Dendrochronological Provenance Patterns. Network Analysis of Tree-Ring Material Reveals Spatial and Economic Relations of Roman Timber in the Continental North-Western Provinces

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ABSTRACT

Over the last decades, Roman wood in various shapes and sizes has been excavated in the region of the continental north-western provinces of the Roman empire. However, it is often unclear whether wood has been transported. Most dendrochronological provenance studies rely on simple comparisons between tree-ring series based on a single similarity measure. In addition, most fail to consider the complex system of relations that is the result of the variables that influence tree-ring patterns. Network analysis is a solution to this problem, because it allows to both visualize and analyze the complex (provenance) relations of tree-ring series as a whole. A network makes it impossible to ignore existing (statistical) relations between tree-ring series. Although networks can be build using any (combination of) similarity measure(s), in this study a combination of the Synchronous Growth Changes (SGC), its related probability of exceedance (p), correlation (r) and overlap define the edges. This paper focusses on networks with site chronologies as nodes, although networks can also be constructed using individual tree-ring series or a combination with site chronologies. A combination of these can also help to refine the (archaeological) interpretation. The location of any tree-ring series in a network reflects its provenance. Material that is placed closer together in the network has similar growth patterns and is generally from the same region. Therefore, network communities reflect wood that has a similar provenance. If tree-ring material was found on different spatial locations, but in close proximity in the network, this indicates that wood has been moved. To determine which wood has been transported, a combination of archaeological and spatial arguments is used. The method is sound, simple and gives insight in the complexity of all tree-ring relations in a simple diagram. The resulting patterns show that most wood was obtained in the region where it was used, but that transport of wood in the Roman period did take place. Three scales are defined to describe the Roman wood economy: local, provincial and imperial. While transport of wood over long distances is attested for both military and civilian sites (provincial and imperial scale), it seems that wood that was transported beyond the provincial borders was only used in civilian sites (imperial scale). The combination of network science, dendrochronology and archaeology is a powerful method to understand patterns in the Roman timber economy.

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1 INTRODUCTION

Over the last decades, Roman wood in various shapes and sizes has been excavated in the region of the continental north-western provinces of the Roman empire. The wood has been found in a wide range of archaeological contexts and has originally been used and reused in a variety of constructions, such as forts, rural settlements, roads, villas and ships. Although the (re)use of wood is generally well known, the provenance of the wood is generally unknown. We often do not know whether the wood was procured locally or elsewhere. During the Iron Age the local population generally depended on local resources for their daily needs, although special materials such as amber or metals were obtained from other sources (Cunliffe 1999). This changed during the Roman period, when large-scale transport over significant distances can be observed for many materials. The scale of movement was unprecedented in the history of north-western Europe. In addition, various new materials from different regions were introduced. Archaeological evidence for resources that were procured elsewhere is wide-ranging, including grain (e.g. Pals and Hakbijl 1992), stone (e.g. Linthout, Paulick and Wijbrans 2009; Russell 2013b), glass (e.g. Degryse and Schneider 2008; Huisman et al. 2009; Rehren and Freestone 2015) and wine (e.g. Peacock 1978). On the other hand, recent research indicates that many natural resources could be obtained locally (van Dinter 2017; van Dinter et al. 2013, 2014). Wood is a resource that was both procured locally and obtained elsewhere, as has been shown for the road along the Roman *limes* (Visser 2015). Although some case studies deal with a selection of Roman timber (van Dinter et al. 2013, 2014; Domínguez-Delmás et al. 2014; van Lanen et al. 2016), a large scale integral analysis of the Roman wood economy in the Lower Rhine region based on all available dendrochronological material was not undertaken before.

This paper deals with the provenance of wood found in the north-western continental provinces of the Roman empire (*Germania Inferior*, *Germania Superior* and *Gallia Belgica*). Whether the procurement of wood from elsewhere was guided by necessity or opportunity is not dealt with in this paper, but has been discussed briefly elsewhere (Domínguez-Delmás et al. 2014; Visser 2015). Wood from an archaeological context has always been

moved, either within the vicinity of the find location or even over long distances. The only known provenance of archaeological wood is the archaeological context. To determine the original provenance of wood, the context is generally insufficient, but tree rings can help us to estimate the growth region of the trees. The width of each annual ring depends of many factors, such as soil, hydrology, temperature, sunlight and precipitation. These factors have been summarized in the linear aggregate model (Cook 1990). All growth factors have a spatiotemporal component, leading to a temporal, but more importantly geographical variation in tree-ring patterns (Ermich et al. 1976; Friedrichs 2008; Friedrichs et al. 2009), although one should always bear in mind that similarities over large distances can also be found (Bridge 2011; Ermich et al. 1976). By combining the archaeological context and find location with the most likely provenance of wood we can start to reconstruct the life cycle of the artefacts or ecofacts (LaMotta and Schiffer 2001: 21–24; Schiffer 1972).

Dendrochronological provenance studies of archaeological and historical wood are as old as the discipline. The fact that tree-ring patterns are influenced by regional factors was already acknowledged by pioneers in dendrochronology, such as the astronomers J.C. Kapteyn and A.E. Douglass, in the late 19th century and published in the early 20th century (Douglass 1909; Kapteyn 1908, 1914). While the first papers on dendrochronological research of archaeological wood in Europe generally focussed on dating (de Geer 1935; Huber 1941; Reinerth 1940), later studies also started to discuss the provenance of wood (Bauch, Liese and Eckstein 1967; Eckstein et al. 1986; Hollstein 1980). The focus has changed in more recent studies towards the provenance of wood, with dating only treated briefly as a necessary and basic aspect of the research (Daly 2007b; Domínguez-Delmás et al. 2014; Fraiture 2009; Haneca et al. 2005; Visser 2015). Most of these studies are based on a single similarity measure (often correlation) to determine the best match with regional or local chronologies (Daly 2007a; Domínguez-Delmás et al. 2014; Eckstein et al. 1986; Haneca et al. 2005; Hellmann et al. 2017; Hollstein 1980). Combining GIS research with the similarities of tree-ring patterns has also been proven useful in the determination of the original growth region of timber used in ships (Daly 2007b). However, all studies rely only on either the best match with chronologies or the (best) individual relation between two tree-ring patterns, often based on a single statistical variable, without considering the complex system of relations between all tree-ring patterns. If for example tree-ring series A matches with tree-ring series B, and C with A, there is an indirect link between B and C. However, it is nearly impossible to describe all matches using standard dendrochronological methods. Therefore, a different approach is needed to study the provenance of wood from historical and archaeological

contexts. This approach should depend on one or more similarity measures and at the same time should be able to visualize the complex system of relationships between tree-ring patterns.

Network science makes it possible to explore and analyse complex relations of combined similarity measures. While network analysis has been used for a wide range of applications (Barabási 2003; Boccaletti et al. 2006; Brughmans 2010; Collar et al. 2015), it has not been applied in dendrochronological research before. Networks are mentioned in dendrochronological studies (e.g. Babst et al. 2018; Fraiture 2009; Friedrichs et al. 2009; Piovesan et al. 2005), but only as a term to describe a geographically distributed collection of tree-ring material or simply said a collection of dots on a map (a nice recent example is: Rayback et al. 2020). In the current study, network analysis is used to detect, visualise and study patterns of relations between research objects (Albert and Barabási 2002; Boccaletti et al. 2006; Newman 2003). Network science is a broad field, which includes, but is not limited to, social network analysis, a sub-field that shares many methods and techniques. While the distribution patterns of the wood in this study are the result of human (social) activity, trees do not form social relations.

For the detection of meaningful groups in tree-ring series, clustering has often been used (Domínguez-Delmás et al. 2014; García-González 2008; Leuschner and Riemer 1989; Riemer 1994). Clustering has many advantages, but it relies strongly on individual relations and a single measure, without considering and visualizing the complex system as whole. The outcome of clustering of tree-ring material is defined by the choice of the common overlap or time interval (often a problem with archaeological or historical material) and a single similarity measure. Edges in a network can be created using more than one similarity measure, although the choices should be carefully considered. While clustering and network construction both rely on first-order relations, the latter visualizes all of them, including indirect relations of a higher order. Therefore, network analysis can overcome these shortcomings and enables a more integral approach to visualise and analyse all relations while retaining complexity.

A new method to explore all possible relations between dendrochronological samples or chronologies is presented. This method is used to assess the provenance of (archaeological) wood. It combines exploratory network analysis, GIS, archaeology and dendrochronology to estimate the provenance of archaeological wood. If we know where wood was procured and finally used, this helps to determine the life cycle of wood (*sensu* Schiffer 1972). A full(er) understanding of the whole process that combines all possible evidence should gain a better understanding of the Roman timber economy, which is

the final aim of this study.

2 MATERIAL

The data was collected to understand provenance patterns in the Lower Rhine region, especially the Netherlands. This area was in the Roman period part of *Germania Inferior* and had economic ties with other regions, both within and beyond the empire. Therefore data was obtained from various laboratories in the north-western continental provinces of the Roman empire. Material beyond the Roman frontier has also been included, since the *limes* has never been a border in the modern sense (Whittaker 1994) and material has moved well beyond. Various laboratories provided oak (*Quercus* sp.) tree-ring width measurements to the author and data from an international digital data library for dendrochronology, the DCCD (Jansma et al., 2012, currently: <https://dataverse.nl/dataverse/dccd>) was also available (Table 1, Figure 1 and supplementary table 1/1a). Most dendrochronological material was obtained from archaeological contexts (259 locations, 3006 samples) and a small subset originates from sub-fossil ‘natural’ contexts (20 locations, 241 samples). For some regions less material was available than for others and this has been addressed by adding published chronologies (Becker 1981; Hollstein 1972, 1980). The data is far from complete and has a spatial and temporal bias. There are many more tree rings available dating to the first century than for the fourth century (see histogram in Figure 1). For some regions no data was available to the author. Also, sampling strategies, or the lack thereof, before, during and after excavation, resulted in a strongly biased collection of wood and timber that was selectively subjected to dendrochronological research. Various factors, such as excavation locations, building activity, budget or simply chance, have therefore influenced the formation of the dataset. The research area is therefore partly defined and limited by the availability of data.

All tree-ring widths (TRW) were measured with a precision of 0.01 mm using a standard measuring table. For dating the TRW various software packages (CATRAS (Aniol 1983, 1987), TSAP (Rinn 1996) and PAST4 (Knibbe 2011)) were used by the original researchers. The mean series length is 106.1 with a standard deviation of 52.8. There are only 199 series with less than 40 tree rings, since dating short tree-ring series is not statistically significant. The dataset therefore consists of more or less mature trees. Through careful study of the dendrochronological material and the related contexts, the aforementioned selection bias in the dataset can be assessed. In addition to this, the large number of tree-ring samples from 259 find locations plus 60 site chronologies normalizes the

Figure 1 The find locations of the complete dataset (each data provider indicated with different colours). The published chronologies used are visualized as diamonds. The top-right histogram shows the number of available tree rings for the complete dataset (excluding published chronologies).

LABORATORY	COUNTRY	RESEARCHERS	SERIES	LOCATIONS	REMARKS
BAAC (Deventer)	Netherlands	S. van Daalen	59	9	
Centre Européen d'Archéométrie – University of Liège (Liège)	Belgium	J. Eeckhout, P. Hoffsummer, D. Houbrechts, P. Hoffsummer	135	8	
University of Freiburg, Chair of Forest Growth and Dendroecology	Germany and France	W. Tegel	1035	54	
Van Daalen Dendrochronologie (Deventer)	Netherlands	S. van Daalen	64	1	

(Contd.)

LABORATORY	COUNTRY	RESEARCHERS	SERIES	LOCATIONS	REMARKS
Labor für Dendroarchäologie – University of Cologne (Cologne)	Germany	B. Schmidt	439	8	From four places: Cologne, Koblenz, Oberaden & Xanten.
RING foundation (Amersfoort)	Netherlands and Belgium	Julia Borquez, S. van Daalen, M. Domínguez-Delmás, D.M. Duijn, H. van Enkevort, A.E. Hanraets, N. van Helmond, E. Jansma, U. Sass-Klaassen, P. van Rijn, T. Vernimmen, R.M. Visser, Y.E. Vorst	1933	172	Data includes measurement series that were collected institutes before the RING existed (Rijksdienst voor het Oudheidkundig Bodemonderzoek (ROB), supervision: J.A. Brongers (1986-1991) and University of Amsterdam (UvA/IPP), supervision E. Jansma (1985-1993))
Vlaams Instituut voor Onroerend Erfgoed (VIOE, Brussels)	Belgium	A. de Groot, K. Haneca	51	7	
Totals			3006	259	

Table 1 The different laboratories that provided their measurement series (oak) for the research.

bias, at least partly.

All research data is stored in a PostgreSQL (<http://www.postgresql.org>) database with PostGIS enabled (<http://postgis.net>). The GIS analyses were performed using PostGIS and Quantum GIS (<http://www.qgis.org>). R (R Core Team 2020) has been used throughout this research, relying on the many libraries, such as those in the Tidyverse (Wickham et al. 2019). All sources of the software are available on GitHub (<https://github.com/RonaldVisser/ProvenanceNetworks/>).

3 METHOD

The research steps are visualized in [Figure 2](#). The dendrochronological analysis starts with the individual tree-ring measurements on Roman wood. These measurements are manually grouped based on their matching dendrochronological patterns resulting in site chronologies (method in section 3.1). The contexts of the wood is also studied. All these data are stored in a database (see section 2). Networks are created based on the pair-wise comparison of tree-ring series. The following statistical similarity measures are used: the Synchronous Growth Changes (SGC) and its related probability of exceedance (p) (Visser 2021), overlap (n_{overlap}), and correlation (r). The SGC expresses the proportion of simultaneous annual growth changes between two tree-ring series. The correlation is calculated after a logarithmic transformation of the tree-ring series (Hollstein 1980). This approach combines a non-parametric measure of growth similarity (SGC) with a parametric measure (r) to get the best estimate of the similarity between two tree-ring series. These measures were calculated using dplR (Bunn 2008), which includes the SGC as of version 1.7.2. All comparisons between

tree-ring curves are also stored in the database. These are retrieved using selection queries to create the edges of the networks. The networks are analysed using standard methods from network science (see the end of section 3.2), including community detection (section 3.3). For the network analysis and visualisation the scientific open-source software Cytoscape (Shannon et al. 2003; Smoot et al. 2011) has been used in combination with the database, R, igraph library (Csardi and Nepusz 2006), RCY3 (Gustavsen et al. 2019), and other libraries. The interpretation of the networks in terms of provenance and economy is based on the networks, the spatial relations and the archaeological contexts (see the results in section 5 and 6).

3.1 GROUPING OF TREE-RING MATERIAL

Site chronologies were created after careful manual comparison of tree-ring curves for each find location using the statistical measures described in section 3 and a visual comparison. TRW-series from a single find location and with a similar (felling) date were often procured together and it is plausible that these series represent a similar provenance if the dendrochronological patterns are similar. Therefore, site groups were created based on their similarity. Material from the same find location but with different growth patterns was grouped in different groups. The resulting groups of tree-ring series were checked using COFECHA (Grissino-Mayer 2001; Holmes 1983).

For each group two chronologies were created, with and without standardization. While many methods for standardization exist (Cook et al. 1990; Hollstein 1980; Wigley, Briffa and Jones 1984), the incompleteness of archaeological material and the unknown provenance prohibits various methods (Briffa et al. 1992; Esper, Cook and Schweingruber 2002). Consequently, a

Figure 2 The research model of this study.

standardization that does not require any *a priori* knowledge of the material or provenance was used. The usage of both standardized and non-standardized material preserves different signals. Thus, for each site chronology two chronologies were created, using the following methods:

- C-chronologies are based on the default standardization incorporated in COFECHA (Cook 1985; Holmes 1983).
- M-chronologies are chronologies without any standardization.

The published chronologies used were standardized by the original authors (Becker 1981; Hollstein 1972, 1980). See supplementary table 4 for an overview of all chronologies.

3.2 DEFINING DENDROCHRONOLOGICAL NETWORKS

Networks were created with dendrochronological material as nodes and the edges defined by a combination of n_{overlap} , r , SGC and p of the pair-wise comparison of the dendrochronological material. These were stored in the database and selected for network creation. Since all relations are reciprocal the network is undirected, and duplicate edges have been removed. The networks were created using various levels of testing (as defined by Daly

2007b), resulting in nodes as:

- 1) Site chronologies
- 2) Site chronologies and trees
- 3) Trees

The use of various levels in dendroprovenance studies has proven its use (Daly 2007b). Network creation using these various levels makes it possible to discern and compare relations on each level. In addition, it also addresses the issues of moving between scales, as was pointed out recently (Babst et al. 2018). The use of site chronologies of material reduces the effect of single trees and enhances the local signal. The second level of testing results in a two mode network which can be transformed for further analysis (Opsahl 2013). Since some individual trees might not match with the material from the same find location due to a different growth region, level 3 is necessary for the interpretation of the results.

In this paper I will focus on the network of the first level of testing, with each node representing a single site chronology. The edges are based on the comparison of both the C and M chronologies. The other levels are often needed for the (archaeological) interpretation of the network. Initially the edges were selected from the database using $r \geq 0,5$, $\text{SGC} \geq 70\%$ with $p \leq 0,0001$ and $n_{\text{overlap}} \geq 50$ for each pair-wise comparison. Previous research has shown that wood from the same region

often show similarities well above these values (Visser 2006; Vorst 2005). To test these values the combination of thresholds for creating edges was varied, leading to four network-types:

- 1) $r \geq 0,5$, $SGC \geq 70\%$ with $p \leq 0,0001$ and $n_{overlap} \geq 50$;
- 2) $r \geq 0,5$, $SGC \geq 70\%$ and $n_{overlap} \geq 50$;
- 3) $r \geq 0,5$, any SGC with $p \leq 0,0001$ and $n_{overlap} \geq 50$;
- 4) A merged network of 2 and 3.

The resulting networks are described using standard variables, such as the number of nodes (N), the number of edges (E), the number of components and the diameter of the network (Δ). The average degree (K) describes the degree to which the nodes in the network are connected. The clustering coefficient of the network (C) is a measure to which degree nodes in the network cluster (Watts and Strogatz 1998).

3.3 COMMUNITY DETECTION

In each network communities are present. Communities are well connected parts of a network, in this case groups of tree-ring series that show strong similarity between each other, i.e. wood with similar growth conditions. Community detection can help to determine which material shows a similar pattern and groups in the network. The detection of communities is limited to the networks of site chronologies. Two different methods have been applied:

- Girvan-Newman-algorithm (GN), and
- Clique percolation method (CPM) (Palla et al. 2005).

The GN-algorithm uses the edge betweenness, i.e. the number of shortest paths between pairs of nodes that run along an edge. Edges with the highest betweenness are removed, since these connect the various communities (Girvan and Newman 2002). The step with maximal modularity was used to determine the cut-off moment (Newman and Girvan 2004). This was performed in R.

CPM is a popular approach for analysing the overlapping community structure of networks. This method was developed bearing in mind that communities consist of highly connected nodes. CPM finds communities using k -cliques, corresponding to complete, i.e. fully connected, sub-graphs of k nodes. For example, a k -clique at $k = 3$ forms a triangle. Communities are defined as a union of adjacent k -cliques. Adjacent cliques are cliques that share $k-1$ nodes. Therefore, if two cliques share less than $k-1$ nodes, the shared node(s) connect(s) the communities, without joining them (Palla et al. 2005). CPM was performed using an R-implementation (based on <https://github.com/angelosalatino/CliquePercolationMethod-R>)

Both methods for community detection have advantages and disadvantages and produce similar, but slightly different, communities for each network type. To benefit from both, a combination of the two methods

has been applied. The GN-algorithm generally leads to more nodes in a community than the CPM, but it ignores the possibility of overlapping communities. Patterns that might fit or connect regions can therefore placed in a single community by the GN-algorithm, whereas CPM can show that they are joining regions. CPM also helps to find which nodes might connect overlapping communities. This might indicate that these can be joined or that they might share some of the same properties since boundaries between the communities are not strict, but rather fluid. Overlapping communities are inherent to dendrochronological networks with edges created based on similarity measures, since growth conditions generally do not change abruptly. A more gradual decrease of the level of similarity is therefore expected if we move from one area to another. However, the incomplete and biased nature of the dendro-archaeological material leads to missing data and therefore incomplete cliques. By combining the CPM and the GN-algorithm these issues are better addressed.

4 DENDROCHRONOLOGICAL NETWORKS

In this section the resulting dendrochronological networks will be discussed. Before discussing the Roman networks, the validity of using networks for provenance studies needs to be assessed. For this purpose, tree-ring material has been used of which both the growth-location and the find-location are the same. After this, the Roman networks will be described and the communities present in these networks.

4.1 NETWORK ANALYSIS AND PROVENANCE DETERMINATION USING DATA FROM THE ITRDB

Since most material in the ITRDB (Grissino-Mayer and Fritts 1997; Zhao et al. 2019) is sampled directly from trees in the landscape and only a small proportion is obtained from archaeological wood or constructional timbers, it can be assumed that most locations in the ITRDB approximate the original growth location. This is therefore a very useful resource to test the validity of the method. As mentioned before, site chronologies are generally better suited for provenance determination than individual series. A few years ago, a collection of site chronologies based on the ITRDB has been published (Zang 2015) and made available as open data (<http://dendrobox.org/>; <https://github.com/cszang/dendrobox>). This dataset is not perfect, but is an available collection of site chronologies with known provenance. Some small adjustments were made to the original dataset. Four chronologies with duplicate ID's (CANA and CO036) could not be used, since it is impossible to discern which is which. For three sites the coordinates had to

be corrected (NM584, NM585 and UT530), because the decimal separator or the negative sign were missing. The countries of origin were retrieved using the country boundaries from Natural Earth Data (<http://www.naturalearthdata.com/downloads/10m-cultural-vectors/>). The coordinates of 29 sites pointed to a location outside of the country borders, which probably points to an error in the coordinates in the ITRDB (a site in Wales is for example located in the sea). The country and the continent were manually corrected for these sites. The locations were used nevertheless, since the spatial error seems to be reasonably small.

The species were initially ignored in the construction of the network. Only network type 4 has been created from the site chronologies built for Dendrobox. Material from the same species tends to cluster together, although strong inter-species links can also be observed. The network consists of 1470 nodes, 8604 edges and 193 components (Figure 3). Since the most material in the ITRDB is American, it is not surprising that the largest network component consists of tree-ring series from the USA. All components consist of material from the same continent. Neighbouring nodes in the network are nearly always from the same country or at least from neighbouring countries.

A kernel density estimate of the geographical distances

between nodes connected in the network shows that site chronologies generally have a relative close proximity of each other (Figure 4). The majority of the directly connected sites lie within 200 km from each other. The wide range of species in the dataset and the inclusion of both inter- and intra-species links, will also lead to connection of material sampled further apart. It has been showed before that some species, such as Silver fir (*Abies alba*), can show higher similarities over longer distances (Becker and Giertz-Siebenlist 1970; Müller-Stoll 1951). If we focus on single species networks of the most common species in the Roman data (Figure 1/ Table 1), differences can be observed with the used thresholds. Oak (*Quercus sp.*) is much less often connected, even over shorter distances, while Scots pine (*Pinus sylvestris*) or Norway spruce (*Picea abies*) exhibit higher similarities over larger distances (Figure 4). Therefore, if a provenance network is constructed for other species than (European) oak, probably other thresholds should be used than defined in section 3.2. It can be concluded that the aforementioned thresholds work well for creating a network that connects site chronologies of oaks (*Quercus sp.*) that have grown within the same geographical region. More importantly, the conclusion can be drawn that the location in the network is related to the provenance of the trees.

Figure 3 Network of the site chronologies from the ITRDB/Dendrobox (Zang 2015). On the left the nodes are coloured by continent on the right by species (for convention of species codes see Grissino-Mayer 1993).

Figure 4 Kernel density estimation of the geographic distances between nodes in the network (4) of site chronologies from the ITRDB (based on data from Zang 2015). On the left all species are shown, on the right only selected species. The selected species are *Abies Alba* (ABAL: 49 site chronologies), *Pinus Sylvestris* (PISY: 127 site chronologies), *Picea abies* (PCAB: 117 site chronologies) and *Quercus* sp. (QUSP: 67 site chronologies). The selection is made based on the frequency in the Dendrobox-dataset and the most often dendrochronologically analysed European tree species from archaeological contexts dating to the Roman period (see also Visser 2015).

4.2 GROUPING MATERIAL PER FIND-LOCATION

The grouping and manual analysis of the Roman tree-ring material resulted in a dataset without duplicate series, since each tree is only represented by a single tree. In addition various site chronologies were created.

While the majority of the TRW-series are single measurements of an individual tree, some trees are represented by multiple samples and therefore TRW-series in the dataset. These are replaced by an average tree series. Measurements are considered to originate from the same tree if $r \geq 0.6$, $t \geq 9$ and $SGC \geq 75\%$ with $p \leq 0.001$, and with a low mean Euclidean distance (MED) (Visser 2015). The latter was used as an extra indicative measure. Furthermore, a visual match should concur with the statistics. The majority of the trees are represented by only two measurements, but some with more, with an extreme of 12 measurements from a single tree (Figure 5). In total 591 TRW-series were replaced by 198 averaged tree curves in the dataset (supplementary

table 2). All TRW-series that represent a single tree will be referred to as a Tree Series (TS).

The grouping of all TS resulted in the creation of site chronologies of 190 groups of TS ($n = 2755$). The majority of these groups consists of oak material, but site chronologies for ash, silver fir, elm and spruce were also created (Table 2/Figure 6). This paper will further focus on the oak material. The material of 23 sites was

	SITE-GROUPS	TREES
Oak (<i>Quercus</i> spp.)	178	2607
Ash (<i>Fraxinus excelsior</i>)	9	84
Silver fir (<i>Abies alba</i>)	7	32
Elm (<i>Ulmus</i> spp.)	2	28
Spruce (<i>Picea abies</i>)	1	4

Table 2 The number of site-groups created.

Figure 5 Histogram with the number of measurements per tree.

Figure 6 Find locations of site chronologies (both published and my own) and material that was not grouped.

grouped in multiple site chronologies per site (mostly two or three chronologies per site, see supplementary table 3 for TS per group and supplementary table 4 for the locations). The material from Valkenburg01 could even be grouped into five different site chronologies. This shows that, although sometimes over a long period of time, wood with different growth patterns and therefore different provenances was sometimes used on a single location. The material of several sites could not be grouped. This was due to the fact that some sites were only represented by a single TS. In some cases, the material from a single context proved to have different tree-ring patterns or was dated to different periods with little overlap. These discrepancies can be attributed the

life cycle of the objects in their systemic context, due to the influx of wood from various regions on a particular site, or due to selective sampling.

4.3 GENERAL DESCRIPTION AND INTERPRETATION OF THE NETWORKS

Table 3 presents an overview of the four types of networks for site chronologies, individual trees and the combined network of chronologies and trees. All duplicate edges were removed. As can be expected, the network created with the strictest thresholds consists of the smallest number of nodes. Network type 4 on the other hand is better connected and has more cliques.

	CHRONOLOGIES				TREES				COMBINED			
NETWORK-TYPE	1	2	3	4	1	2	3	4	1	2	3	4
Components	7	10	5	6	107	35	98	38	44	23	44	22
N	130	151	155	171	1255	1741	1331	1778	1551	1794	1680	1927
E	214	287	407	486	2175	5048	2664	5529	2150	3508	2634	4113
C	0,224	0,256	0,376	0,360	0,193	0,168	0,212	0,185	0,000	0,000	0,000	0,000
K	3,552	4,266	5,542	6,064	4,088	6,037	4,642	6,505	2,934	4,034	3,306	4,399
	14	12	12	11	29	20	27	19	22	16	16	16

Table 3 The network variables describing oak network types 1-4 for site chronologies, series and the combined networks of chronologies and series.

Figure 7 The degree distribution of the networks of site chronologies on the left and the network of measurements series on the right. All exhibit a power-law distribution.

All networks exhibit a power-law degree distribution as the Kolmogorov-Smirnov test of the power-law fit resulted in values generally below 0.5 with larger p values (Clauset, Shalizi and Newman 2009). The power-law degree distribution is an indication for a scale-free topology (*Figure 7*). This means that the majority of the nodes are connected to a few other nodes, while a minority forms well connected hubs (Barabási 2003; Barabási and Albert 1999). The clustering coefficient exhibits no power-law relation, excluding the possibility of a modular scale-free network (Ravasz and Barabási 2003; Vázquez, Pastor-Satorras and Vespignani 2002).

The presence of a scale-free topology reflects how growth patterns are connected. This has several consequences for the study of tree-ring patterns. Foremost, the presence of hubs illustrates that the relation between similarity of a tree-ring pattern and distance is not as linear as often assumed, otherwise the links would be more evenly divided over the material and a random network would emerge (Erdős and Rényi 1960). Hubs strongly influence communities in the network. They can either form the centre of a community or connect different ones. Furthermore, the scale-free nature also

explains why some material is more easily dated than other material. It also shows the importance of sampling multiple pieces of wood from an excavation. The chances of sampling and measuring tree-ring patterns of wood with the most general pattern are equal to sampling those with only a few connections. Considering a tree with a degree of 10 or more as a hub, this would mean that about 6.4% of the trees in network type 1 are hubs. The undated material in the dataset used amounts to about 25%, indicating that about 4.8% of all measured dendrochronological material will be a hub. About 57.7% of the dated trees in the network type 1 has a degree of 1 or 2. The large proportion of trees with a low degree in the network(s), clearly shows how important it is to take and study as many samples as possible from a site.

The presence of hubs has a spatial component and influence on provenance studies. On the one hand, it is interesting to note that most hubs in the networks are found with oaks found in northern France and Germany. The material from this region seems to match with higher similarity than material with a more northern find location. The proportion of hubs in a network of trees or chronologies can therefore indicate their provenance. On

the other hand, the promiscuous behaviour of a tree that acts as a hub in the network, can have negative influence on the determination of the provenance. The material used to build a water well in Venlo (Schotten 1994, 1995; Schotten and Machiels 1994) functions as a hub. In an earlier study, this material was used to create groups (Visser 2006). However, their promiscuous nature can also lead to combine materials from different regions or network communities. An example of this can be found in several studies on Dutch datasets where hubs are not recognized as connectors, but as incorrect indicators for provenance (Jansma, Haneca and Kosian 2014; van Lanen et al. 2016), leading to results that will need re-evaluation. The effect of hubs of individual series can be tempered by averaging them with material from the same context, or using site chronologies. Hubs should therefore be treated with extra caution for provenance studies, but can be useful for connecting regions.

Although well-connected hubs are often found in networks, they can also be indicative of mistakes. In an earlier stage, most material from Oss-Ussen was grouped together into a single site chronology. This chronology functioned as a hub within the network of chronologies, joining material that did not seem to match. After considering the grouping of the material from this find location, the initial grouping included too much material. A new evaluation of the tree-ring series from this find location indicated that the material should be placed

into two different groups. After correcting the mistake, the hub was gone and the different provenances were better reflected.

The degree of the nodes in the networks is more or less related to the geographical distance between the find location of the wood. This also concurs with earlier conclusions (e.g. van Dinter et al. 2013, 2014; Hanson 1978; Visser 2006, 2015) that the majority of the Roman wood and timber was obtained and used locally, but in specific cases wood was transported over longer distances. Histograms of the spatial distances of nodes in the network clearly show that the larger the degree, the larger the spatial distances (*Figure 8*). The spatial distances first-degree nodes peak within 150 kilometres, but the peak moves toward the larger distances for larger degrees. This clearly shows that wood was generally used in the region where it was found, but also that wood could be transported over longer distances.

4.4 COMMUNITIES OF OAK

Various communities were discerned. The number of communities, and nodes being placed in a community, vary not only for the CPM and GN, but also for each network type (*Table 4*). Whereas application of the GN-algorithm leads to many communities incorporating all nodes (*Figure 9*), CPM places a selection of well-connected nodes in fewer communities (*Figure 10*). There is a linear dependency of the number of nodes and edges

Figure 8 Histograms showing the count of distances between nodes, faceted per network degree for network type 1 (site chronologies).

in the network and the number of nodes being placed in a community by CPM. The communities found with CPM are much more strongly connected and the smallest community is dependent on k , therefore no communities with less than 3 nodes are found. The GN-method on the

other hand results in a number of communities with only 2 nodes. The largest clique size for the various network types varied between $k = 4$ for network type 1 and $k = 8$ for network type 3 and type 4, but only with $k \leq 5$ multiple communities were found in all network types. This is

NETWORK TYPE	GN	CPM					
		$K = 3$	$K = 4$	$K = 5$	$K = 6$	$K = 7$	$K = 8$
1	19(130)	8(61)	4(29)	2(10)			
2	19(151)	7(76)	5(41)	2(15)			
3	14(155)	7(110)	6(68)	3(39)	1(22)	1(10)	1(8)
4	15(171)	8(122)	8(86)	3(42)	2(29)	1(13)	1(8)

Table 4 The number of communities and, between brackets, the total number of nodes in communities that were found in the networks of site chronologies using the Girvan-Newman algorithm (GN) and the Clique Percolation Method (CPM).

Figure 9 Communities as detected by applying the GN-algorithm in the network of means (network type 4).

Figure 10 Communities as detected with the CPM for network type 4 (upper left: $k = 3$, upper right: $k = 4$, lower left: $k = 5$, lower right: $k = 6$).

most likely due to the incompleteness of the dataset and formation processes.

Various communities found both with CPM and GN bear strong resemblance, the full list is included in supplementary table 5. Both community finding methods produce similar, but slightly different, communities for each network type. It should be noted that the boundaries between the communities are not strict, but rather fluid. This is in concordance with the gradual changes in environmental conditions in North Western Europe. Some communities might be split into smaller communities, for example CPM-communities found with $K = 3$, divide into smaller ones with $K = 4$. Network-type 1 leads to smaller communities, while network-type 4 leads to larger ones.

The combination helps the understand the possibilities. Therefore, it is important to consider both community-detection methods and to study the combined results carefully.

5 PROVENANCE OF THE MATERIAL

The main problem when provenancing wood from an archaeological context is the large number of unknown variables in both the natural and systemic context. The biased nature of the dataset does not allow the use of strict variables defining the provenance. However, when various factors combined are taken into account, regions and areas of provenance can be discerned. These factors

are:

1. Matches between tree-ring patterns and place in the network;
2. The communities discerned in the networks;
3. The comparison of the network and spatial distribution of the find locations, considering the possibility of transportation of wood;
4. The relation between spatial distribution of the find locations and the landscape, including factors such as elevation or soil;
5. The contexts or structures that yielded the material;
6. The type of conversion that the wood has undergone in the past;
7. The level of organization behind timber procurement;
8. The temporal distribution of the material with special attention to similar felling or germination dates;
9. Common signals within the dendrochronological pattern of the material, for example long periods of reduced or increased growth (e.g. Kooistra, van Rijn and Sass-Klaassen 2006).

Network communities are indicative of material with similar growth conditions and most likely share the same provenance. The next logical step is to compare the spatial location of the wood with the location in the network. The networks can be visualized on a map, but with the nodes placed in the geographical find location (spatial network). The differences with the analytical network (e.g. [Figure 10](#)) might be caused by movement of wood. When first neighbours in the network are also geographically close, it is an indication of a similar provenance. If a node forms a close neighbour in the network to a site that is geographically distant, this can indicate transport over a larger distance. This

can be illustrated by an example in [Figure 11](#). The community GN_3 in network type 1 is highlighted with blue diamonds. The analytical network on the right shows this community as central in the network that connects many site chronologies. The majority of the archaeological wood in this community was found during excavations in a region that was situated in the Roman province *Germania superior* or the southern part of *Germania inferior*. This can also be seen in the spatial network on the left, but this also shows that some material was also found in more northern regions, in the west of the current Netherlands. Since the dendrochronological patterns strongly match, a similar provenance can be expected. The material in GN_3 excavated downstream along the lower Rhine was mainly used to build towns or other civilian buildings, but not in rural settlements. These civilian contexts and their downstream locations justify the interpretation that the material was moved from the more southern region, supporting the results of an earlier study (Dominguez-Delmás et al. 2014).

Based on the detected communities (both GN and CPM) in all four network types, with consideration of the spatial networks and the other factors mentioned above, several provenance groups have been discerned:

- NL_Bog
- NLB_Sandy (Southern Netherlands and Western Belgium)
- NL_Eastern
- Corbulo
- ROMLIMES
- NL_Sand_Mid
- NL_West
- Germania Superior

Figure 11 The community GN_3 in network type 1 with the analytical network on the right and the spatial network on the left.

Figure 12 Provenance groups projected on the different GN-communities, network type 4 (see also [Figure 8](#)).

- Gallia Belgica (East)
- Alsace
- Gallia Belgica (North East)
- Late Roman (NL)

These provenance groups are visualized in [Figure 12](#) (based on [Figure 9](#)). The grouping is dynamic and no strict boundaries exist, with some hubs in the network connecting groups. Based on the location in the analytical and spatial network the most probable provenance of the material can be determined. It should be noted that some groups carry the name of the contexts that makes up the material. The strong grouping of material that has been published as ROMLIMES earlier (Visser, 2015), is clearly present in all network types. Although different methods were used, the results are similar. The use of

networks, however, makes grouping and provenance much more easy and transparent. NL_Bog is a group of bog oak material found in an area around Amsterdam. Corbulo consists of material that was used for the revetments of the *Fossa Corbulonis* (Kort and Raczynski-Henk 2014). The connection to the coastal material from Western Belgium is logical with a local provenance, but its separate location in the network shows that it has some distinct attributes. The material in NLB_Sandy was excavated from Pleistocene sandy soils in the Netherlands and Flanders. The material matches well, but may be split into two groups (Southern Netherlands and Western Belgium, including the coastal region). The strong similarity within this group does not justify any strict division. Therefore the material is interpreted as one group with two subgroups with the location of

a site within the network indicating the provenance. The network indicates the strong connections between the material and indicates the provenance. Without a network this complex pattern of connections is easily overlooked leading to incorrect provenance attributions (as done by Jansma, Haneca and Kosian 2014; van Lanen et al. 2016), leading to incorrect (historical) conclusions. The Late Roman group is a somewhat strange group. Due to the lack of overlap with most material no clear provenance can be estimated. If future research yields more late Roman material, it will be better possible to determine its provenance.

The network and the communities/provenance groups show that regions that are geographically close are often also situated closely in the network. This is in concordance with the expected gradual changes in environmental conditions in general. In some cases

we see that this is not the case, this generally points to transport of wood over longer distances, although there can be strong differences in the growth signal due to, for example, abrupt soil changes or altitudinal differences. The long time period that is included in the network also leads to some temporal trends in the network(s). New material will alter the network, but it has been observed that changes in the material do not lead to large changes. New material will fine-tune some of the observations, but the robust and integral approach will safeguard the quality and sustainability of the results.

6 THE ROMAN TIMBER ECONOMY

The networks also shed light on the Roman timber

Figure 13 Network (type 1) with nodes coloured using a typology of sites, with the categories military, civilian, religious, natural and unknown/unclear. Military clusters are marked in transparent green.

economy. Each node can be characterized based on their context. **Figure 13** shows the nodes coloured using a simple typology of sites. The following types are discerned: military (e.g. forts, fortresses), civilian (e.g. rural settlements, towns, villas), religious (e.g. temples, sacred places), natural (e.g. sub-fossil material). These are not always mutually exclusive, but the most fitting type is chosen.

The network shows some grouping of the military sites in the network. One of these groups matches the ROMLIMES material that was used to build the military *limes*-road in 124/125 CE (Visser 2015) and the other (upper group in **Figure 3**) is material used in forts (amongst others Velsen [Bosman 1998] and Alphen aan den Rijn [Polak, Kloosterman and Niemeijer 2004]), the canal of Corbulo (Hazenbergh 2000) and various revetments (e.g. Graafstal 2000; Luksen-IJtsma 2011) in the western parts of the current Netherlands. This wood was locally obtained and used within the region. The ROMLIMES material on the other hand was obtained elsewhere and transported over more than 100 kilometres to be used in the same region as the other group. There is also a smaller network component of only military material studied by Becker in the early 1980's (Becker 1981). The material comes from Rainau Buch (waterwell in military *vicus*), Mainhardt (water well in military *vicus*) and Schwabsberg (*limes*-palisade). Schwabsberg en Rainau are situated only a few kilometres apart, but Mainhardt

is over 50 kilometres away. The military personnel may have made use of the same woodlands or region for their timber procurement. The pattern of clustering of some military material might point to woodlands being exclusively available to the Roman army, while there are also regions where soldiers and civilians made use of the same resources. Whether these were specialized troops, such as the *vexillationes agentis in lignariis* that are known from the early third century (Herz 1985), soldiers tasked with timber procurement (Wierschowski 1991), or civilians (for example a *materiarus* [CIL 13, 7553]), remains speculative. The procurement of timber for military use seems to be limited within the provincial boundaries, which is in concordance with the military stone procurement (Bauchhenss 1986). The provincial boundary may also have been the legal limit of the army of a province (Vittinghoff, 1994, 1974).

The material from both civilian and religious contexts is found everywhere in the network. It is striking to notice that material found in a civilian context was obtained from all possible places. The norm seems to be local procurement, but there is also evidence for material procured beyond the provincial boundaries, such as used in Forum Hadriani, currently Voorburg, (partly published in Domínguez-Delmás et al. 2014) or wood used for a bridge in Maastricht (Vos 2004).

The above is summarized in a model for the Roman timber economy (Figure 14). The model shows that wood was generally obtained and used locally or

Figure 14 A model to describe the Roman timber economy in relation to provenance of wood.

regionally, say within a radius of 25 to 50 kilometres. This is attested in all types of sites. In the Roman period some wood was obtained within a larger region, but confined within the provincial boundaries, which can be described as the provincial wood provision and generally within a 100–120 kilometre radius. This also holds for all type of sites. The third group is wood that was obtained in areas far from the site where it was found. This can be characterized as the imperial scale, or beyond the provincial boundaries. It is interesting to note that there are no military sites in the dataset that show this kind of provenance. Timber provision on an imperial scale therefore seems limited to civilian use. The amount of transported material seems to decrease with increasing distances, although not necessarily linear. There is also a temporal pattern that underlies the model. While the local provenance can be found in the full Roman period, procurement from elsewhere seems to start around the beginning of the second century, at least from 125 CE onward (Visser 2015), but the import over larger distances only starts in the second half of the second century CE. Whether the increasing import is related to depletion of local woodlands remains unclear, since local wood sources are used as well and other materials also show a decline over the whole Roman empire during this period (e.g. Bowman and Wilson 2009; Russell 2013a; Scheidel 2009). In addition, there is also an increase of stone as building material in the same period (Buijtendorp 2010; Haalebos 1977; Polak, Kloosterman and Niemeijer 2004; Precht 1989; Vos and Hingh 2005). The histogram in [Figure 1](#) also shows that there is less dendrochronological material available from the second century onwards, seeming to point to less wood use, or at least to less dateable material. Future research may fill this gap. The current data show that local wood procurement was the norm, only in specific cases wood was transported over long distances, and only for civilian contexts from beyond the provincial borders ([Figure 14](#)).

7 LIMITATIONS AND POSSIBILITIES

From the above it becomes clear that network analysis is a powerful way to explore, find and visualize patterns within tree-ring material. It makes it easy to determine the provenance of timber if a large enough dataset is available. If the current dataset would be expanded spatially, this will most likely make the provenance more accurate and/or enhance our understanding over the movement of wood in a wider region. If, for example, data from Britain were added, it becomes possible to study the transport of wood overseas. However, this is beyond the scope of this paper and will be an interesting avenue for future research.

The network approach is much more transparent than other methods that have been applied in other dendroprovenance studies. The networks are built using clearly defined thresholds and show all matches, rather than finding the best match and using that to define the provenance. The thresholds used for this study were useful, but these can be varied for different regions or different species. It might even be enough to only use network-type 1 and/or 4. The method is very flexible in the choice of nodes, addressing issues of scale within dendrochronological data. However, networks of individual samples or trees can be tricky. A single sample can act even more strongly as promiscuous tree-ring series than an averaged mean chronology. It is therefore important to know the context of the samples and the site. The complexity of all matches shown as a network of relations provides a sound visual and statistical basis. The various network types used are useful, although the first type gives the strictest indication of the provenance, while the other types can help to understand the patterns and/or include more material for a better understanding.

It would be useful to build similar network for other periods, such as the Medieval or Early Modern period. However, this would mean that site chronologies need to be created manually before networks can be constructed. In addition, the amount of available data is a limiting factor. To build a graph at least two nodes are needed, but to determine patterns more nodes are needed. Three nodes make it possible to create at least one CPM-community ($k = 3$) if the network is complete. One could state that there need to be at least 10 nodes to start determining patterns with site chronologies, with enough temporal overlap (for the current study 50 years or more). For each site, at least 5 timbers should be analysed dendrochronologically per archaeological structure and phase, although more is preferable, since not all material will be dateable. Generally speaking a success rate of 70% can be obtained, although this depends of the amount of material available in a certain region.

8 CONCLUSION

The paper shows that networks can be used to explore and study the relation between tree-ring series in order to understand the provenance of archaeological wood. The use of both standardized and unstandardized material leads to the creation of robust networks. The network approach provides a robust exploratory approach that enables both archaeologists and dendrochronologists to discern patterns of matching material, even when sparse data is available to construct a network. One should especially pay attention to material that forms

a hub. A hub can be indicative of either strong grouping, or of promiscuous tree-ring series. The latter can lead to wrong groupings and therefore wrong provenances. These promiscuous tree rings should therefore always be treated with care and analysed carefully. The network can thus function as both an analytical and control tool. The use and combination of two methods for community detection proved valuable and resulted in dendrochronological groups. These groups are more sound than the result of (hierarchical) clustering, since clustering is strongly influenced by promiscuous matching series (hubs). In addition, the diversity of (indirect) relations is taken into account in the networks, which is impossible in traditional clustering. The provenance of these communities in the network can be determined by taking various factors into account, amongst others the geographical location, soil, formation of the archaeological record and the contexts of the material. New material might be added to the networks in the future, but it is expected that this will not overthrow the current interpretations.

The spatial and analytical networks of archaeological tree-ring material create transparent insight into the Roman timber economy and prove that the majority of wood and timber in the Roman period in the Lower Rhine Area was obtained and used regionally, but that there was also some wood transported over long distances. A model can be used to understand the scales of provenance in the Roman timber economy: local, provincial and imperial.

ADDITIONAL FILE

The additional file for this article can be found as follows:

- **Supplementary Tables.** Supplementary tables 1 to 5. DOI: <https://doi.org/10.5334/jcaa.79.s1>

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COMPETING INTERESTS

The author has no competing interests to declare.

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