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Review

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 8000 years that could profit from dendrochronological research. Future research possibilities in relation to the available Iberian heritage in Spain, Portugal and worldwide are proposed.

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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,

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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 3000 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).

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*.

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

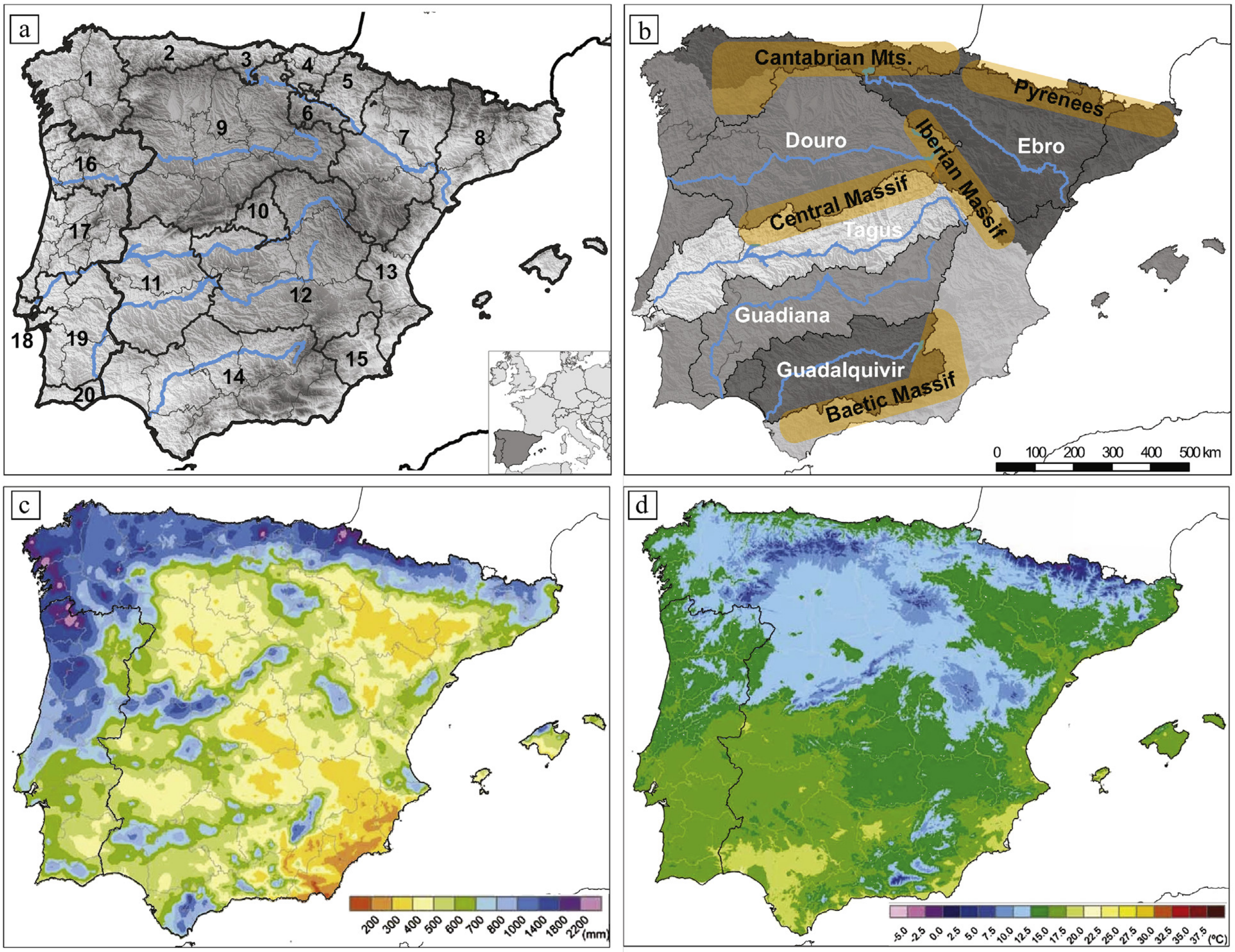

Fig. 1. Geographical and climatological maps. a) Location map and Spanish and Portuguese regions according to current political division (thinner lines delineate provinces): 1, Galicia; 2, Asturias; 3, Cantabria; 4, Basque Country; 5, Navarra; 6, La Rioja; 7, Aragon; 8, Catalonia; 9, Castilla y Leon; 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).

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 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

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 (1,000 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**

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 (Rodríguez 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.

The Cantabrian Mountains in the north and the Baeticas in the south kept on supplying wood from deciduous oaks and black pine respectively for shipbuilding until the late 18th century (De Aranda y Antón, 1990; De la Cruz Aguilar, 1980). This activity caused an important deforestation in the Peninsula, which explains partly why the remaining old forests are located in almost inaccessible areas that could not be exploited.

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.

5.1. Four decades of dendrochronological studies

The first dendrochronological studies in the Iberian Peninsula date back to the 1970s, when Creus Novau and Puigdefàbregas

Fig. 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).

(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, 1993; 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 databank 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.

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 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

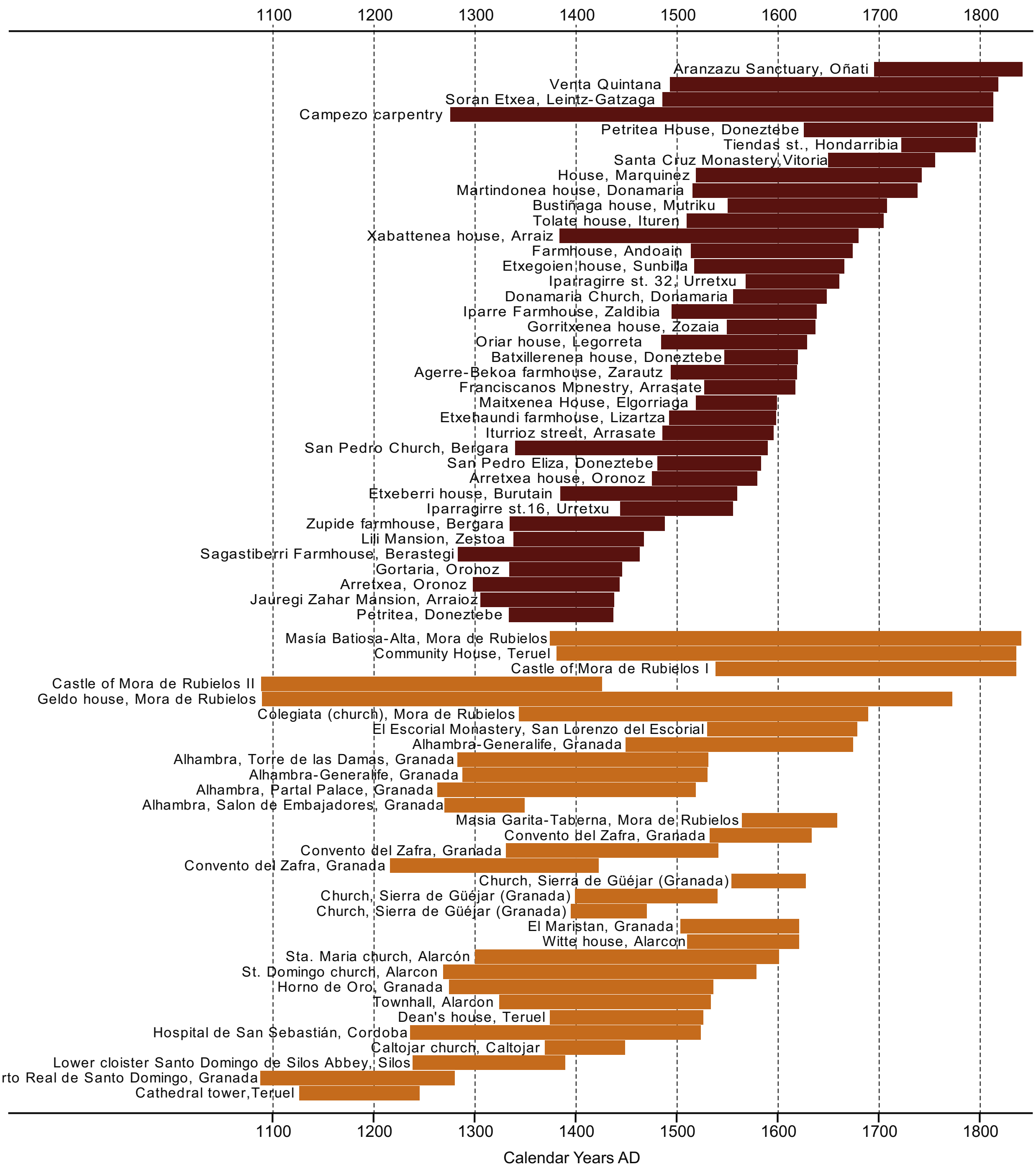

Fig. 3. Time span of the absolutely dated chronologies from historical buildings currently existing in the Iberian Peninsula. Dark bars represent deciduous oaks (*Quercus* subg. *quercus*); light bars represent pines (*Pinus sylvestris/nigra/pinaster/halepensis*) (see Table S1 for a list of references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

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 developing 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

Fig. 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).

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.

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*

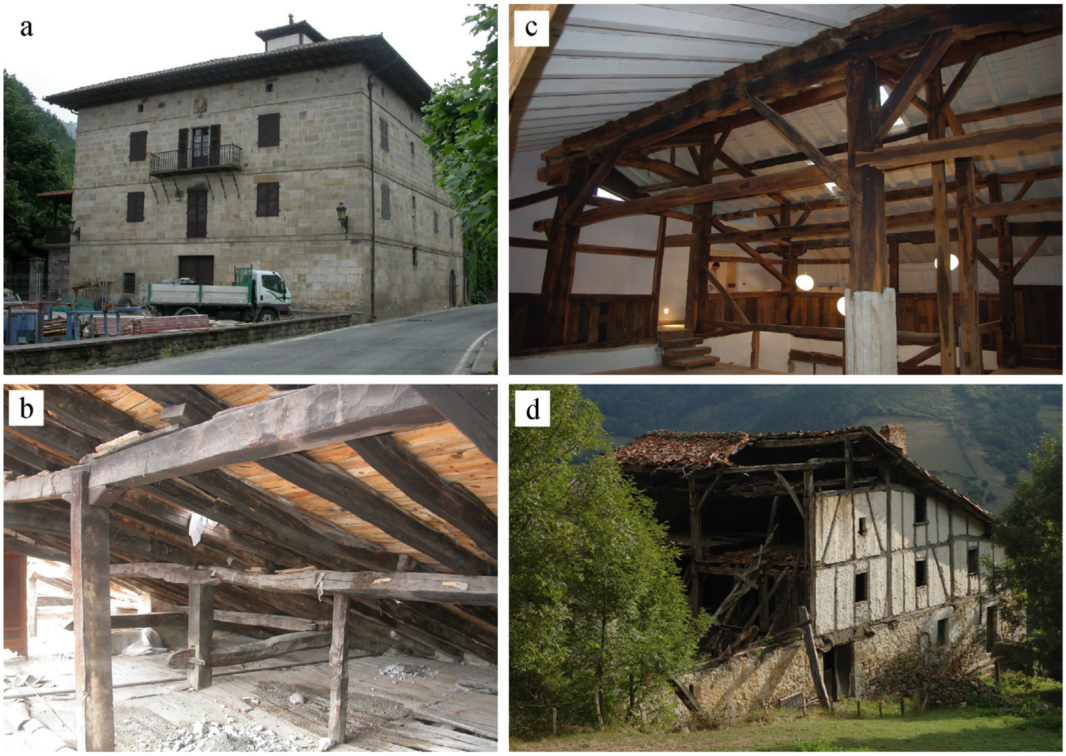

Fig. 5. Examples of buildings researched in the Basque Country. a) Sagardia Palace in Ituren, Nafarroa; b) Clarisas convent in Salvatierra, Araba; c) *Caserío* Urdaneta-azpi in Legorreta, Gipuzkoa; d) *Caserío* Axura-Goiene in Lizartza, Gipuzkoa. Photos: Arkeolan Foundation.

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.

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

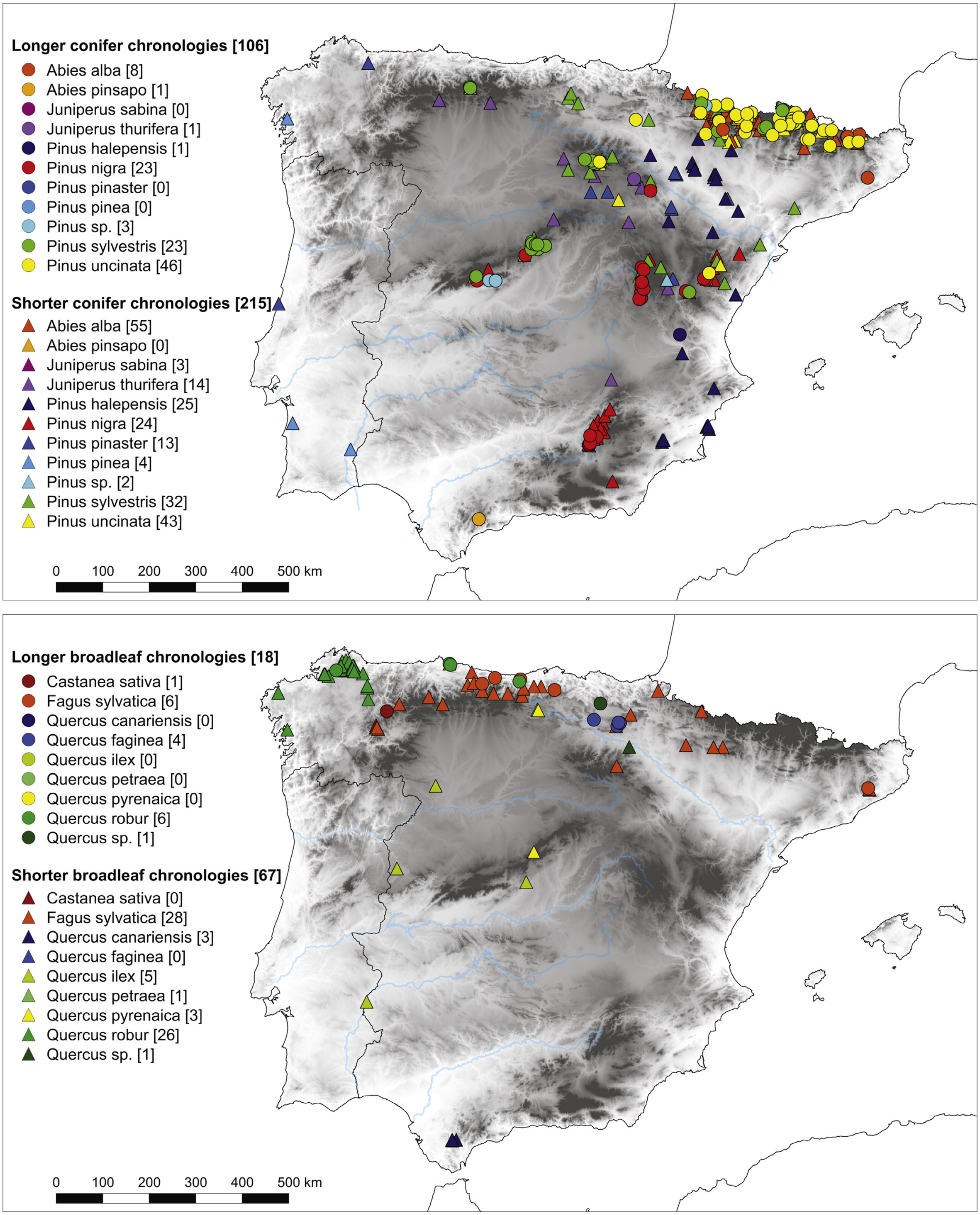

Fig. 6. Sites and species of tree-ring chronologies from living trees published up to date in the Iberian Peninsula. Only chronologies spanning from the present up to AD 1950 and beyond have been considered. They have been divided into chronologies reaching up to AD 1800 (shorter chronologies) and chronologies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

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 (Nailing 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.

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, focussing 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)

Fig. 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 by K. Vandenhole, courtesy of F. Castro). 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.

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.

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

Fig. 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.

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, 2002; 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, 2002).

The research of shipwrecks must be pursued under the premise that the wood may originate from anywhere, given that from the 13th century onward ships were also rented and bought from other nations such as Italy (Genoa), England and later on Holland (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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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2015.02.011.

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