naturvidenskabelige Undersøgelser* rapport nr. 2001: 7. København.

Daly, A., 2001b. Dendrokronologisk undersøgelse af tømmer fra Suså, Næstved, Storstrøms amt. *Nationalmuseets Naturvidenskabelige Undersøgelser rapport nr*. 31, 2001. København.

Daly, A., 2007. *Timber, Trade and Tree-rings. A dendrochronological analysis of structural oak timber in Northern Europe, c. AD 1000 to c. AD 1650*. Doctoral dissertation, University of Southern Denmark, Copenhagen.

Daly, A., 2008. Amager Strand Vraget. *dendro.dk rapport nr*. 2008 : 17. København.

Daly, A., 2009. WM2307 Gåsehage ship. *Dendro.dk rapport nr*. 2009 : 15, København.

Daly, A., 2011. Barcode vrag 5, vrag 8 og vrag 14, Oslo. *Dendro.dk rapport nr*. 2011: 24. København.

De Vries, J., Van der Woude, A.M., 1997. The first modern economy. Success, failure, and perseverance of the Dutch Economy, 1500–1815, Cambridge University Press, Cambridge.

Dow, J., 1969. Scottish trade with Sweden 1512–80. *Scot Hist Rev* **48**, 64–79.

Eckstein, D., 2005. Wood science and art history – interdisciplinary research illustrated from a dendrochronological point of view, in Van de Velde, C., Beeckman, H., Van Acker, J., Verhaeghe, F. (Eds.), *Constructing Wooden Images: Proceedings of the Symposium on the Organization of Labour and Working Practices of Late Gothic Carved Altarpieces in the Low Countries*, Brussels 25–26 October 2002. VUB Press, Brussels, pp. 19–26.

Eckstein, D., Bauch, J., 1969. Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit. *Forstwissenschaftliches Centralblatt* **88**, 230– 250.

Eckstein, D., Wrobel, S., 2007. Dendrochronological proof of origin of historic timber- retrospect and perspectives, in Haneca, K., Beeckman, H., Gärtner, H., Helle, G., Schleser, G. (Eds.), *TRACE - Tree Rings in Archaeology, Climatology and Ecology*, Vol. 5, pp. 8–20.

Fernández- Golfín, J.I., Díez, M.R., Baonza, M.V., Gutiérrez, A., Hermoso, E., Conde, M., Vanden, V., 2001. Caracterización de la calidad y propiedades de la madera de Pino laricio (*Pinus nigra* Arn. ssp. *salzmannii*). *Invest Agrar Sist Recur For* **10(2)**, 311-331.

Fraiture, P., 2009. Contribution of dendrochronology to understanding of wood procurement sources for panel paintings in the former Southern Netherlands from 1450 AD to 1650 AD. *Dendrochronologia* **27(2)**, 95–111.

Gómez Bárcena, M., 2004. Arte y devoción en las obras importadas. Los retablos 'flamencos' esculpidos tardogóticos: estado de la cuestión. *Anales de la historia del Arte* **14**, 36–37.

Henriques, F., Bailão, A., Garcia, M., 2010. The Conservation-Restoration of the "Charola" Paintings of the Convent of Christ in Tomar. *e-conservation magazine* **14**, 55–69, http://www.e-conservationline.com/content/view/882

Hernández Díaz, 1937. Arte Hispalense en los siglos XV y XVI. *Documentos para la historia del arte* vol. IX, 41–49.

Haneca, K., Čufar, K., Beeckman, H., 2009. Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. *J Arch Sci* **36**, 1-11.

Hillam, J., Tyers, I., 1995. Reliability and repeatability in dendrochronological analysis: tests using the Fletcher archive of panel-painting data. *Archaeometry* **37(2)**, 395–405.

Jansma, E., Hanraets, E., Vernimmen, T., 2004. Tree-ring research on Dutch and Flemish art and furniture. In: Jansma E, Bräuning A, Gärtner H, Schleser G (Eds.), *TRACE - Tree Rings in Archaeology, Climatology and Ecology*, Vol. 2, pp. 139 – 146.

Jiménez Martín, A., 2006. Las fechas de las reformas. Selección crítica de fuentes documentales para la cronología del edificio medieval, in Jiménez Martín, A. et al. (Eds), *La catedral gótica de Sevilla. Fundación y fábrica de la obra nueva. Universidad de Sevilla*, Collección de Divulgación Científica 7, Sevilla, pp. 15–113.

Klein, P., 1996. Dendrochronological findings in panels of the Campin group, in Foister, S., Nash, S. (Eds), *Robert Campin. New directions in scholarship.* National Gallery in collaboration with Brepols Publishers: London, Turnhout (Belgium), 77-86.

Klein, P., Esteves, L., 2001. Dencrochronological analyses in Portuguese panel paintings, in Van Schoute and Verougstraete (eds), *La peinture et le laboratoire. Procédés, Méhodologie, Applications*, 213–220.

Knibbe, B., 2012. PAST4, Personal Analysis System for Treering Research. URL: www.sciem.com

Larsson, 2011a. Cybis CooRecorder - Image Coordinate Recording program, URL: www.cybis.se.

Larsson, 2011b. CDendro - Cybis dendro dating program, URL: www.cybis.se.

Llaguno, E., 1829. *Noticias de los arquitectos y arquitectura de España desde su Restauración*. Tomo III. Imprenta Real Madrid.

Magdaleno Granja, R., Pérez Cano, Mª V., Gutiérrez Carrasquilla, E., García de Casasola Gómez, M., Martín García, L., Sameño Puerto, M., 2005. Retablo de los Evangelistas de la Catedral de Sevilla. Investigación e intervención. *PH Boletín del Instituto Andaluz del Patrimonio Histórico* **53**, 84**–**106.

Miles, D.H., 2006. Refinements in the interpretation of tree-ring dates for oak building timbers in England and Wales. Vernacular Architect. 37, 84–96.

Millard, A., 2002. A Bayesian approach to sapwood estimates and felling dates in dendrochronology. *Archaeometry* **44(1)**, 137–43.

Otte Sander, E., 2008. *Sevilla, siglo XVI: Materiales para su historia económica: herederos de Enrique Otte Sander*. Centro de Estudios Andaluces.

Palomero Páramo, J.M., 1983. *El retablo sevillano del Renacimiento: análisis y evolución (1560–1629)*. Diputación Provincial de Sevilla.

Paton, H.M., 1957. *Accounts of the Master of Works*. Vol. 1 AD 1529–1615. HMSO Edinburgh.

Rodríguez Trobajo, E., 2008. Procedencia y uso de madera de pino silvestre y pino laricio en edificios históricos de Castilla y Andalucía. *Arqueología de la Arquitectura* **5**, 33–53.

Serradilla Avery, D.M., 2007. *Seville: between the Atlantic and the Mediterranean, 1248–1492. Pre-Columbus commercial routes from and to Seville*. Master of Philosophy, University of St. Andrews.

Sohar, K., Vitas, A., Läänelaid, A., 2012. Sapwood estimates of pedunculate oak (*Quercus robur* L.) in eastern Baltic. *Dendrochronologia* **30**,: 49-56.

Tyers, C., 2008. Bayesian interpretation of tree-ring dates in practice. *Vernacular Architect.* **39**, 91-106.

Wazny, T., 2005. The origin, assortments and transport of Baltic timber: historic dendrochronological evidence, in Van de Velde, C., Beeckman, H., Van Acker, J., Verhaeghe, F. (Eds), *Constructing Wooden Images: Proceedings of the Symposium on the Organization of Labour and Working Practices of Late Gothic Carved Altarpieces in the Low Countries*, Brussels 25–26 October 2002. VUB Press, Brussels, pp. 115–126.

Zunde, M., 1999. Timber export from old Riga and its impact on dendrochronological dating in Europe. *Dendrochronologia* **16–17**, 119–130.

ARTICLE 5

Dendrochronological dating and provenancing of timbers from the *Arade 1* wreck, Portugal.

Domínguez-Delmás, M., Nayling, N., Wazny, T., Loureiro, V., Lavier, C., 2013.

International Journal of Nautical Archaeology **42(1)**, 118-136.

Plank from the *Arade 1* shipwreck (photo: M. Domínguez Delmás).

DENDROCHRONOLOGICAL DATING AND PROVENANCING OF TIMBERS FROM THE *ARADE 1* SHIPWRECK

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Abstract

As part of a larger project promoting the development of historical dendrochronology in the Iberian Peninsula, ship-timbers from the *Arade 1* wreck (mostly planking and framing elements), stored at the DANS/IGESPAR in Lisbon, were examined. Fifty-two samples were identified as deciduous oak (*Quercus* subg. *quercus*) and two as chestnut (*Castanea sativa*). Twenty-three out of 24 timbers selected for dendrochronological research could be dated, placing the origin of the wood in western France and the felling of trees between AD 1579 and 1583. Their homogeneity suggests they are part of the original construction, which probably took place shortly after AD 1583.

Keywords

Dendrochronology, provenance, Iberia, *Arade 1*, shipwreck, heteroconnections

1. INTRODUCTION

The application of dendrochronological analysis to timbers from wooden shipwrecks has, in certain geographical regions, become the norm in nautical archaeology. The potential of this scientific discipline to provide precise dates for the felling of trees where the bark edge (the last ring formed before felling) survives on some timbers makes dendrochronology attractive and particularly useful for cultural heritage studies. Its high-precision (down to the year or even the cutting season) is possible because the sequence of thinner and thicker rings on a sample is characteristic for a given species, in a specific geographical area and time frame. Consequently, when comparing the tree-ring series (TRS) from a wooden sample of unknown date and origin with master chronologies of the same species representing different geographical areas and covering the period when the tree grew, there will be a unique position in which the researched series will match the chronologies of a specific area. In this way, an exact calendar year can be assigned to each ring of the investigated sample.

Precise felling dates help inferring construction dates and allow us to place ship-finds in their historical context. Furthermore, the provenance of the wood can be deduced from the area represented by the chronologies providing the best statistical matches (dendro-provenancing). This has proved of particular importance in the field of nautical archaeology, allowing us to examine the origins of ships, which by their very nature are portable antiquities *par excellence*. Tree-ring analysis of the hull timbers of the five Skuldelev wrecks provide an exemplar case study on how the scientific technique can address questions of origin, date, and repair (Bonde and Crumlin-Pedersen, 1990; Crumlin-Pedersen and Olsen, 2002). Recent articles within this journal (for example Daly, 2007; Daly and Nymoen, 2008) highlight the need for thoughtful interpretation of the results of dendrochronological studies of ships and the potential for error when equating origin of timber with origin of ship construction.

For dendrochronology to be successful, however, a network of well replicated ring-width master chronologies (absolutely anchored in time) must be available for the tree species investigated, the region of provenance of the wood and the period of interest. Whilst this condition is met in many parts of central and northern Europe (including most of France, Ireland, Great Britain, the Netherlands, Germany, Scandinavia and the Baltic countries) for certain time-periods, this is not the case for the Iberian Peninsula. In an attempt to redress this imbalance, the project '*Filling in the blanks in European dendrochronology*' funded by the Netherlands Organization for Scientific Research (NWO) was launched in 2009. Part of this project aimed at identifying ship hull-assemblages in or (expected to be) from Iberia, which might benefit from dendrochronological analysis and/or provide tree ring-width data to assist in the construction of long-span regional chronologies. This approach follows to an extent the successful strategy employed by Guibal and others in the development of long chronologies for the Mediterranean region using *in situ* Mediterranean ship sites (see Guibal and Pomey, 2003).

The numerous ship-timbers held in store at the facilities of the *Divisão de Arqueologia Náutica e Subaquática, Instituto de Gestão do PatrimónioArquitectónico e Arqueológico* (DANS/IGESPAR) in Lisbon, Portugal, provided an opportunity to examine a substantial timber collection from a number of ship sites of note, and to assess their suitability for dendrochronological analysis. In October 2010, M. Domínguez-Delmás and N. Nayling visited the facilities of the DANS/IGESPAR and, with the kind

assistance of their staff, examined, assessed and sampled numerous timbers (Fig. 1). The hull assemblage from the Arade 1 wreck proved the most productive wreck-site group, containing numerous substantial ceiling and hull planks, as well as framing elements in good condition, with a sufficient number of rings for dendrochronological analysis and retention of either partial or complete sapwood (outermost part of stems and branches, clearly visible in species from the genus *Quercus* amongst others) in several timbers. This provided the potential for reasonably constrained felling-date ranges for the parent trees, in some cases accurate to the year or even the season. A second sampling of timbers from this wreck, directed specifically at framing elements, was conducted in September 2011 by M. Domínguez-Delmás, in order to complete a group of samples representing all structural parts of the ship.

Figure 1. Inspection and selection of timbers for dendrochronological research at the DANS in Lisbon. Photo: N. Nayling.

2. MATERIALS AND METHODS

2.1. The *Arade 1* wreck

The *Arade 1* shipwreck was originally discovered in 1970 by recreational divers in the Arade River, on the southern coast of Portugal (Fig. 2). Reported missing by 1972, the remains were relocated in 2001, by the former *Centro Nacional de Arqueologia Náutica e Subaquática* (CNANS, now DANS) (Castro, 2006). This was followed by five field missions (Castro, 2002; Rieth et al., 2004; Alves et al., 2005; Loureiro and Alves, 2005, 2006), including the dismantling and recovery of the upper portion of the hull in 2003 (Rieth et al., 2004), and the central section and the lower hull in 2005 (Loureiro and Alves, 2005, 2006, 2008). Devoid of significant artefacts, this wooden vessel caught the attention of national and international researchers for its characteristics and its excellent state of preservation. More than five years of post-excavation study revealed a skeleton-first carvel planked vessel (where the frame was used as reference during the shipbuilding process, as opposed to the shell-first principle, where major importance is given to the hull), planned from a set of pre-established key dimensions and the evolution of predetermined frames. The latter implies that the transversal structure was made of two sets of frames, distinct in shape and function: the filling timber frames, Y-shaped, which held and closed the extremities of the ship, and the pre-designed frames which defined the shape of the central part of the hull (Loureiro, 2011). The pre-designed frames, on the posterior side (facing the master

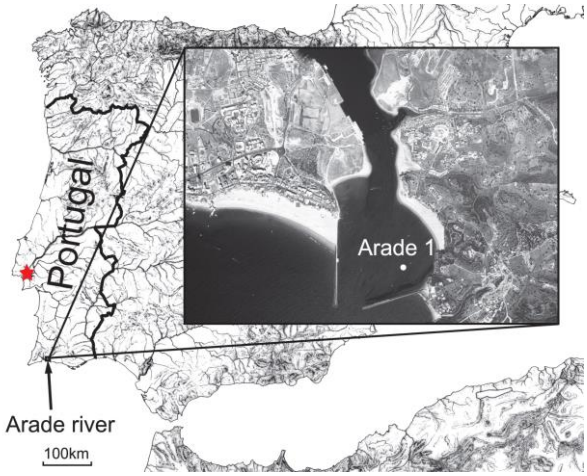

Figure 2. Location where the Arade 1 wreck was found at the mouth of the Arade River, in Portugal. Red star: Lisbon.

frame), have carvings which served as reference points in the construction process, revealing that frames forward and aft were designed using the master frame as reference but modified in three ways: rising and narrowing the floor and adjusting the shape of the futtocks (Loureiro, 2011).

2.2. Previous analyses on wood elements from the Arade 1 wreck

Since the wreck was first found in 1970 a series of analyses including radiocarbon and dendrochronological dating, as well as identification of wood species of several timber elements, have been carried out on different occasions.

2.2.1. Radiocarbon and dendrochronological dating

Between 1972 and 2003, radiocarbon (^{14}C) dates of five different wooden elements have been published, providing a potential construction date anywhere between the second half of the 15th century and the first half of the 17th century (Loureiro and Alves, 2008). However, in addition to the imprecision of the ^{14}C results, which is inherent to the nature of the method (Mitchels, 1973), the published ^{14}C reports do not specify where in the timbers the samples for radiocarbon dating were taken. This information is crucial for the interpretation of the results, as a sample taken close to the pith of a tree that was centuries old when it was cut will provide a date range that will be hundreds of years earlier than the felling date of the tree. Without a more precise dating of well selected timber elements, the accurate chronological placement of the Arade 1 wreck with its associated shipbuilding characteristics would remain problematic.

In 2005, T. Wazny, from the Institute for the Study, Conservation and Restoration of Cultural Heritage at Nicolaus Copernicus University in Torun, Poland, had the chance to examine and sample timbers from the wreck for dendrochronological research. His research on five timbers (planks, filler pieces and a patch) identified by him as deciduous oak (*Quercus* subg. *quercus*) resulted in the dating of a filler piece (TAB3) and a plank from an unknown element (A1-X005), with the dates of their outermost surviving rings in AD 1576 and AD 1546 respectively (Wazny, unpublished report). Whereas sapwood was absent in the sample A1-X005, it was present on the sample TAB3, allowing an estimation of the felling date of the parent tree between AD 1577 and AD 1589 (Wazny, unpublished report). Given that only two of the samples had dated, Wazny pointed out the need to examine and dendrochronologically research more timbers containing sapwood, in order to determine whether the ones dated by him belong to the original structure or represent repairs or re-use.

2.2.2. Identification of wood species

After the field campaigns of 2002 and 2005, some samples were sent for determination of wood species to the *Centro de Investigacão em Paleoecologia Humana* of the former *Instituto Português de Arqueologia* in Lisbon. In 2002, the only sample analysed was identified as *Quercus faginea* (commonly known as Portuguese oak) by Van Leeuwaarden and Queiroz (2002). In 2005, another 18 elements were investigated. Fifteen samples were identified as *Q. faginea*, two as *Q. suber* (cork oak) and one as *Quercus* subg. *quercus* (deciduous oak) (Queiroz et al., 2005). These are all species commonly found in the Iberian Peninsula. Hence the wood identifications, together with the shipbuilding method and other construction characteristics of the ship, were taken as support for the hypothesis of a local or regional origin for the ship's construction (Castro, 2006; Loureiro and Alves,

2008). Such accurate identification of the oaks as *Q. faginea* (down to the species level) is controversial though and requires some considerations, which are outlined in the following.

The group of deciduous oaks (*Quercus* subg. *quercus*) is represented in Iberia by the species *Q. robur*, *Q. petraea*, *Q. pubescens*, *Q. faginea*, *Q. canariensis* and *Q. pyrenaica* (Amaral Franco, 1990) and their numerous hybrid taxa. The differentiation of the living trees of these species and some of their hybrids can be done by the morphology of their leaves and acorns, but their wood anatomical features are too similar to discern one species from another (Schweingruber, 1990, 1993). In the late 1990s, Feuillat et al. (1997) announced a method to distinguish samples from *Q. robur* and *Q. petraea*. They reported that for trees of a cambial age between 60 and 120 years old, rings c. 2 mm wide in *Q. robur* would present more than two rows of earlywood vessels and a percentage of latewood less than 60% of the total ring-width, whereas in *Q. petraea* such wide rings would present less rows of earlywood vessels and a percentage of latewood higher than 70%. However this observation only proved valid for an 80% of the samples. Furthermore, the limitations of this method when working with (pre)historical timbers are obvious, since samples may not contain such wide rings and in most cases, the pith and the bark are not present in the samples, therefore the estimation of the cambial age is difficult (if not impossible). Hence, the differentiation of the wood from these two species still remains a challenge. In the last decade, a new attempt to identify anatomical characteristics that would allow the systematic differentiation between, amongst others, deciduous oak species present in Portugal was carried out at the *Centro de Investigacão em Paleoecologia Humana* from the IGESPAR by the group of P. Queiroz (pers. comm. P. Queiroz). However, before a significant number of samples from deciduous oaks was analysed, the study was abandoned. Therefore, despite some promising preliminary results, the research remained inconclusive (pers. comm. Queiroz). A last controversial point regarding the identification of *Q. faginea* is that its wood has been described as ring-porous to semi-ring porous in forest-stands in the centre of Spain (García Esteban et al., 2003) and as ring-porous in Portuguese forests (Carvalho, 1997). This indicates a high variability in the anatomy of the species depending on site conditions, further complicating the potential for discriminating between different species of deciduous oak on the basis of wood anatomy.

In view of these considerations, and taking into account the implications of such precise wood identification for interpretation of the potential construction area of the ship, we decided to re-examine the group of samples identified by Queiroz and others in 2005.

The goals of our study were to find out the precise date and provenance of timbers used in the construction of the Arade 1 through a dendrochronological approach. The absolute dendrochronological dating of well selected timbers from the wreck could anchor the construction of the ship in time, providing a precise chronology for her structural characteristics. Discerning the provenance of the wood could shed some light on the potential geographical origin of the ship or the trade in timber for her construction. Additionally, the identification of the wood species of a large number of timbers of different types would increase our knowledge of the selection of species related to their technological properties and according to the function of specific elements. Furthermore, it could provide information about availability and supply, repairs and re-use of timbers.

2.3. Selection and sampling of ship-timbers for dendrochronological research

To be considered suitable for dendrochronological research, the selected timbers must first of all be of a wood species that produces clearly distinct annual rings. This is not always the case for evergreen oak species found in the Iberian Peninsula such as *Q. suber* (Sousa et al., 2009) or *Q. ilex* (Cherubini et al., 2003; Campelo et al., 2007), nor for tropical species used in shipbuilding after the establishment of European colonies in the Americas, Africa and Asia. The determination of the wood species may also provide the first clue towards the provenance of the wood (Giachi et al., 2003; Guibal and Pomey, 2003; Wicha et al., 2003), therefore it is a crucial step when researching shipwrecks. Hence, our first task while inspecting the timbers was to identify groups of species (tropical wood, evergreen oaks, deciduous oaks, others), discarding at once those from groups presenting limitations for dendrochronological dating. The next step was evaluating by rough counting the number of rings contained in the timbers, as samples for dendrochronological research must have a sufficient number of tree-rings to allow statistically sound results (preferably more than 80). And finally, to obtain the felling dates of the parent trees (or to be able to estimate them), priority was given to timbers presenting sapwood, or even better, bark edge. In the absence of samples with bark or bark edge, sampling several timbers with sapwood may help narrowing the estimated felling date range of the trees to within a few years. In such case, exceptionally, some timbers with few rings (less than 50 for example) but retaining sapwood, can also be considered for dendrochronological research. In addition, it is desirable to sample as many suitable timbers as possible, preferably from elements that are likely to belong to the original ship-structure, in different parts of the ship (for example the keel, floor timbers, futtocks and planks). This way, the chances of establishing relative dates between (presumably) original timbers increase, and object-chronologies can be constructed. These object-chronologies are easier to date than tree-ring series from single samples, as they contain a stronger environmental signal (Fritts, 1976; Hillam, 1979).

Taking into account all these aspects we examined the sides of the timbers in search of sapwood and the transverse sections at the ends of planks and framing elements, where the tree-rings and the medullary rays are usually visible. We selected a total of 42 timbers (all planking and framing elements), including six elements (two planks and four frames) previously researched for wood identification by Queiroz et al. (2005). The wood of 40 elements was identified at once as deciduous oak (*Quercus* subg. *quercus*), based on the observation of macroscopic characteristics of the anatomy in the transverse section of the timbers, after cleaning the surface slightly with razorblades and applying chalk powder. The deciduous oaks are relatively easy to identify with the naked eye, as they show a ring-porous disposition of earlywood vessels, abrupt transition from earlywood to latewood, clearly visible multiseriate medullary rays and clearly distinguishable ring boundaries (Fig. 3a). Amongst these timbers was a first-futtock (B-17Eb) that had been identified previously by Queiroz et al. (2005) as cork oak (*Q. suber*). This evergreen oak species has been described as semi-ring porous, presenting a gradual transition between earlywood and latewood with round, solitary vessels gradually decreasing in size in the latewood, and large multiseriate rays (Schweingruber, 1990; Sousa et al., 2009). However, these characteristics were absent in all the examined timbers.

Two other timbers (first-futtock B-9Eb and second-futtock Ap0Bb) were identified as chestnut (*Castanea sativa*). The wood anatomy of this species is similar to that of the deciduous oaks (ring-

porous, with clearly distinguishable ring boundaries, flame-like groups of pores in the latewood, uniseriate rays) but it differs in that it lacks multiseriate medullary rays (Schweingruber, 1990) (Fig. 3b).

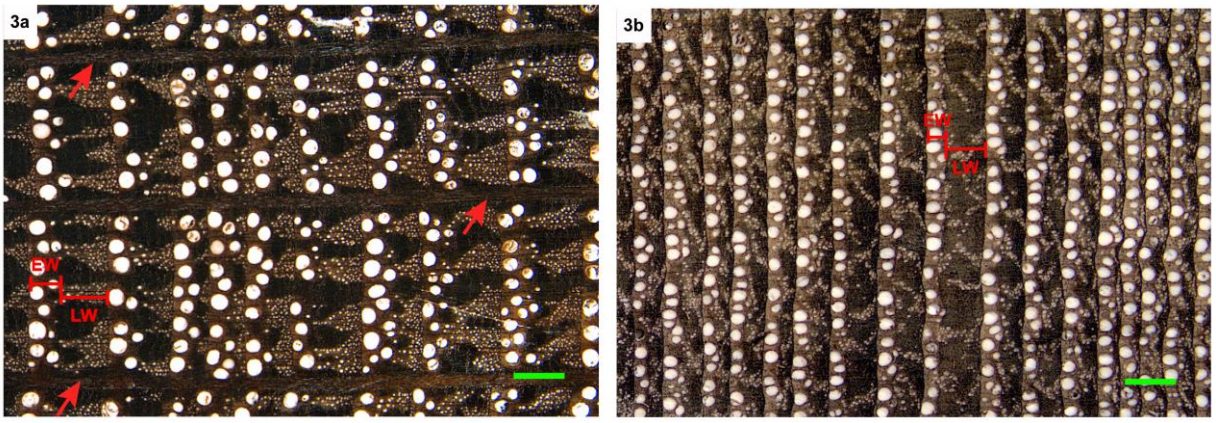

Figure 3. Macroscopic characteristics of wood anatomy from 3a) deciduous oak species (Quercus subg. quercus) (timber-element St6Bb[2] with dendro-code PAR020) and 3b) chestnut (Castanea sativa) (timber-element Ap0Bb with dendro-code PAR130) in the transverse section. Both species present a ring-porous distribution of earlywood vessels and a sharp transition between earlywood (EW) and latewood (LW). However, chestnut lacks the multiseriate rays (indicated by red arrows in 3a) clearly visible by the naked eye in oak species. Chalk has been applied on the surface to facilitate the visualization of anatomical features. Growth direction towards the right. Green bar: 1 mm. Photos: M. Domínguez-Delmás.

Cross-sections (2-4 cm thick) were manually sawn from the timbers selected for dendrochronological analysis. For wood identification, fragments of c. 3 cm^3 were removed from the timbers that were not selected for dendrochronological research and that needed microscopic verification. All the samples were stored in sealed plastic bags with water to prevent them from drying during their transport to the laboratory.

2.2.4. Dendrochronological research

Once at the laboratory of the Cultural Heritage Agency of the Netherlands, in Amersfoort, the transverse faces of the samples were cleaned with razor-blades from the inner to the outermost ring. Chalk was rubbed into the cleaned surface to enhance the contrast between the ring boundaries. When necessary, micro-slides of the transverse, radial and tangential sections from the samples were prepared for detail observation of key anatomical features, which were photographed with a Zeiss AxioCam MRc5 connected to a Zeiss Stereomicroscope Discovery-V8.

Ring-widths were measured to the nearest 0.01 mm with a TimeTable measuring device (University of Vienna, VIAS) coupled with PAST4 software (B. Knibbe, SCIEM). The resulting series were statistically compared with each other and with four of the measurements obtained by Wazny in 2005 (internal crossdating). The fifth timber-element researched by Wazny in 2005 (A1-X005) could not be confirmed as belonging to the Arade 1 wreck and was therefore excluded from this research. Statistical crossdating was done with PAST4, using Student's *t*-values (*t*) calculated after normalization of the raw data with Baillie and Pilcher's algorithm (Baillie and Pilcher, 1973) and the percentage of parallel variation or *Gleichläufigkeit* (Gl) (Eckstein and Bauch, 1969). The combination of these two statistical tests, supported by a high significance level (ρ) of the Gl has proven a reliable and effective method

for dendrochronological dating. Sound statistical matches were visually verified comparing the graphs representing the TRS.

The internal crossdating allows the identification of groups of samples derived from trees growing under similar environmental conditions (their series will cross-match well, with t>6, Gl>63% and ρ<0.005, for example) and even samples that originated from the same tree. Usually, the latter provide very high statistical values (for example t>10 and Gl>70% with a ρ <0.0001), although lower values may also occur, and the visual inspection of the matching TRS and the respective wooden samples by experienced dendrochronologists is the key to a final decision. Series from the same tree were averaged and a new internal crossdating was run. Then, similar, cross-matched TRS were averaged into object-mean curves following a hierarchical approach as described by Eckstein et al. (2009). The resulting object-mean curves and the remaining single TRS series were compared with master and local chronologies from western, central and northern Europe available to the authors. In addition, the tree-ring data were sent to the dendrochronology laboratory at Arkeolan, in Irun (Spain), where J. Susperregi compared it with chronologies from *Quercus* spp. (*Q. robur, Q.petraea* and *Q. faginea*) representing the northeast of Spain. Finally, an object-chronology was computed with the matching dated series using the program ARSTAN (Cook and Holmes, 1986). For this, the TRS were standardised by fitting them to a 53-year smoothing cubic spline (length of the shortest series representing an individual tree), with 50% cut-off variance, which we observed acted similarly to a negative exponential curve, but seemed more suited for the dynamic growth trends of the Arade 1 samples (Cook and Peters, 1981). In this manner, low-frequency trends due to age of the trees, forest-stand dynamics and other natural or human disturbances that would reduce the quality of the chronology for future dating purposes, were partially removed from the series, while keeping the high-frequency (year-to-year) variation crucial for dendrochronological dating. The standardised (indexed) series were then averaged with a biweight robust mean into the object-chronology.

The provenance of the wood can be inferred from the chronologies dating the samples, as long as chronologies representing specific areas are used. Ideally, the area represented by the chronologies providing the best statistical matches will be the area of provenance of the wood. But if the wood originates from an area where reference chronologies for the species being studied are lacking, the samples will most likely remain undated.

3. RESULTS

Our final set of samples comprised a total of 58 elements, including the 42 timbers inspected and sampled for this research (24 for tree ring research and 18 for wood identification, six of which had already been identified by Queiroz and others in 2005), the rest of the samples analysed by Queiroz et al. (2005) and four oak TRS from the timbers previously researched by Wazny (two filler pieces, a ceiling plank and a patch from a framing element) (Table 1 and Fig. 4).

3.1. Wood identifications

The identifications of 42 selected timber-elements done during the inspection at the DANS (40 deciduous oaks and two chestnuts), were verified and confirmed at the laboratory by the observation of wood anatomical features under the microscope. In this way, the identifications from 2005 of the first-futtock B-17Eb and a treenail from the ceiling plank A1-151 as cork oak (*Q. suber*) were

definitely discarded (Fig. 5a,b,c). Furthermore, this treenail was a peculiar case, as it had been wedged tight with a smaller wooden nail driven into the middle (Fig. 5c). As a result, the nail (made of deciduous oak) had caused the vessels, rays and fibres of the treenail to compress around the point of entry, therefore the wood appeared to have a higher density of rays (which is a key characteristic of cork oak) in macroscopic observation. However, the microscopic observation of the transverse section (Fig. 5b,c) allowed the observation of the multiseriate rays and the compressed fibres, making also obvious the abrupt change from earlywood to latewood. These features led to the identification of this treenail as deciduous oak rather than cork oak.

The observation of key anatomical features on the rest of the samples previously researched by Queiroz et al. (2005) resulted in the identification of all of them as deciduous oak (*Quercus* subg. *Quercus*) (Table 1). In general, these samples showed differences in growth rate (some derived from fast grown trees and others from slow grown trees) and some presented abundant large multiseriate rays (Fig. 6).

Table 1. List of researched elements (including those researched in 2005), results wood identification and description of samples; A: researched by Queiroz et al. (2005) for wood identification (indicating in brackets the sample number); B: researched by Wazny in 2005 for wood identification and dendrochronological dating; Q: Quercus subg. quercus; C: Castanea sativa; N: number of rings in the sample; Pith: present (+) or absent (-); SW: sapwood; MRW total: mean ring-width (mm) total length series; MRW(-35): mean ring width (mm) excluding 35 years juvenile wood. Shaded rows: samples with bark edge present. *The exact type of elements could not be identified.

Samples from previous studies	Dendro-code	Element code	Type	Function	Species	N	Pith	SW	MRW total (mm)	MRW (-35) (mm)
-	PAR010	St1Bb[2]	Hull plank	Hull	Q	131	+	-	1.26	0.93
-	PAR100	St8/9Bb	Hull plank	Hull	Q	103	-	-	1.12	1.00
-	PAR030	St5Bb[1]	Hull plank	Hull	Q	121	-	5	1.15	0.98
-	PAR090	A1-242	Plank*	Undetermined	Q	101	+	-	1.44	1.21
-	PAR020	St6Bb[2]	Hull plank	Hull	Q	130	+	11	1.24	1.09
-	PAR040	A1-258	Plank	Ceiling	Q	74	-	-	0.82	0.82
-	PAR050	A1-61	Hull plank	Hull	Q	78	-	-	1.18	1.18
-	PAR060	St7Eb[2]	Hull plank	Hull	Q	138	-	-	0.87	0.87
-	PAR070	St7Bb[1]	Hull plank	Hull	Q	152	+	5	1.01	0.67
A (9)	PAR230	St6Eb[1]	Hull plank	Hull	Q	56	-	(+4s.b.)	2.23	2.23
-	PAR240	St11Bb	Hull plank	Hull	Q	102	+10	-	1.41	1.17
B	PT00105	TAB3	Filler piece	Ceiling	Q	49	-	14	1.80	1.80
B	PT00104	TAB2	Filler piece	Ceiling	Q	41	-	16	1.47	1.47
-	PAR080	St5Eb[2]	Hull plank	Hull	Q	47	-	6	2.63	2.63
-	PAR221	St2Eb[3]	Hull plank	Hull	Q	83	-	-	1.72	1.72
B	PT00102	TN4	Ceiling plank	Ceiling	Q	79	-	-	1.71	1.71
B	PT00103	C-10	Patch of C11 floor timber	Frame	Q	112	-	-	0.79	0.79
-	PAR110	B-8Eb	First-futtock	Frame	Q	126	-	21(+1)	0.95	0.80
-	PAR120	B-9Eb	First-futtock	Frame	C	92	-	-	1.58	1.58
-	PAR130	Ap0Bb	Second-futtock	Frame	C	152	-	-	1.01	1.01
-	PAR140	A1-141	Second-futtock	Frame	Q	91	+	25	1.17	0.77
-	PAR150	Ap5Bb	Second-futtock	Frame	Q	142	+	60(+1)	0.77	0.58
-	PAR160	B2Eb	First-futtock	Frame	Q	88	-	23	1.60	1.60
-	PAR170	Ap6Bb	Second-futtock	Frame	Q	138	+	14	0.92	0.91
-	PAR180	A1-237	Frame*	Frame	Q	139	+	8(+6)	0.90	0.84
-	PAR190	A1-239	Second-futtock	Frame	Q	70	+	24	1.27	1.23
-	PAR200	A1-10	Indetermined	Frame	Q	73	+5	21	1.15	0.85

A (5)	PAR210	B-16Eb	First-futtock	Frame	Q	106	+	45(+1)	1.06	0.69
-	-	St1Eb	Hull plank	Hull	Q	-	-		-	-
A (6)	-	A1-141	Treenail	Frame	Q	-	-		-	-
A (8)	-	A1-151	Ceiling plank	Ceiling	Q	-	-		-	-
A (1)	-	A1-151	Treenail	Ceiling	Q	-	-		-	-
-	-	C5	Floor-timber	Frame	Q	-	-		-	-
-	-	B1Eb	First-futtock	Frame	Q	-	-		-	-
-	-	B4Bb	First-futtock	Frame	Q	-	-		-	-
-	-	A1-185	Second-futtock	Frame	Q	-	-		-	-
-	-	A1-195	Second-futtock	Frame	Q	-	-		-	-
-	-	C9	Floor-timber	Frame	Q	-	-		-	-
-	-	A1-248	Second-futtock	Frame	Q	-	-		-	-
A (14)	-	C-19	Floor timber	Frame	Q	-	-		-	-
-	-	C-18	Floor timber	Frame	Q	-	-		-	-
A (3)	-	B-17Eb	First-futtock	Frame	Q	-	-		-	-
-	-	B-18Eb	First-futtock	Frame	Q	-	-		-	-
A (2)	-	A1-64	Hull plank	Hull	Q	-	-		-	-
A (4)	-	R Pr	Stempost	Longitudinal	Q	-	-		-	-
A (7)	-	B-6Eb	First-futtock	Frame	Q	-	-		-	-
A (10)	-	A1-158	Stringer	Ceiling	Q	-	-		-	-
A (13)	-	St7Eb(1)	Hull plank	Hull	Q	-	-		-	-
A (11)	-	St7Eb(1)	Treenail	Hull	Q	-	-		-	-
A (12)	-	Tn3A/B	Ceiling plank	Ceiling	Q	-	-		-	-
A (15)	-	Tab1	Filler piece	Ceiling	Q	-	-		-	-
A (16)	-	Tab4	Filler piece	Ceiling	Q	-	-		-	-
A (17)	-	C-19	Treenail	Floor-timber	Q	-	-		-	-
A (18)	-	B-16Eb	Treenail	First-futtock	Q	-	-		-	-
-	-	B-14Eb	First-futtock	Frame	Q	-	-		-	-
-	-	C-5	Floor timber	Frame	Q	-	-		-	-
-	-	B3Bb	First-futtock	Frame	Q	-	-		-	-
-	-	B4Eb	First-futtock	Frame	Q	-	-		-	-

3.2. Description of dendrochronological samples

From the 24 timbers selected for dendrochronological research, five hull-planks (St5Bb[1], St6Bb[2], St7Bb[1], St6Eb[1] and St5Eb[2]) and five framing elements (A-141, B2Eb, Ap6Bb, A1-237 and A1-10) contained partial sapwood, whereas two first-futtocks (B-8Eb, B-16Eb) and two second-futtocks (Ap5Bb, A1-239) retained complete sapwood and bark edge (Table 1). The tree used to make the second-futtock A1-239 was felled in late summer or winter (September to March of the following year) as inferred from the completeness of the outermost ring, whereas the other three trees were felled during the growing season (somewhere between April and June), as implied by the presence of an incomplete outermost ring at the bark edge. Furthermore, these samples presented numerous sapwood vessels filled with tyloses (Fig. 7), a common reaction of oak trees that have been cut during the growing season (Murmanis, 1975; pers. comm. F. Schweingruber).

All the planks had been tangentially converted, suggesting they were sawn (as opposed to split or cleaved) from the log. The framing elements were all halved or quartered timbers. Their sizes, together with the presence of sapwood and pith, allowed an estimation of the diameter of the parent trees of between 200 and 300 mm.

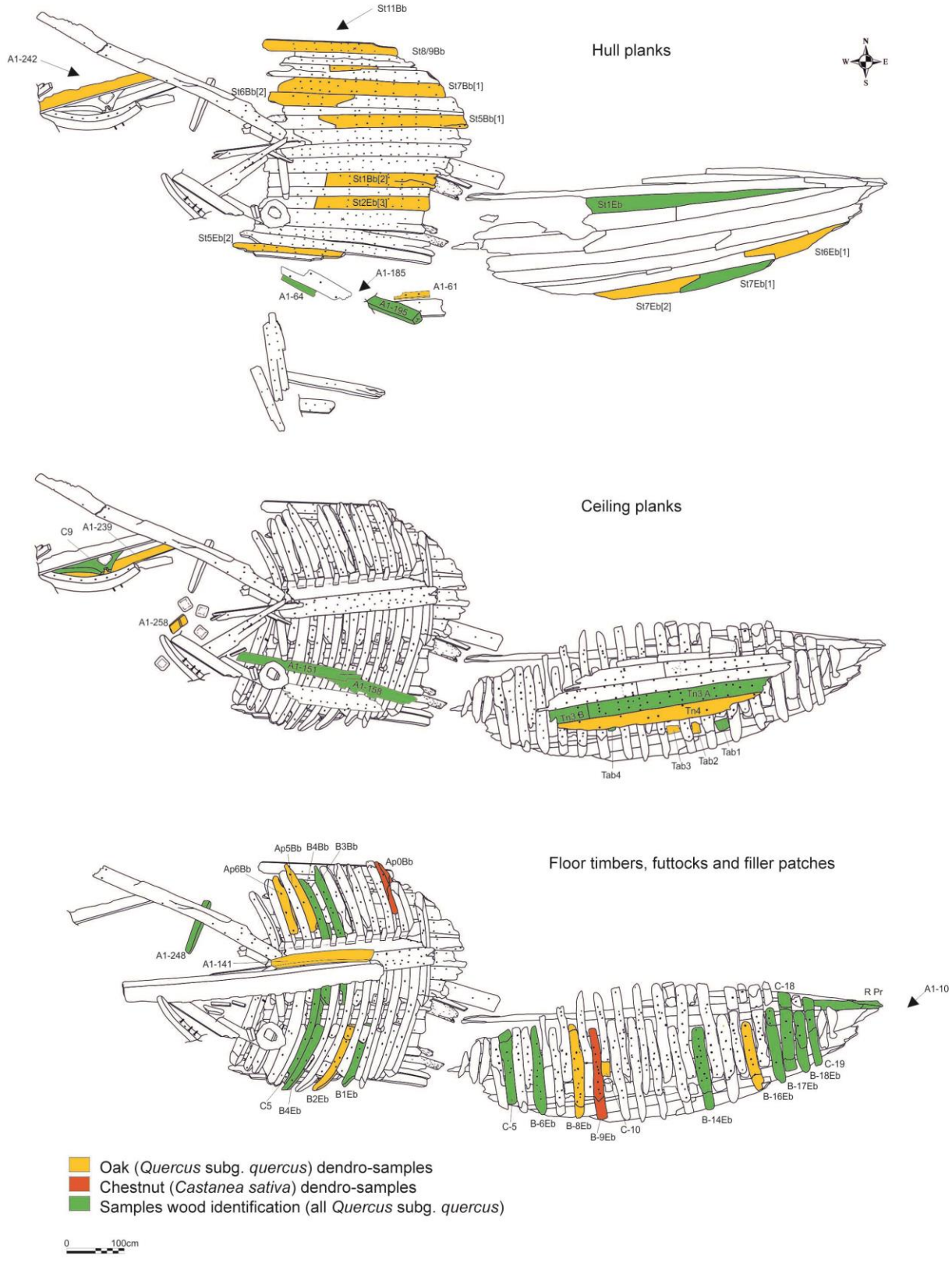

Figure 4. Researched timber-elements in the Arade 1 wreck. Drawings: V. Loureiro and J. Gachet Alves.

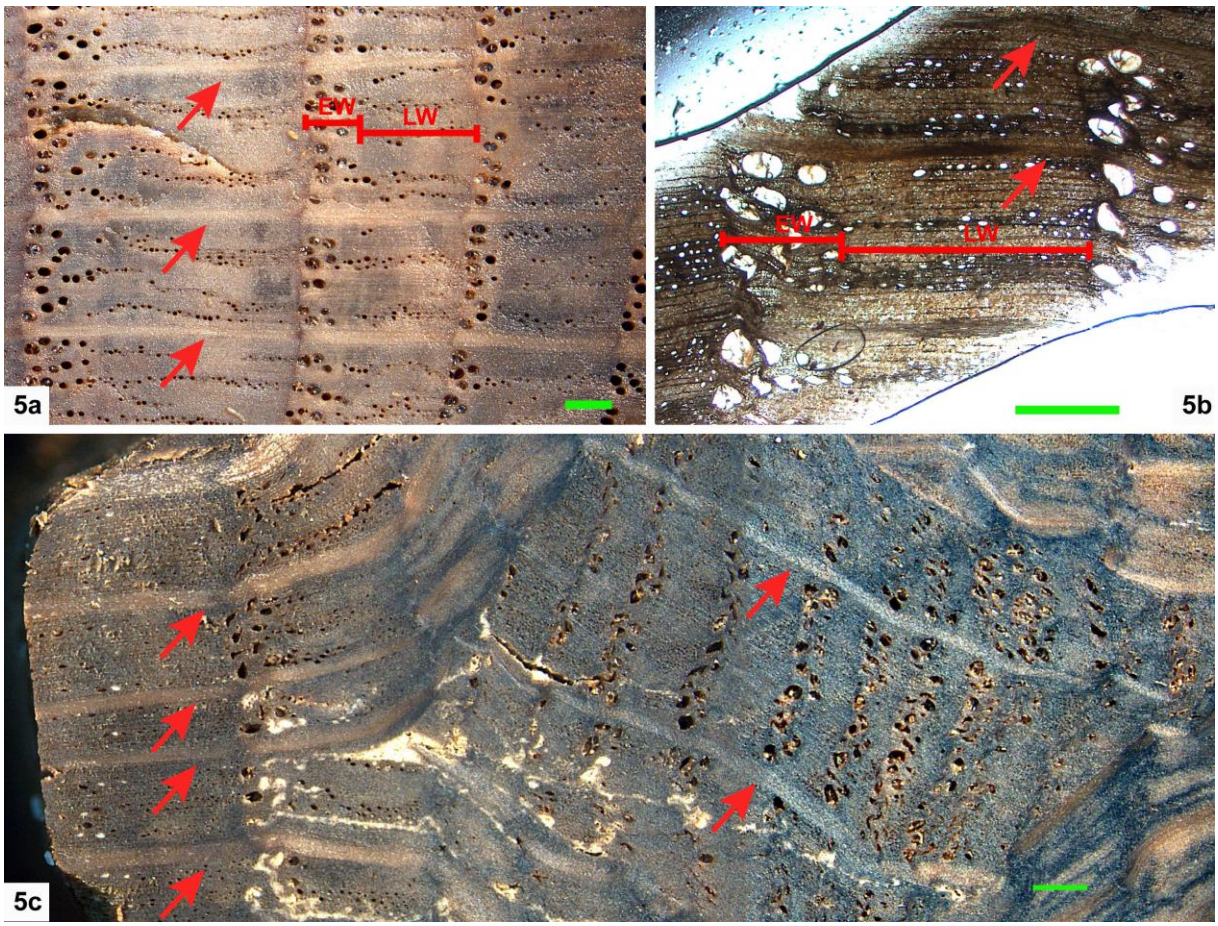

Figure 5. Transverse section of wood from first-futtock B-17Eb (5a) and a treenail from the ceiling plank A1-151 (5b) with wooden nail inserted in the middle (5c). Both samples, as well as the nail inserted on the treenail, present anatomical characteristics typical for deciduous oaks (Quercus subg. quercus) described in the text. Green bar: 1 mm. Photos: M. Domínguez-Delmás.

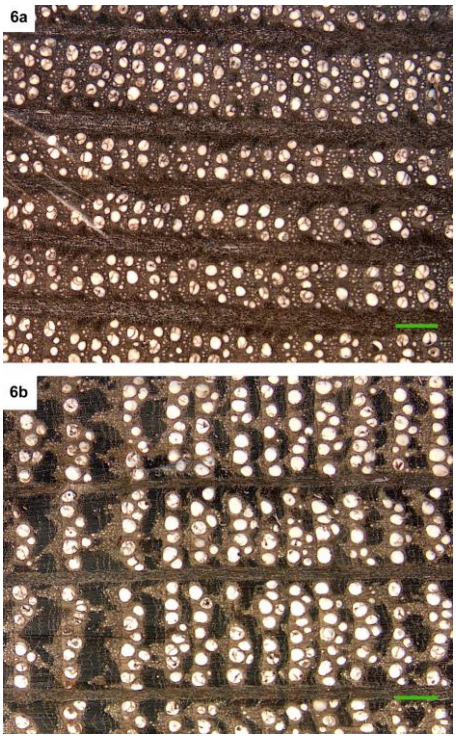

Figure 6. 6a) Transverse section of sample from timber-element B-8Eb (dendro-code PAR110), showing large and abundant multiseriate rays; 6b) Sample A1-237 (dendro-code PAR180) used for comparison. Chalk has been applied on the surface to facilitate the visualization of anatomical features. Green bar: 1 mm. Photos: M. Domínguez-Delmás.

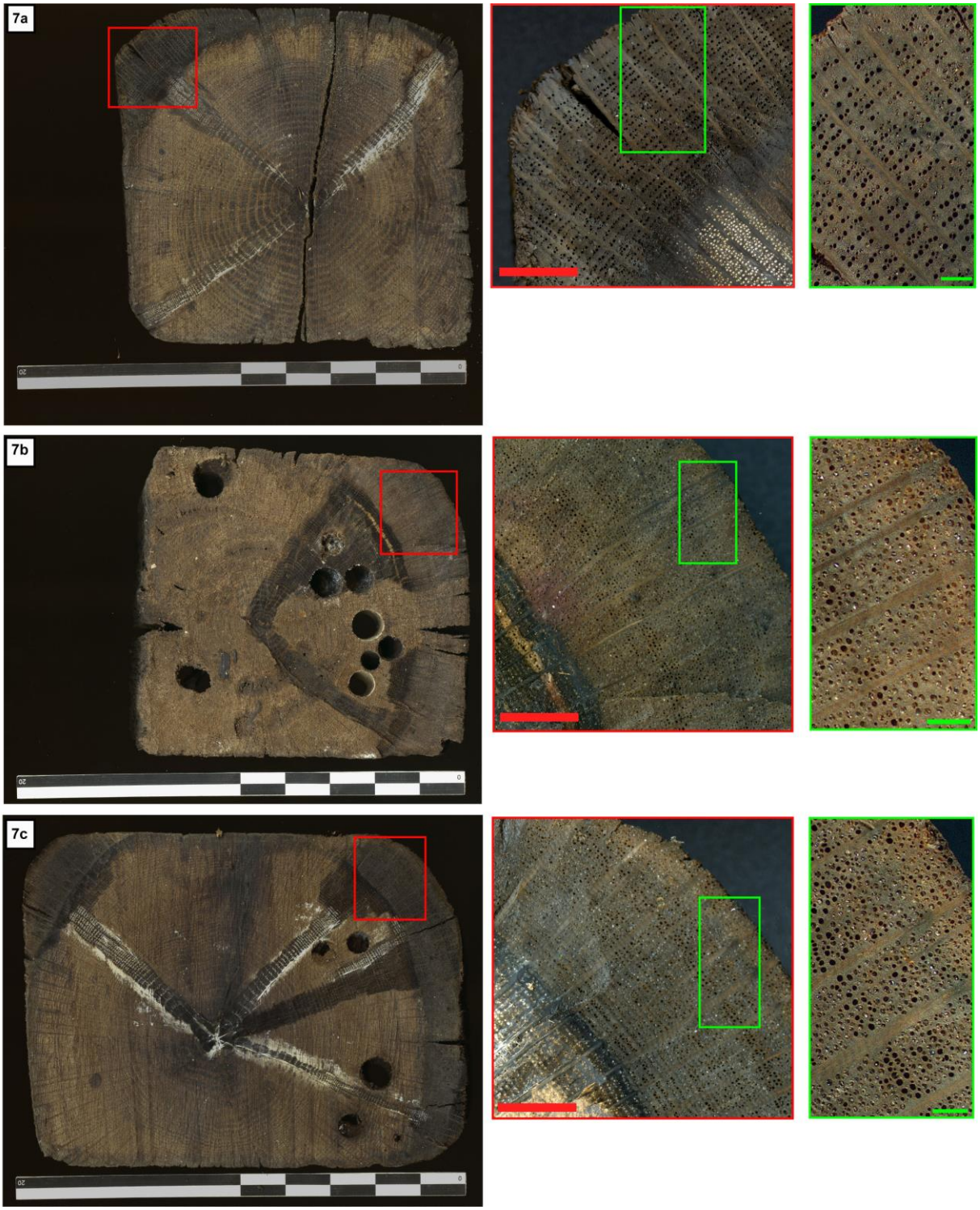

Figure 7. Cross-sections of samples from framing-elements A1-141 (7a, dendro-code PAR140), Ap5Bb (7b, PAR150) and B-16Eb (7c, PAR210) with detail of a portion of the sapwood with vessels free of tyloses (7a) and with numerous vessels abnormally filled with tyloses (7b,c). Black and white scale represents 200 mm, red bar 10 mm and green bar 1 mm. Photos: M. Domínguez-Delmás.

3.3. Tree-ring typology: fast- versus slow-grown

The TRS from the researched timbers were of different lengths and, although most of them presented similar growth patterns, with slow-growth rates after the initial fast-grown juvenile period (30-40 years), the planks presented more regular patterns than the framing-elements, which showed dynamic ones. Some planks however (hull-planks St6Eb[1], St5Eb[2] and St2Eb[3], filler pieces TAB3 and TAB2, and ceiling plank TN4) showed fast-growth rates, with mean ring-width values close or over 1.50 mm per year and two of them having mean year growths over 2.20 mm (Table 1). The fast-grown trees from which these planks were sawn, grew in favourable conditions, without shortage of water or lack of light. Three of these samples (hull-plank St5Eb[2] and the filler pieces TAB3 and TAB2 researched by Wazny in 2005) presented less than 50 rings, but had also been selected for the research because they contained sapwood. Excluding the fast-grown planks and the first 35 rings of juvenile wood in the rest of the planks containing the pith, the mean ring-width was found to drop down to 0.98 mm per year (Table 1). Such slow-growth is characteristic for oak trees living under limiting conditions (for example, competition for light when growing in a dense forest).

Most of the framing elements contained the pith and showed similar growing conditions to that of the slow-grown trees used for planking (juvenile period of dynamic growth, followed by a growth reduction afterwards). Applying the same criterion of exclusion of juvenile wood as with the planks, the mean ring-width value of framing elements is 0.97 mm per year. Having estimated the diameters of these elements containing pith and sapwood between 200-300 mm and considering their number of tree-rings (between 70 and 142), we can also describe them as derived from slow-grown trees.

3.4. Dating results and provenance of the wood

The dendrochronological research included four TRS obtained by Wazny in 2005 and 24 series obtained from the new samples. The first internal crossdating (comparison of all TRS among them) resulted in the identification of planking elements derived from the same tree. The outstanding statistical results between the pairs of TRS from hull-planks St1Bb[2]-St8/9Bb (PAR010-PAR100, t=8.44 and Gl=75.7 with ρ<0.0001), St5Bb[1]- A1-242 (PAR030-PAR090, t=10.7, Gl=85.4% and ρ<0.0001), hull plank St2Eb[3] and ceiling plank TN4 (dendro-codes PAR221-PT00102 respectively, t=11.2 and Gl=83.3 with ρ<0.0001) confirmed by visual match, indicate that the six planks were sawn from three trees.

Furthermore, the plank St5Eb[2] (PAR080) gave an outstanding visual match with the filler pieces TAB2 (PT00104A) and TAB3 (PT00105A) researched by Wazny in 2005, indicating also that the three timbers derived from the same tree. This observation, although not sustained by outstanding statistical values as a result of the short overlaps (mean group overlap= 42.3 rings, t= 5.25 and Gl=76.2), is supported by the fact that all three planks are sawn from the same tangential axis of the stem, and therefore have a similar shape, growth pattern and number of rings. These TRS of samples from the same tree were averaged into the tree mean-curves PARQT1 (PAR010-PAR100), PARQT2 (PAR030-PAR090), PARQT3 (PAR080-PT00104A- PT00105A) and PARQT4 (PAR221-PT00102).

The second internal crossdating, including these tree-mean curves and the rest of the TRS, resulted in the relative dating of almost the entire group of timbers (Table 2). The results on Table 2 show high statistical values between most of the planking elements among them (PARQT1, PARQT2, PAR020,

PAR040, PAR050, PAR060, PAR070, PAR230 and PAR240) and with some of the framing elements (PAR110, PAR140, PAR150 and PAR190) which also showed excellent correlation values between them. This indicates that these oak timbers represent a rather homogeneous group. Therefore it was decided to join all these TRS into a tentative object-mean curve (PARQMC), which was then compared with the remaining TRS. PT00103A and PARQT3 were finally added to the object-mean curve, as they still correlated with highly significant statistical values (t= 4.18, Gl=65.2, ρ<0.001 and t= 4.01, Gl=71.7, ρ<0.001 respectively). The statistical values of the initial relative match of PARQT4 with PAR050 (see Table 2) decreased drastically when compared to the object-mean curve (t= 1.95, Gl=62.7, ρ<0.005), hence it was excluded from the mean. Likewise, the TRS from oak framing elements PAR170, PAR200 and PAR210 were left out of PARQMC.

The TRS from the chestnut timbers showed a good synchronization between them (t=4.74, Gl=66.3, ρ<0.005) and with some TRS from oak elements (Table 2). The chestnut series were averaged into the mean curve PARCSM.

The comparison of the oak and chestnut mean curves (PARQMC and PARCSM respectively) and the remaining unassigned TRS (PARQT4, PAR170, PAR200, PR210) with the master and local chronologies resulted in the dating of all the TRS except for PARQT4 (Fig. 8). Framing elements containing bark edge provided precise felling dates: PAR210, spring/summer AD 1579; PAR190, late summer/winter AD1582/83; and PAR110 and PAR150, spring/summer AD1583. To estimate the felling dates of samples with partial sapwood or the *terminus post quem* for samples without sapwood, sapwood estimations from the source area should be used. Regional chronologies dating the series represented predominantly the west of France. Given that sapwood statistics for this area are lacking, we used the sapwood estimates proposed by Pilcher (1987) for northern France. Pilcher calculated that the number of sapwood rings in oaks growing in the north of France can be expected to range between 15.25 and 43.26 within a 95% confidence interval. Applying this sapwood estimate, the calculated felling date ranges for the samples with partial sapwood were found to span dates between AD 1551 and AD 1608 (Fig. 8). For the samples lacking any sapwood only *terminus post quem* dates can be provided (dates after which the trees were felled). However, considering the homogeneity of the researched material and most of the felling date ranges of the samples with partial sapwood, it seems very likely that all timbers were felled between the late 1570s and AD1583.

The object-mean curve PARQMC shows excellent matches (t higher than 9) with local oak chronologies from the Pays-de-Loire region derived from timbers of buildings in the area between Nantes, Angers and the Royal Abbey of Fontevraud (Fig. 9). This indicates that the researched timbers very likely originate from forest areas along the Loire River, in this region of western France. Furthermore, it also presents high correlation values with chronologies further north, indicating that the object-mean contains a strong regional signal. The resulting oak chronology (PARQCR) has been plotted against the French local chronology (49)-Vendée which provided the best statistical match (Fig.10).

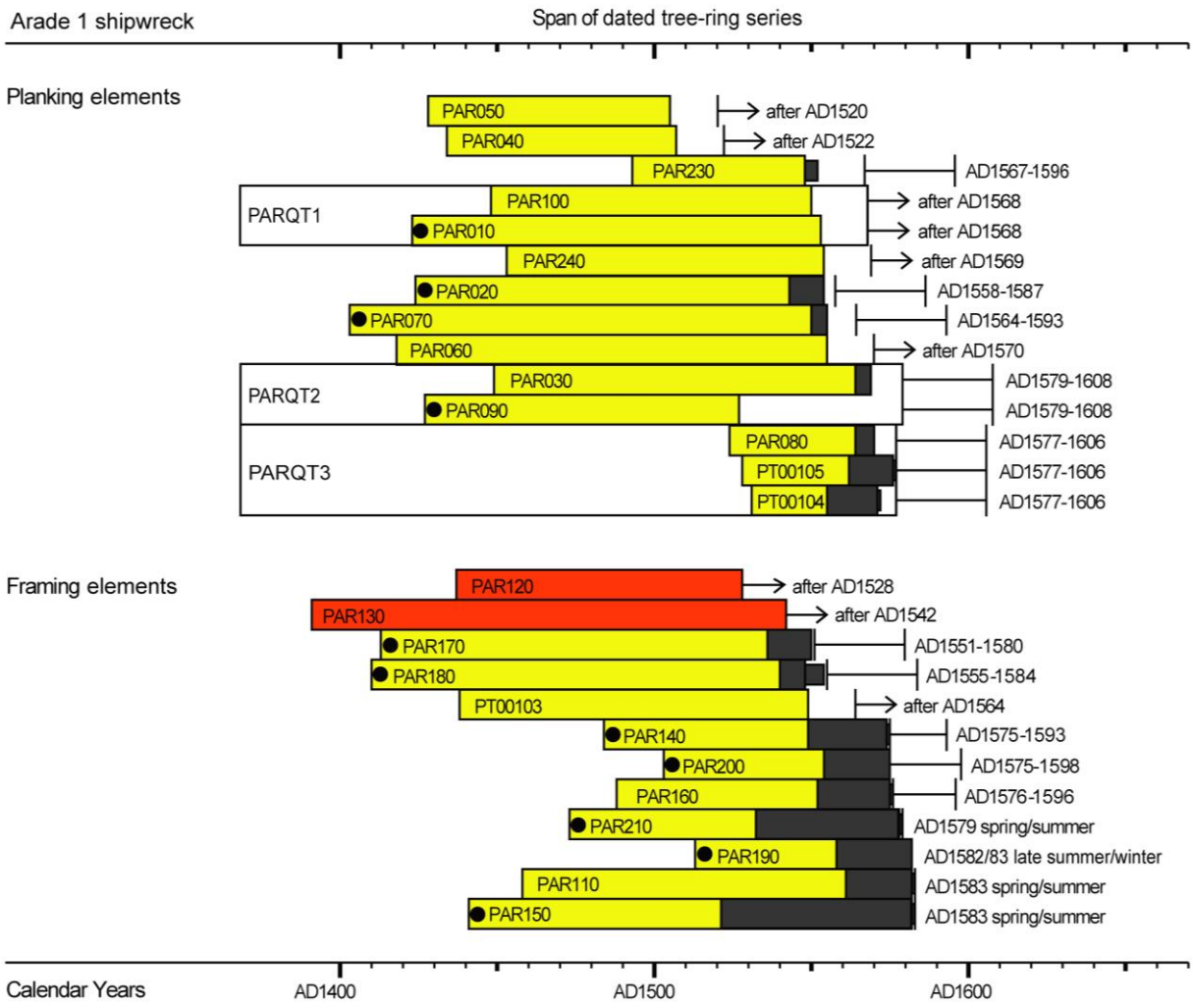

Figure 8. Time-span of the dated oaks (yellow) and chestnuts (orange) TRS. The dot indicates that the pith is present in the sample and the grey filling shows the sapwood rings in the oak samples. Clustered bars represent timbers made from the same tree (bar diagram obtained with software Dendro for Windows by Tyers 1997).

Regarding the TRS not included in the mean, PAR200 showed highly significant correlations with local chronologies by or closer to the western coast (Olonne-sur-Mer (85), t=6.23, Gl=71.2, ρ<0.0005 and (85)-Ven, t=6.04, Gl=72.6, ρ<0.0002). Similarly, PAR210 and PAR170 showed a good correlation with the coastal chronology from Olonne-sur-Mer (t=4.01, Gl=64.6, ρ<0.01 and t=4.15, Gl=67.3, ρ<0.0005 respectively).

The chestnut mean curve PARCSM also showed excellent matches (t higher than 5.5) with local oak chronologies from the Pays-de-Loire region (Fig. 11). These heteroconnections served to absolutely date the chestnut framing elements to the calendar year, although the lack of bark edge in the samples and visible sapwood in this species hampered the possibility to ascertain the felling date of the parent trees.

Dendro-codes	PARQT1	PARQT2	PAR020	PAR040	PAR050	PAR060	PAR070	PAR230	PAR240	PARQT3	PARQT4	PT103A	PAR110	PAR120	PAR130	PAR140	PAR150	PAR160	PAR170	PAR180	PAR190	PAR200	PAR210
PARQT2	5.56 65.4###																						
PAR020	6.61 61.2##	5.17 58.6#																					
PAR040	3.48 64.9##	4.21 68.2###	<3																				
PAR050	4.66 66.0##	3.08 65.4##	<3	5.16 73.6####																			
PAR060	6.4 64.5###	4.6 60.5##	7.01 68.3###	n.s.	<3																		
PAR070	5.1 66.4###	5.01 64.0###	3.64 59.5#	3 62.2#	<3	n.s.																	
PAR230	5.0 73.2###	<3	<3	<3	<3	5.67 76.8####	<3																
PAR240	5.96 62.9##	3.83 65.2##	5.47 62.7##	5.39 64.5#	4.8 70.8##	4.22 60.3#	5.47 60.3#	3.8 71.4###															
PARQT3	<3	<3	<3	n.o.	n.o.	<3	<3	<3	<3														
PARQT4	<3	<3	<3	<3	4.2 71.3##	<3	<3	n.o.	<3	n.o.													
PT103A	<3	<3	n.s.	<3	<3	<3	<3	n.s.	<3	<3	<3												
PAR110	3.65 70.8###	<3	<3	<3	<3	<3	3.11 60.2#	3.6 71.4###	5.61 69.6###	4.39 68.9##	<3	<3											
PAR120	<3	3.51 69.0###	<3	<3	<3	<3	3.01 64.7##	<3	3.42 66.4##	<3	<3	3.16 62.1#	3.42 62.7#										
PAR130	<3	5.66 66.8###	<3	<3	<3	<3	4.15 57.2#	<3	4.61 68.3###	<3	3.69 63.7##	<3	<3	4.74 66.3###									
PAR140	<3	n.s.	3.11 64.8##	<3	<3	<3	4.87 61.8#	3.33 71.4###	3.37 62.0#	<3	n.o.	<3	4.3 65.9##	3.46 64.4#	<3								
PAR150	<3	<3	<3	<3	<3	<3	<3	3.59 68.8##	3.87 61.3#	4.97 63.2#	<3	<3	6.42 65.6###	<3	<3	4.68 68.7####							
PAR160	3.15 67.4##	3.07 61.0#	3.22 66.4##	<3	<3	<3	5.63 64.7##	5.13 67.9##	4.43 64.9##	<3	<3	<3	3.51 66.5###	3.16 67.1#	3.37 66.4##	4.54 59.2#	4.73 68.8####						
PAR170	<3	<3	<3	<3	<3	<3	<3	<3	4.25 62.8##	<3	<3	3.97 62.9##	3.97 62.9##	<3	<3	<3	3.5 71.4###	3.4 66.7##					
PAR180	3.84 63.1##	3.15 64.8###	4.04 58.0#	<3	<3	n.s.	<3	5.59 67.0##	3.93 67.7###	<3	<3	3.32 62.2##	3.09 64.3##	<3	<3	<3	<3	3.91 67.2##	<3				
PAR190	<3	<3	<3	n.o.	n.o.	<3	<3	5.57 72.2##	<3	n.s.	n.o.	3.72 74.3##	6.65 67.9##	<3	<3	5.45 71.8####	6.98 67.9##	4.87 69.0##	<3	<3			
PAR200	<3	<3	<3	<3	<3	<3	n.s.	<3	<3	<3	n.o.	3.73 62.8#	<3	<3	<3	4.36 63.2#	<3	3.27 61.0#	<3	<3	3.26 64.3#		
PAR210	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	n.s.	<3	3.77 65.6###	<3	<3	3.35 61.5#	<3	3.34 67.0###	3.92 66.0##	<3	3.53 65.9##	<3	

Table 2. Results second internal crossdating. Dendro-codes represent individual trees. #: ρ<0.05; ##: ρ<0.01; ###: ρ<0.001; ####: ρ<0.0001; n.s.: not significant; n.o.: no overlap. Student's t-values lower than 3 are not shown.

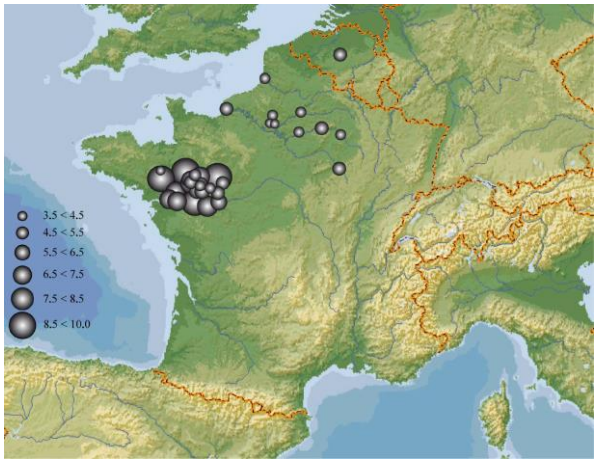

Figure 9. Map showing the spatial distribution of t-values resulting from crossdating the oak object-chronology PARQMC with local oak chronologies from France and Belgium.

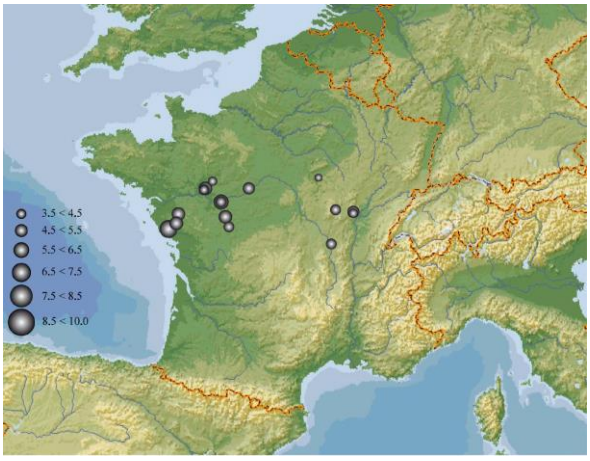

Figure 11. Spatial distribution of t-values resulting from crossdating the chestnut mean curve PARCSM with local oak chronologies from France.

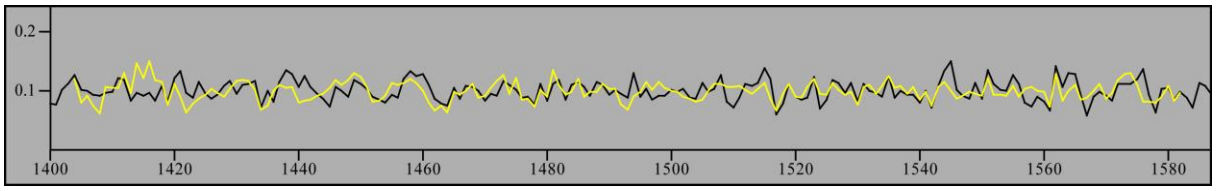

Figure 10. Visual synchronization between the standardized oak object-chronology PARQCR (yellow) and the French local chronology (49)-Vendée (black); X-axis: calendar years; Y-axis: dimensionless ring-width indices.

4. DISCUSSION

The researched samples constitute a homogeneous group of timbers, originating from the west of France, very likely from the area around Fontevraud, in the Pays-de-Loire region. This implies that the dated oak timbers belong to some of the deciduous species predominant in that area (*Q. robur* , *Q. petraea*, or *Q. pubescens*). This region is outside the natural distribution range of *Q. faginea* (Tutin et al., 2001), therefore this species can be excluded as species for the researched timbers. The macroscopic wood anatomy within a tree species may differ not only between sites, depending on environmental conditions such as local disturbances, but also within a tree, from juvenile to mature wood or from stem to branch wood. Differences in growth rate among deciduous oak species are exclusively related to the site where the trees grow and are by no means associated with the genetics of certain species. The presence of abundant large rays is indeed a key characteristic of evergreen oak species such as *Q. ilex* or *Q. suber*, but this is also an anatomical peculiarity frequent in the proximities of branches and other protuberances in the wood of other oak species (pers. comm. F. Schweingruber), hence it could indicate that the timber was obtained from a branch, instead of stem-wood. However, as of yet, no comprehensive studies are available on this subject and no conclusions can be drawn in this respect. Nevertheless, considering that certain timbers for shipbuilding were specifically selected from branches or from the part of the stem where the branches fork (Albion, 1926; De Aranda y Antón, 1990, 1999), it should not be surprising to find such aberrant rays. Therefore caution should be the norm when using them as a key to identify the wood down to the species level in the case of deciduous oaks.

High similarity between the chestnut and oak TRS (heteroconnection) indicates that the trees of both species selected for ship-timber must have been growing under similar conditions, very likely in the same area. This is very plausible, as the distribution of some deciduous oak species overlaps broadly with that of chestnut in the west of France (Fig. 12). Heteroconnections between oak species and chestnut from the same region have been observed before in the Pays de Loire in construction timbers from the Castle of Dukes of Brittany at Nantes and the Court of the convent of Château-Gontier, for example, but also on painting panels made of chestnut at Limoges, which could be dated with local oak chronologies (C. Lavier unpublished data). These examples reinforce the idea that the chestnut and oak trees from this study were growing in close proximity.

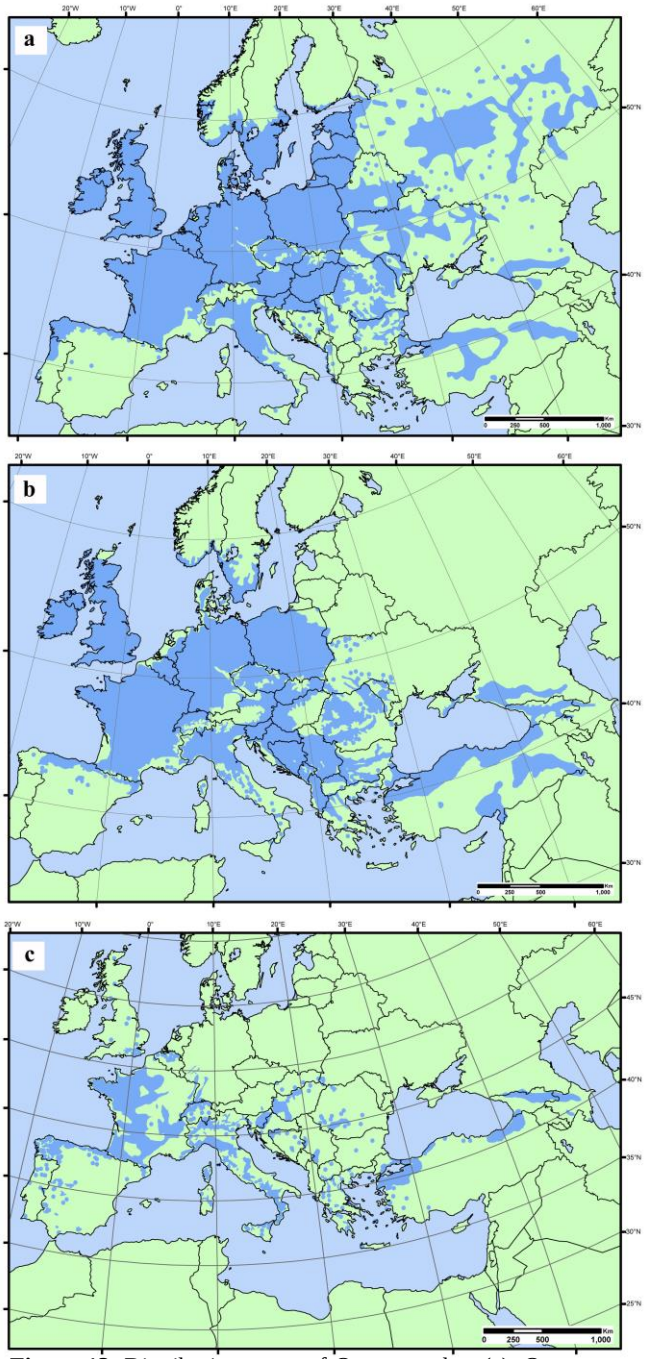

Figure 12. Distribution maps of Quercus robur (a), Q. petraea (b) and Castanea sativa (c) (source: EUFORGEN 2009, www.euforgen.org).

The tree-ring patterns of the timbers presenting pith and sapwood (fast grown in the juvenile period with a decrease in growth-rate shortly afterwards), are probably the result of the trees growing under a relatively closed canopy (in a relatively dense forest). Such gradual decrease in growth does not seem to be due to the natural age-trend of trees, given that these trees were still relatively young (70 to 142 years), therefore they might be due to light-competition with adjacent trees (canopy closure) as the trees matured. The fast-grown pattern found in two planks, is common for trees growing from coppice-stools or in relatively open landscapes or coastal areas, for example, where the availability of light or water is not a limiting factor for tree-growth (Schweingruber, 1996; Beeckman, 2005; Haneca et al., 2006). The fact that the TRS from the fast-grown trees match the ones from the slow-grown ones and that there is not a division of timber-elements based on growth-rates, but rather on tree size, indicates that the selection of trees was restricted to a certain geographical area with variable cover density (some parts would be more open than others). In the last decade, combined dendrochronological and historical research in eastern France (Beck et al., 2002) demonstrated that in Burgundy, for example, from the middle ages until the beginning of the Modern Period, construction timber for buildings was supplied

from areas within a distance of 10 to 50 km. The selection of such construction timber was based on quality (sound wood free of rot, wounds, fungi), shape (straight, forked, curvy) and diameter depending on the needs, but the wood usually originated from the same forest areas (C. Lavier, unpublished data; Locatelli et al., 2011). Similarly, the homogeneity in the sizes of the framing elements points at a selection of trees based on diameter and shape. The planks originated from bigger trees, as inferred from the estimated minimum size of the few ones containing pith and sapwood (400-500 mm diameter). Finding wood derived from the same tree in different types of elements (as in the case of the filler pieces TAB2, TAB 3 and the hull-plank St5Eb[2], or the hull plank St2Eb[3] and ceiling plank TN4) suggests that the wood was transported to the dockyard as full logs, to be processed once there into the required shape.

Although the number of selected timbers for dendrochronological research represents a low percentage of the total amount of recovered wooden elements, their different timber type and wide distribution within the ship makes them representative. The homogeneity in provenance of the wood, with precise felling dates (and estimated ones) for the oak timbers ranging between AD 1579 and 1583 indicates that they most likely belong to the original construction of the ship. Different felling dates point at stock-piling practices, as the timbers did not show signs of re-use. The construction of the ship could then be placed shortly after AD 1583, as seasoning time for the wood before its use as ship-timber has been described to be short (Dodds and Moore, 1984). An alternative, but less likely interpretation of the results, is that the ship was constructed soon after AD 1579 and that the timbers from trees felled around AD 1583 represent repairs. The fact that chestnut wood was used in framing elements could indicate either that those futtocks were repaired or that oak and chestnut were used together because they were available. Guibal and Pomey (2003) argue that the homogeneity of timbers is a reflection of quality and an effective and abundant supply of the raw material. In this study, the lack of precise felling dates for the chestnut trees makes it impossible to ascribe them to a specific event (original construction, re-use or repair).

The place where the ship was built remains undetermined. The high strength and durability of oak wood made it a preferred species for structural ship elements (Albion, 1926; De Aranda y Antón, 1999). Its limited availability in the more populated and less forested areas of western Europe prompted its trade (for shipbuilding and other uses) during the early modern period from forested areas in north-eastern Europe, mainly Germany, Scandinavia, Poland and other Baltic countries (Wazny and Eckstein, 1987; De Vries and van der Woude, 1995; Delmás and Van den Berselaar, 2009). This trade was for a large part carried out by Dutch and Flemish merchants, as well as Hanseatic traders, who served as a link between north-eastern and south-western Europe (De Vries and van der Woude, 1995; Delmás and Van den Berselaar, 2009). In Iberia, documentary evidence for this trade can be found in Cantabrian and Basque archives for the 15th and 16th centuries (Casado Soto, 1998; Orella Unzué, 2003) and for the 16th century in the north of Portugal, Lisbon and Seville, for example, where oak timber was imported from the Baltic to be used in shipbuilding and art-pieces (Devy-Vareta, 1986; Bruquetas, 2002; Klein and Esteves, 2001; Otte Sander, 2008). Furthermore, Devy-Vareta (1986) describes the import of French timber to harbours in the northwest of Portugal from the 13th to the 16th centuries. In the context of such active timber trade, the Iberian construction of the Arade 1 ship cannot be ruled out as working hypothesis. However, it would have to be

supported by accurate documentary evidence, as the 16th century was a time of diplomatic developments and political instability (especially the last quarter of the century), hence trade connections prevailing in the first decades of the century may have been disrupted by the 1580s.

The construction characteristics of the Arade 1 alone cannot provide conclusive evidence for the ship's construction location. By the late sixteenth century, carvel ship construction had become widespread on the Atlantic seaboard and in the southern North Sea, with the shipyard of Rouen having played an important role in the transfer of Mediterranean nautical technologies (Rieth, 1989). The development and spread of carvel-built vessels is one of the most important questions in nautical archaeology and the role of Iberian ships in this technological expansion has been the subject of numerous site-specific explorations, doctoral theses and symposia (for example Alves, 2001; Castro and Custer, 2008). Many of these studies have focused on details of construction, often in an attempt to define a specifically Iberian-Atlantic shipbuilding tradition. More nuanced approaches, integrating studies of wood science and documentary sources have advocated, or sought to achieve, synthesis of technological detail with the evidence for forestry management and timber supply (for example Grenier et al., 2007; Creasman, 2008). Only through such multi-disciplinary approaches, including research on the dynamics of timber trade, can the full complexity of developments in shipbuilding traditions at that time in history be understood.

5. CONCLUSIONS

Dendrochronological research has provided a precise date and accurate provenance for the researched timbers. However, the question of where the ship was built still remains open. The identification of deciduous oak of the type *Q. robur/petraea/pubescens* and chestnut originating from the Pays-de-Loire, in western France, implies either that the ship was built in some French dockyard, or in some other shipyard trading French timber. Further historical research on timber trade from France in the late 16th century could shed some light on this question.

This study illustrates the potential of dendrochronological research when applied to shipwreck assemblages through employment of an appropriate sampling strategy, which includes examination of a broad range of structural elements and sampling of numerous, well selected timbers. The existence of a dense network of well-replicated local chronologies available for the source area has been the key to the successful dating and provenancing of the timbers. If the timber had originated from areas where such tree-ring networks are lacking (for example the Iberian Peninsula), the tree-ring series would probably have remained undated. The development of reference tree-ring chronologies in areas which acted as ship-timber suppliers is still a much needed step towards the assessment of wooden ship remains all over the world. Timber from shipwrecks is an excellent key for understanding past shipbuilding traditions and forest management practices, as well as a resource for developing tree-ring width data to improve existing chronologies and develop new ones. This paper seeks to encourage nautical archaeologists (especially those studying ship remains in areas where these approaches have not been extensively used) to implement and fully exploit the potential of wood science through appropriate sampling strategies, and contribute in this way to the understanding and preservation of this particular form of cultural heritage.

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References

Albion, R.G., 1926. *Forests and Sea Power: the Timber Problem of the Royal Navy, 1652-1862*. Harvard University Press, Cambridge.

Alves, F. (Ed), 2001. *Proceedings of the International Symposium 'Archaeology of Medieval and Modern Ships of Iberian-Atlantic Tradition'*. Lisbon.

Alves, F., Machado A., Castro, F., 2005. Resultados preliminares da campanha de trabalhos arqueológicos Arade 2001, realizada no âmbito do projecto Pró-Arade, in M.J. Gonçalves (Ed.), *Actas do 2o Encontro de Arqueologia do Algarve*, XELB **5**, 257-266.

Amaral Franco, J., 1990. Quercus. In G. López, (ed.) *Flora Ibérica*, vol. II. Real Jardín Botánico de Madrid, Servicio de Publicaciones del CSIC, 15-36, Madrid.

Baillie, M.G.L., 1982. *Tree-Ring Dating and Archaeology*, University of Chicago Press, Chicago.

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

Beck, P., Auloy, G., Blondeaux, L., Canat, C., Desvignes, J., Locatelli, C., Maerten, M., Morlon, J.C., Pinette, M., Pousset, D., 2002. *Vie de cour en Bourgogne à la fin du Moyen Age. Marguerite de Flandre et Germolles (1380-1405)*, Sutton Ed.

Beeckman, H., 2005. The impact of forest management on wood quality. The case of medieval oak, in C. Van de Velde, H. Beeckman, J. Van Acker and F. Verhaeghe (eds), *Constructing wooden images, Proceedings of the symposium on the organization of labour and working practices of late gothic carved altarpieces in the Low Countries*, Brussels, pp. 93-113.

Bonde, N., Crumlin-Pedersen, O., 1990. The dating of wreck 2, the long ship, from Skuldelev, Denmark, *News*WARP **7**, 3-6.

Bruquetas, R., 2002. *Técnicas y materiales de la pintura española en los Siglos de Oro*, Fundación de

Apoyo a la Historia del Arte Hispano, Madrid.

Campelo, F., Gutierrez, E., Ribas, M., Nabais, C., Freitas, H., 2007. Relationships between climate and double rings in Quercus ilex from northeast Spain. *Canadian Journal of Forest Research* **37(10)**, 1915-1923.

Carvalho, A., 1997. *Madeiras Portuguesas. Estrutura anatómica, Propriedades e utilizações*. Vol. II, Direcção-Geral das Florestas, Lisboa.

Castro, F., 2002. The Arade 1 Ship - 2002 Field Season - Vol. 1 - The Site - ShipLab Report 3. On file in IPA/CNANS' library, 2002, and in Nautical Archaeological Program Library, Texas A&M University.

Castro, F., 2006. The Arade 1 shipwreck. A small ship at the mouth of the Arade River, Portugal, in L. Blue, F. Hocker and A. Englert (eds), *Connected by the Sea. Proceedings of the 10th Symposium on Boat and Ship Archaeology* 2003 (ISBSA 10), 300-305, Roskilde.

Castro, F., Custer, K. (Eds.), 2008. *Edge of Empire: Proceedings of the Symposium 'Edge of Empire' held at the 2006 Annual Meeting of the Society for Historical Archaeology, Sacramento,* Sintra.

Casado Soto, J.L., 1998. Aproximación a la tipología naval cantábrica en la primera mitad del siglo XVI, *Itsas Memoria. Revista de Estudios Marítimos del País Vaco* **2,** 169-191.

Cherubini, P., Gartner, B.L., Tognetti, R., Bräker, O.U., Schoch, B. and Innes, J.L., 2003. Identification, measurement and interpretation of tree rings in woody species from Mediterranean climates. *Biology Reviews* **78**, 119-148.

Cook, E.R., Holmes, R.L., 1986. Guide for computer program ARSTAN, in R. L. Holmes, R. K. Adams and H. C. Fritts (eds), *Tree-Ring Chronologies of Western North America: California, eastern Oregon and northern Great Basin*, Laboratory of Tree Ring Research, The University of Arizona, 50-65, Tucson.

Cook, E.R., Peters, K., 1981. The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies, *Tree-Ring Bulletin* **41**, 45–53.

Creasman, P.P., 2008. Ship timber: forests and ships in the Iberian peninsula during the age of discovery, in F. Castro and K. Custer (eds), *Edge of Empire: Proceedings of the Symposium 'Edge of Empire' held at the 2006 Annual Meeting of the Society for Historical Archaeology, Sacramento*, Sintra, 235-248.

Crumlin-Pedersen, O., Olsen, O., 2002. The Skuldelev Ships I: Topography, Archaeology, History, Conservation and Display, *Ship and Boats of the North* **4.1**, 360.

Daly, A., 2007. The Karschau Ship, Schleswig-Holstein: Dendrochronological Results and Timber Provenance, *IJNA* **36(1)**, 155-166.

Daly, A., Nymoen, P., 2008. The Bøle ship,Skien, Norway –Research history, dendrochronology and Provenance, *IJNA* **37(1),** 153-170.

De Aranda y Antón, G., 1990. *Los Bosques Flotantes: historia de un roble del siglo XVIII*, Colección Técnica, Ministerio de Agricultura, Pesca y Alimentación, ICONA, Madrid.

De Aranda y Antón, G., 1999. *El camino del hacha: la selvicultura, industria y sociedad. Visión histórica*, Ministerio de Medio Ambiente, Organismo Autónomo de Parques Nacionales.

De Vries, J., Van der Woude, A.M., 1995. *Nederland 1500–1815. De eerste ronde van moderne economische groei*, Amsterdam.

Delmás, M., Van den Berselaar, H., 2009. 'Nederlands' hout op drift. Over houthandelsroutes en de herkomst van hout van de Late Middeleeuwen tot in de 18de eeuw, *Vitruvius* **2(6),** 12-18.

Devy-Vareta, N., 1986. Para uma geografia histórica da floresta portuguesa: do declínio das matas medievais à política florestal do Renascimento (XV-XVI), *Revista da Faculdade de Letras-Geografia* 1.1, Porto, 5-37.

Dodds, J., Moore J., 1984. *Building the wooden fighting ship*. London: Chatham Publ.

Eckstein, D., Bauch, J., 1969, Beitrag zu Rationalisierung eines dendrochronologischen Verfahrens und zu Analyse seiner Aussagesicherheit. *Forstwissenschaftliches Centralblatt* **88**, 230-250.

Eckstein, J., Leuschner, H.H., Bauerochse, A., Sass-Klaassen, U., 2009. Subfossil bog-pine horizons document climate and ecosystem changes during the Mid-Holocene, *Dendrochronologia* **27(2),** 129-146.

Feuillat, F., Dupouey, J.L., Sciama, D., Keller, R., 1997. A new attempt at discrimination between *Quercus petraea* and *Quercus robur* based on wood anatomy, *Canadian Journal of Forest Research* **27**, 343-351.

Fritts, H.C., 1976. *Tree rings and climate*, Academic Press, London.

García Esteban, L., Guindeo Casasús, A., Peraza Oramas, C. and De Palacios de Palacios, P., 2003, *La madera y su anatomía*, Fundación Conde del Valle de Salazar y Mundi-Prensa, AITIM, Madrid.

Giachi, G., Lazzeri, S., Mariotti Lippi, M., Macchioni, N., Paci, S., 2003. The wood of "C" and "F" Roman ships found in the ancient harbour of Pisa (Tuscany, Italy): the utilization of different timbers and the probable geographical area which supplied them. *Journal of Cultural Heritage* **4**, 269-283.

Grenier, R., Ringer, R. J., Bernier, M. (Eds), 2007. *The Underwater Archaeology of Red Bay: Basque Shipbuilding and Whaling in the 16th Century*. Ottowa

Guibal, F., Pomey, P., 2003. Timber Supply and Ancient Naval Architecture, in C. Beltrame (ed.), *Boats, Ships and Shipyards Proceedings of the Ninth International Symposium on Boat and Ship Archaeology*, 12/2000, Venice, pp. 35-48.

Haneca, K., Boeren, I., Van Acker, J., Beeckman H., 2006. Dendrochronology in suboptimal conditions: tree-rings of medieval oak from Flanders (Belgium) as dating tool and archives of past forest management, *Vegetation History and Archaeobotany* **15(2),** 137-144.

Hillam, J., 1979, Tree-rings and archaeology: some problems explained, *Journal of Archaeological Science* **6**, 271-278.

Klein, P., Esteves, L., 2001. Dendrochronological analyses in Portuguese panel paintings, in R. van Schoute and H. Verougstraete (eds.), *Colloque XIII Dessin sous-jacent et la technologie dans la*

peinture: la peinture et le laboratoire, procédés, méthodologie, applications, Bruges, 15-17 septembre 1999, Uitgeverij Peeters, Leuven, Bruges, pp. 213-220,

Locatelli, C., Lavier, C., Pousset, D., 2011. Synopsis des chantiers de bois de la cathédrale d'Auxerre depuis 1235, in C. Sapin (ed), *Saint-Etienne d'Auxerre, la seconde vie d'une cathédrale*, Actes de colloque d'Auxerre (27-28 sept. 2007), Auxerre, Centre d'études médiévales Saint-Germain d'Auxerre, Editions Picard, 177-181.

Loureiro, V., 2011. L'Épave Arade 1: l'influence des chantiers régionaux sur la tradition de construction navale ibéro-atlantique, Unpublished doctoral dissertation, Université de Paris I – Panthéon Sorbonne.

Loureiro, V., Alves, J. G., 2005. O navio Arade1. Relatório da campanha arqueológica de 2004, *Trabalhos do CNANS* 28, Lisbon: Centro Nacional de Arqueologia Náutica e Subaquática.

Loureiro, V., Alves, J. G., 2006. O navio Arade1. Relatório da campanha arqueológica de 2005, *Trabalhos do CNANS* 32, Lisbon: Centro Nacional de Arqueologia Náutica e Subaquática.

Loureiro, V., Alves, J. G., 2008. The Arade 1 Shipwreck: Preliminary Results of the 2004 and 2005 Field Seasons, *IJNA* **37(2**), 273-282.

Mitchels, J. W., 1973. *Dating methods in archaeology*, Studies in Archaeology, Seminary Press, New York.

Murmanis, L., 1975. Formation of tyloses in felled *Quercus rubra* L., *Wood Science and Technology* **9(1)**, 3-14.

Orella Unzué, J.L., 2003. Comerciantes vascos en Normandía, Flandes y La Hansa, 1452-1526. *Itsas memoria: revista de estudios marítimos del País Vasco* **4**, 65-114.

Otte Sander, E., 2008. *Sevilla, siglo XVI: Materiales para su historia económica*, Herederos de Enrique Otte Sander. Centro de Estudios Andaluces. Consejería de la Presidencia, Junta de Andalucía.

Pilcher, J. R., 1987. A 700 year dating chronology for northern France. Applications of tree-ring studies. Current research in dendrochronology and related subjects. *BAR International Series* 333: 127-139.

Queiroz, P. F., Oliveira, H., Pereira, T., 2005. Identificação de um conjunto de madeiras provenientes da estrutura do navio Arade 1, *Trabalhos do CIPA* 91. Lisbon.

Rieth, E., 1989. Le clos des galées de Rouen, lieu de construction navale à clin et à carvel (12-93-1419), *Medieval Ships and the Birth of Technological Societies* **1**, 71-77.

Rieth, E., Rodrigues, P., Alves, F., 2004. Relatório da campanha de 2003 de desmontagem e recuperação da parte exposta do navio Arade I, *Trabalhos do CNANS* 19, Lisbon: Centro Nacional de Arqueologia Náutica e Subaquática.

Schweingruber, F.H., 1990. *Anatomy of European woods*. Haupt Verlag, Bern, Stuttgart.

Schweingruber, F.H., 1993. *Trees and wood in dendrochronology*. Springer Series in Wood Science. Springer Verlag, Heidelbeerg.

Schweingruber, F.H., 1996. *Tree rings and Environment. Dendroecology*. Paul Haupt Verlag, Berne.

Sousa, V.B., Leal, S., Quilhó, T., Pereira, H., 2009, Characterization of cork oak (*Quercus suber*) Wood anatomy. *IAWA Journal* **30(2**), 149-161.

Tutin, T.G., Heywood, V.H., Burges, N.A., Valentine, D.H., Walters, S.M. and Webb, D.A., 2001. *Flora Europaea*. Cambridge University Press, Cambridge.

Tyers, I., 1997. *Dendro for Windows Program Guide*. Archaeological Research and Consultancy at the University of Sheffield, Report 340.

Van Leeuwaarden, W., Queiroz, P. F., 2002. Identificação de um conjunto de madeiras provenientes da estrutura dos navios recuperados no rio Arade, *Trabalhos do CIPA* 35, Lisboa.

Ważny, T., Eckstein, D., 1987. Der Holzhandel von Danzig/Gdansk -Geschichte, Umfang und Reichweite, *Holz als Roh-Werkstoff* **45**, 509-513.

Wicha, S., Guibal, F., Medail, F., 2003. Archaeobotanical characterization of three ancient Mediterranean shipwrecks. In Fouache E. (Ed.), *The Mediterranean world environment and history*, Elsevier, pp. 233-237.

Appendix 2

APPENDIX 2. QUALITY INDEX OF THE PUBLISHED ARTICLES

Article 1

Domínguez-Delmás, M., Alejano-Monge, R., Van Daalen, S., Rodríguez-Trobajo, Susperregi, J., García-González, I., Wazny, T., Jansma, E., 2015. Forest history, tree-rings and cultural heritage: current state and future prospects of dendroarchaeology in the Iberian Peninsula. *Journal of Archaeological Science* **57**, 180–196.

Impact Factor 2014 (©Thomson Reuters Journal Citation Reports 2015):

- 2.196

Indexed in:

- Social Sciences Citation Index
- British & Irish Archaeological Bibliography
- Scopus

Article 2

Domínguez-Delmás, M., Alejano-Monge, R, Wazny, T., García-González, I., 2013. Radial growth variations of black pine along an elevation gradient in the Cazorla Mountains (South of Spain) and their relevance for historical and environmental studies. *European Journal of Forest Research* **132**(4), 635-652.

Impact Factor 2014: 2.095

Indexed in:

Science Citation Index Expanded (SciSearch), Journal Citation Reports/Science Edition, SCOPUS, Chemical Abstracts Service (CAS), Google Scholar, EBSCO, CSA, ProQuest, CAB International, Academic OneFile, AGRICOLA, CAB Abstracts, Current Contents/ Agriculture, Biology & Environmental Sciences, EMBiology, Gale, Geobase, GeoRef, Global Health, OCLC, ReadCube, SCImago, Summon by ProQuest

Article 4

Rodríguez-Trobajo, E., **Domínguez-Delmás, M.,** 2015. Swedish oak, planks and panels: dendroarchaeological investigations on the 16th century *Evangelistas* altarpiece at Seville Cathedral (Spain). *Journal of Archaeological Science* **54**, 148–161.

Impact Factor 2014 (©Thomson Reuters Journal Citation Reports 2015):

- 2.196

Indexed in:

- Social Sciences Citation Index

- British & Irish Archaeological Bibliography
- Scopus

Article 5

Domínguez-Delmás, M., Nayling, N., Wazny, T., V. Loureiro, Lavier, C., 2013. Dendrochronological dating and provenancing of timbers from the *Arade 1* wreck, Portugal. *International Journal of Nautical Archaeology* **42(1)**, 118-136.

The *International Journal of Nautical Archaeology* was founded in 1972. It is published biannually by the Nautical Archaeology Society. The Society was founded in 1981 to further research in all aspects of nautical archaeology and to ensure the publication of the results. It aims to advance education in nautical archaeology at all levels; to improve techniques in excavating, conservation and reporting; and to encourage participation by members of the public at all stages. The Society produces a Newsletter and organizes, both on its own behalf and in association with other bodies, conferences, symposia, lectures, field projects and expeditions.

The International Journal of Nautical Archaeology exists as a forum for the exchange of ideas and research relevant to all aspects of nautical archaeology.

ACADEMIC AND RESEARCH BIOGRAPHY

Marta Domínguez Delmás was born in Castellón de la Plana (Spain) on 5 October 1977. She graduated in Technical Forestry Engineering (BSc Eng, 2000) and Forestry Engineering (MSc Eng, 2004) respectively at the Polytechnic University of Valencia and the University of Lleida, in Spain. Soon in her academic career she got interested in wood anatomy and all aspects related to tree growth. She pursued her interest doing her BSc Eng Thesis in dendroecology at the University of Padova, Italy, supported by the Erasmus European program (1998-1999), and carrying out an internship at the Ring Foundation – Netherlands centre for Dendrochronology, in The Netherlands, funded by the Leonardo da Vinci European program (1999-2000). This initial training was followed by the MSc Eng Thesis at the University of Santiago de Compostela, in Spain (2002-2003), and a research assistantship at the Forest Research Centre of Southern Sweden in Alnarp, Sweden (2003-2004).

In 2006 she co-founded the laboratory DendroLab NL for wood anatomical and dendrochronological research in the Netherlands. Her research interest turned towards dendroarchaeology, with a focus on the historical timber trade from the Baltic and Scandinavia to the Netherlands and the Iberian Peninsula in the Early Modern Period, and in 2007 she was employed as dendrochronologist and head of laboratory at the Ring Foundation. There she carried out research on the age and provenance of wood from archaeological excavations, shipwrecks, buildings, art pieces and furniture, and got acquainted with different wood species dating from the sixth millennium BC until present. Simultaneously, following her interest on dendroarchaeology and moved by the scarcity of dendrochronological studies on wooden heritage in the Iberian Peninsula, she launched the project "Filling in the blanks in European dendrochronology: building a multidisciplinary research network to assess Iberian wooden cultural heritage worldwide", funded by the Netherlands Organisation for Scientific Research (NWO) and the participating partners. This project gathered a multidisciplinary group of researchers (dendrochronologists, historians, foresters and underwater archaeologists) and had a duration of two years, from September 2009 until September 2011. After its completion, she enrolled in the doctoral Master on Historical and Natural Heritage at the University of Huelva, in Spain, to pursue her PhD, and in 2012 she started the research period of the doctoral thesis at the department of History I of the same university, which she combined with her position at the Ring Foundation until 2013, and her freelance work as dendrochronologist in 2014. In September 2014, she was employed as Marie Curie Early Stage Researcher at the department of Botany of the University of Santiago de Compostela, within the Marie Curie ITN ForSEAdiscovery project.

PUBLICATIONS IN PEER REVIEWED JOURNALS AND CONFERENCE PROCEEDINGS

Domínguez-Delmás, M., Alejano-Monge, R., Van Daalen, S., Rodríguez-Trobajo, E., Susperregi, J., García-González, I., Wazny, T., Jansma, E., 2015. Forest history, tree-rings and cultural heritage: current state and future prospects of dendroarchaeology in the Iberian Peninsula. *Journal of Archaeological Science* **57**, 180–196.

Rodríguez-Trobajo, E., **Domínguez-Delmás, M.,** 2015. Swedish oak, planks and panels: dendroarchaeological investigations on the 16th century *Evangelistas* altarpiece at Seville Cathedral (Spain). *Journal of Archaeological Science* **54**, 148–161.

Domínguez Delmás, M., 2014. Avances de la dendrocronología al servicio de la arqueología subacuática española: ¿qué información podemos extraer de la madera de los pecios?. In Nieto Prieto, X., Ramírez Pernía, A., Recio Sánchez, P. (Coords. Eds.), Actas del I Congreso de Arqueología Náutica y Subacuática Española. Ministerio de Educación, Cultura y Deporte, pp. 1080-1095. https://sede.educacion.gob.es/publiventa/detalle.action?cod=20070C.

Domínguez-Delmás, M., Driessen, M., García-González, I., Van Helmond, N., Visser, R., Jansma, E., 2014. Long-distance oak supply in mid-2nd century AD revealed: the case of a Roman harbour (Voorburg-Arentsburg) in the Netherlands. *Journal of Archaeological Science* **41**, 642-654. DOI: 10.1016/j.jas.2013.09.009.

Domínguez-Delmás, M., Alejano-Monge, R, Wazny, T., García-González, I., 2013. Radial growth variations of black pine along an elevation gradient in the Cazorla Mountains (South of Spain) and their relevance for historical and environmental studies. *European Journal of Forest Research* **132(4)**, 635-652.

Domínguez-Delmás, M., Nayling, N., Wazny, T., V. Loureiro, Lavier, C., 2013. Dendrochronological dating and provenancing of timbers from the *Arade 1* wreck, Portugal. *International Journal of Nautical Archaeology* **42(1)**, 118-136.

Soberón Rodríguez, M., Pujol Hamelink, M., Llergo López, Y., Riera Mora, S., Juliá Brugues, R., **Domínguez Delmás, M.,** 2012. El Barceloneta I. Una embarcación medieval a tingladillo en Barcelona. *ITSAS Memoria* **7**, 411-422. (Barceloneta I. A medieval clinker-built ship in Barcelona).

Domínguez-Delmás, M., Benders J.F., Kortekaas G.L.G.A., 2011. Timber supply in Groningen (north-east Netherlands) during the early Modern period (16^{th}-17^{th} centuries). In: Fraiture, P. (Ed.), *Tree-Rings, Art and Archaeology*, proceedings, Brussels, Collection *Scientia Artis* **7**, 151-173.

Nijland, W., Jansma, E., Addink, E., **Domínguez-Delmás, M**., De Jong, S., 2011. Relating ring width of Mediterranean evergreen species to seasonal and annual variations of precipitation and temperature. *Biogeosciences* **8(5)**, 1141–1152.

GRANTS AND HONOURS

Jun 2014 – Dec 2015	National Geographic Society Waitts Grant, granted project 'Millennia old black pines and Andalusian Cultural Heritage to unravel human-environment interactions in the Western Mediterranean' (co-applicant).
Mar – May 2013	**Agnese N. Haury Visiting Fellowship** at the Laboratory for Tree-Ring Research, University of Arizona, Tucson, USA.
Sep 2012	**Doctoral MA thesis in Historical and Natural Heritage**: 'Estudio dendroarqueológico del uso de madera de pino salgareño de las sierras de Cazorla y Segura en cubiertas de edificios andaluces postmedievales' (Dendroarchaology of black pine from the Cazorla and Segura mountains used in roof structures of post medieval buildings in Andalusia). **Qualification: 10 (A+) with Honours**.
Sep 2009 – Sep 2011	**Principal investigator NWO-project** 'Filling in the blanks in European dendrochronology: building a multidisciplinary research network to assess Iberian wooden cultural heritage worldwide' (a.k.a. Iberian Heritage Project; section Humanities, funding program "Internationalization in the Humanities", Netherlands Organization for Scientific Research project number 236-61-001) (0.2 fte).
Oct 2002 – Apr 2003	**MSc Eng Thesis** at University of Santiago de Compostela, department of Plant Biology, Lugo: 'Estudio dendrocronológico del Quercus pyrenaica Willd. en las Sierras Galaico-Leonesas de Ancares y Courel' (Dendrochronological study of Q. pyrenaica Willd. In the Ancares and Courel Mountains). **Qualification: 10 (A+) with Honours**.
Oct 1999 – May 2000	**Leonardo da Vinci European Program**. Laboratory assistant at the RING Foundation – Netherlands Centre for Dendrochronology (Stichting RING), Amersfoort, The Netherlands. Working plan included three dendroecological

projects, as well as sampling and researching wood from archaeological excavations (underwater and terrestrial), buildings, furniture, art pieces and sub-fossil material.

Oct 1998 – Jun 1999 **Socrates-Erasmus European Exchange Program**. Technical (BSc) Eng Thesis at the University of Padova, Faculty of Agricultural Studies, Padova, Italy: 'Estudio dendroecológico de las especies Larix decidua Mill., Pinus cembra (L.) y Picea abies (L.) Karst. en el límite superior arbóreo de los Dolomitas (Alpes italianos orientales)' (Dendroecological study of Larix decidua Mill., Pinus cembra (L.) and Picea abies (L.) Karst at the timberline in the Eastern Italian Alps). **Qualification: 10 (A+) with Honours**.

COMMUNICATIONS AT CONFERENCES, DISSEMINATION EVENTS AND UNIVERSITY LECTURES

30 Apr 2015 **Wageningen University**, The Netherlands (oral communication): 'Forest history and shipbuilding: developing a tree-ring network for provenancing oak and pine ship timber from Atlantic Iberia'

23 Apr 2015 **University of Cologne, Faculty of Arts and Humanities**, Germany (invited lecture): 'Long-distance timber transport in Roman times: insights from a dendroarchaeological perspective'

12 Jan 2015 **CSIC**, Spain (oral comm.): 'Development and implementation of a tree-ring data network for the assessment of the date and provenance of Iberian ship-timbers'

11 Dec 2014 ***Escuela de Conservación y Restauración de Pontevedra***, Spain (invited lecture): Dendrocronología aplicada al estudio del Patrimonio: principios, aplicaciones y casos prácticos

8-12 Sept 2014 **Eurodendro 2014,** Lugo, Spain (oral comm.): Swedish *borne*, planks and panels: dendroarchaeological investigations on the 16th century *Evangelistas* altarpiece at Seville Cathedral (Spain)'

7 Sep 2014 **Dissemination day** ForSEAdiscovery project at Plaza Mayor in Lugo, Spain.

13-17 May 2013 **2nd Ameridendro Conference**, Tucson, USA (oral comm.): 'Ships of the Early Modern Age: innovative tree-ring approaches to the Atlantic challenge'

8 May 2013 **Tree-Ring Talks, University of Arizona**, Tucson (oral comm.): 'Dendroarchaeology in the Western Mediterranean: tree rings from Iberian cultural and natural heritage to bridge the last two millennia'

14-16 Mar 2013 **I Congreso de Arqueología Náutica y Subacuática Española**, Cartagena, Spain (oral comm.): Avances de la dendrocronología al servicio de la arqueología subacuática española: ¿Qué información podemos extraer de la madera de los pecios?

7 Nov 2012 **University of Western Australia**, Perth, Australia (invited lecture): 'In the bridge of disciplines: tree-ring research and its applications in Northern Europe'.

October 2012 **13th International Symposium on Boat and Ship Archaeology ISBSA**, Amsterdam, The Netherlands (poster): 'Tracing the Ghost Ship: can the *hoekman* reveal her construction date and origin?'

29-30 Mar 2012 **11th NAC Conference**, Vedhoven, The Netherlands (poster): 'Long-distance timber supply for the Roman harbour at Voorburg-Arentsburg (NW Netherlands): using high resolution tree-ring data networks to establish wood provenance'.

28 Jan 2012 **Schervendag**, Amersfoort, The Netherlands (oral comm.): '*Bemonstering van scheepswrakken voor dendrochronologie*' (Sampling shipwrecks for dendrochronological research).

29 Sep–2 Oct 2011	**IKUWA 4 Conference**, Zadar, Croatia (poster): 'Iberian ships, wrecks and tree-rings: assessing and sampling of timbers for dendrochronological research'.
24–25 Sep 2011	**1st Workshop Historical Wood Utilization**, Stübing, Austria (poster): 'Historical timber rafting in the Guadalquivir River (south of Spain)'.
19–23 Sep 2011	**Eurodendro 2011**, Engelberg, Switzerland (oral comm.): 'A 700-year long *Pinus nigra* chronology from the Eastern Andalusian Mountains (S Spain) and its relevance as a historical dating tool'.
14 Apr 2011	**Restauratiebeurs SHR Houtsymposium**, 's- Hertogenbosch, The Netherlands (oral comm.): '*Houthandel in Groningen in de 16de en 17de eeuw*' (Timber trade in Groningen in the 16th and 17th century).
14–18 Jun 2010	**WorldDendro 2010 - 8th International Conference on Dendrochronology**, Rovaniemi, Finland (oral comm.): 'Filling in the blanks in European dendrochronology: building a multidisciplinary research network to assess Iberian wooden cultural heritage worldwide'.
26 Mar 2010	**Vrije Universiteit Amsterdam, Faculty of Archaeology**, Amsterdam, The Netherlands (invited lecture): 'Dendrochronology and timber trade: the case study of the timber supply in Groningen (NE Netherlands) in the early modern period'.
26 Feb 2010	**Contactdagen BNAB**, 's-Hertogenbosch, The Netherlands (oral comm.): '*Dendrochronologie en Houthandel*' (Dendrochronology and timber trade).
10–12 Feb 2010	**TRAA (Tree-Rings in Art and Archaeology)**, Brussels, Belgium (oral comm.): 'Timber supply in Groningen (NE Netherlands) during the early modern period (16th -17th centuries)'.
26–30 Oct 2009	**Eurodendro 2009**, Mallorca, Spain (poster): 'Shipwreck *Barceloneta I* - a 14th century Spanish Cantabrian vessel?'.
5–8 Jun 2009	**III Dendro-Provenance Workshop**, Saaremaa, Estonia (two oral comm.): ''Dutch' wood adrift: Timber trade and provenance of wood from the late Middle Ages until the 18th century' and 'Digital Collaboratory for Cultural Dendrochronology in the Low Countries (DCCD): NWO Projectnr. INVMG-07-03: Progress report 2007-2009'.
15 Oct 2008	**University of Huelva, Faculty of Forestry,** Huelva, Spain (invited lecture): '*Introducción a la dendrocronología: aplicaciones en el norte de Europa y potencial en la Península Ibérica*' (Introduction to dendrochronology: Applications in the North of Europe and potential in the Iberian Peninsula).
1–4 Sep 2007	**II Dendro-Provenance Workshop,** Sigulda, Latvia (oral comm.): 'Digital Collaboratory on Cultural Dendrochronology in the Low Countries (DCCD)'.
20–22 Apr 2006	**TRACE (Tree-Rings in Archaeology, Climatology and Ecology)**, Tervuren, Belgium (poster): 'Dendrochronological techniques applied on standing structures: a pilot study on the Czar Peter House in Zaandam, The Netherlands'.
10–14 Sep 2003	**Eurodendro 2003**, Obergurgl**,** Austria (poster): 'Two 300-year long master chronologies of oak for the Northwest of the Iberian Peninsula'.

TRAINING AND SUPERVISION OF STUDENTS AT THE RING FOUNDATION

Jose Pedro Pinto Andrade, MA Thesis, University of Coímbra, Faculty of Biology (Oct 2010-Jul 2011): 'Dendrochronology applied in the Humanities: Dendrochronological analysis of historical and archaeological timbers in The Netherlands'.

Wiebe Nijland, PhD candidate Utrecht University, Faculty of Geosciences (May 2010): tree-ring research related to the article 'Nijland, W., Jansma, E., Addink, E., Domínguez-Delmás, M. & De Jong, S., 2011. Relating ring width of Mediterranean evergreen species to seasonal and annual variations of precipitation and temperature. *Biogeosciences* **8**, 355–383.'

Anne van der Meer, BSc Thesis, Utrecht University, Faculty of Geosciences (Apr-Jun 2010): 'Dendrochronological dating and provenancing of a wooden stern decoration from Dutch East Indiaman Zuytdorp, using X-ray computed tomography images'.

Karl Hjalte Maack Raun, Leiden University, Faculty of Archaeology (internship Oct-Dec 2009: methods of dendrochronology (selection and sampling of timbers, analysis and interpretations of results).

Maaike de Natris, BA Thesis, University of Leiden, Faculty of Archaeology (May-Sep 2009): 'Dendrochronological analysis of barrels form the Early Medieval trade centre Dorestad'.

Bert van Zandhoven, BA Thesis, University of Leiden, Faculty of Archaeology (May-Sep 2009): 'Two well dwellings fromDorestad: A dendrochronological investigation to determine the age of a cask and a hollowed-out tree'.

Julia Bohórquez Rodríguez de Medina, University of Huelva, Faculty of Technical Forest Engineering (Erasmus program internship Nov 2008-Jul 2009): methods of dendrochronology (selection and sampling of timbers, analysis and interpretations of results), report writing and laboratory management.

Dieuwertje Duijn (internship Jul 2008- Jul 2009): methods of dendrochronology (selection and sampling of timbers, analysis and interpretations of results). After hr training, Dieuwertje Duijn was employed at the Ring Foundation (0.2 fte).

Niels van Helmond, BSc Thesis, Utrecht University, Faculty of Geosciences (May-Jul 2008): 'Forum Hadriani: A dendrochronological study to determine the age and origin of wood from a Roman quay and landing stage'.

Joas van der Laan, Utrecht University, Faculty of Geosciences (internship Apr 2008): 'Dendrochronological research on 15 staves from a barrel found in Gorinchem'.

Marije Vlaar, MSc Thesis, Universidad de Utrecht (May-Sep 2007): 'Reconstruction of the Palaeo-ecology of the Eem Polder by means of dendrochronology, pollen and macrofossil analysis'.