Pith location tool and wood diameter estimation: Validity and limits tested on seven taxa to approach the length of the missing radius on archaeological wood and charcoal fragments

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Abstract

The study of timber wood and wood charcoal fragments from archaeological sites (aka anthracology) constitutes a relevant archaeobotanical field of research for both landscape reconstruction and the study of past people-woodlands interactions. Regarding this second research field, variables other than taxa are known to be a key to the social organization of woodland management. In this sense, wood diameter constitutes a core factor of fire management, fuel provisioning and both firewood and timber procurement. These wood uses are most commonly represented in the archaeological record by charcoal fragments (both dispersed in the sediment and/or concentrated in fire structures) due to the fact the wood experiences both mass loss and fragmentation during carbonization. So the original form of the wood used (trunk, branch, twig) is no longer recognizable. Different pith-location tools (PLT) have been proposed previously in order to virtually locate the charcoal fragment in relation to the central part of the stem or trunk (pith) where the used wood originally came from. Among them, PLTs based on trigonometry are proven to be the most reliable, but have not yet been

extensively tested on referential datasets in order to establish reliable analysis of the accuracy of the measurement of the missing radius, margins of error and correction factors. In this study we present an experimental referential dataset for 7 different taxa, both angiosperms and gymnosperms. The first aim was to move forward on the establishment of the trigonometric tool by testing if it is also suitable and valid for all the woody species producing tree rings. The second purpose was to provide a ready-to-use tool to estimate the missing radius with an interval of confidence. Lastly we also tested the effect of the carbonization on two taxa. According to the results obtained, a measuring protocol, correction factors and guidelines to interpret the subsequent results are established. In addition, an R function is now available to estimate the real radius from the calculated one with PLTs.

Keywords: wood pith location; referential datasets; software; dendro-anthracology; wood diameter estimation; firewood and timber exploitation

Introduction

Wood diameter constitutes a social selection criterion as relevant as species, whether to manage a fire according to the uses of the hearth or to select timber for construction or woodworking as shown by diverse ethnoarchaeological studies (Zapata Peña et al., 2003; Dufraisse et al., 2007; Picornell-Gelabert et al., 2011). The carbonized and fragmented residues of this use of wood as firewood or timber are most often preserved in the archaeological record (charcoal fragments dispersed on the sediments and/or concentrated in fire structures, such as hearth and ovens). Wood experiments both mass loss and fragmentation during carbonization, so the original form of the wood used (trunk, branch, twig) is no longer recognizable. This fact makes it difficult to archaeologically evaluate the role of the wood diameter as a selective criteria of wood uses and woodlands management by past human societies.

In recent years, new measurement techniques have been developed in order to estimate the diameter of the wood from which the archaeological charcoal fragments originates. One of the main research fields in this sense is the establishment of reliable techniques to measure the distance between the preserved archaeological charcoal fragment and the pith of the trunk/branch where the fragment comes from. This measurement technique consists of virtually positioning a charcoal fragment in relation to the central part of the stem or trunk (pith), which is missing in most of the cases (pith-location tool, PLT). This measurement constitutes a necessary first step to latter estimate the original diameter of the wood exploited in the past (Dufraisse and Garcia-Martinez, 2011).

Different "naked-eye" methods guided by a printed graduated target and based on tree-ring boundary' morphology (ring curvature) were proposed to estimate the length of the missing radius (Applequist, 1958; Willerding, 1971; Lundström-Baudais, 1986; Ludemann and Nelle, 2002; Rozas, 2003; Dufraisse, 2005; Marguerie and Hunot 2007).

Later on, experimental research was set up to evaluate two techniques of measurement using image-analysis software. The "circle tool technique" is one of them, initially proposed by J. Chrzavzez (2006) and based on the curvature of tree-ring boundaries. Another tool tested, the "trigonometric tool", is based on the measurement of angles and distance between ligneous rays, proposed by A. Dufraisse and developed together with S. Paradis-Grenouillet and M.S. Garcia-Martinez (Paradis-Grenouillet et al., 2013; Dufraisse and Garcia-Martinez, 2011). These studies were developed on different taxa, *Quercus petraea*, *Pinus halepensis* and *Fagus sylvatica.* They showed that measurements of the radius of curvature based only on the curvature of the tree-ring boundaries must be avoided due to the fact that calculated missing radius did not correspond to the real radius.

On the contrary, the estimation of the missing radius on the 3 taxa tested (*Quercus petraea, Fagus sylvatica* and *Pinus halpensis*) with the trigonometric tool (angle and distance between ligneous rays) in a right-angled triangle provides relevant results:

i) Strong correlation exists between the exact value of the length of the missing radius (real radius, RR) and its measurement (calculated radius, CR);

ii) Other trigonometric techniques, such as Thales' theorem and trigonometry in an isosceles triangle, provide similar results (Paradis-Grenouillet et al., 2013).

Building on this previous research, the aim of this study is to move forward on the establishment of the trigonometric tool by testing if it is also suitable and valid for all the woody species producing tree rings and to provide a ready-to-use tool to estimate the missing radius with an interval of confidence. To do so we establish an empirical reference dataset for seven different taxa with different wood anatomy (both conifers and angiosperms) and commonly identified in archaeological charcoal spectra in Europe. We later compare the relative errors between species according to 1) the angle and the distance between the two ligneous rays 2) and the diameters.

As the Pith Location Tool (PLT) is mainly applied to wood charcoal fragments, we also investigate the effect of the carbonization, which induces deformation (distortion of shape and shrinkage), on the efficiency in evaluating the missing radius with the PLTs.

Materials and methods

The referential dataset was developed in the framework of the DENDRAC project "Development of DENDRometrical tools used in anthrACology: study of the interactions between man, resources and environments" funded by the French National Agency of Research (http://dendrac.mnhn.fr/). This program follows key experimental principles to allow relevant subsequent comparisons of the data obtained, mainly the use of common protocols for all the different taxa and a restricted number of operators.

Measurement tools and materials

All the measurements were performed using the NIS Element image-analysis software developed by Nikon. The NIS Elements software was associated to a Nikon camera assembled to a multizoom microscopes (Nikon AZ100) with objectives covering a diverse range of magnifications (from x5 to x400) and to a binocular stereo microscope (Nikon SMZ 745, x6 to x50). Different PLTs based on trigonometric principles were tested. They are all based on the acquisition of two measures at the same ring boundary: 1) the angle between two ligneous rays and 2) the distance between the same two ligneous rays. These measurements allow estimating the length of the missing radius (this is, the distance between the ring boundary measured and the missing pith).

The first PLT is a manual one, based on the trigonometry in a right-angled triangle and involving 12 landmarks fixed by using the NIS element software. The measurements were carried out under a binocular stereoscope with x10 magnification and a measurement field of L0,84 cm x h0,63 cm, compatible with small fragments often found in archaeological charcoal assemblages.

The second PLT is a semi-automatic method based on 4 landmarks, which is less time-consuming and more adapted to a routine use. Based on the trigonometry in an isosceles triangle, it was tested under the multizoom microscope with an objective of x0.5 magnification and digital zoom (e.g. measurement field dimensions with the lowest magnification: L 2,2 cm x h1,7 cm).

The two PLTs (manual and semi-automatic) were tested on perfect targets printed on white paper. The referential based on fresh and carbonized wood slices was realised with the manual PLT and completed with the semi-automatic PLT.

- Perfect target

The PLTs were first calibrated on perfect targets with a range of radius between 0.5 cm and 17.5 cm (i.e. range of diameter : 1;2;3;5;10;12;15;18;20;25;30;35 cm) and angles between 2 and 70°.

For each method of measurement (manual and semi-automatic), from 25 to 30 measures were carried out according to radius and angles, e.g. 1320 measures / method and 2640 measurements in total (Table 1). In some cases (see * in Table 1), measurements could not have be taken due to either the dimension of the measurement field or printing problems with the target especially between 0.5 and 1 cm of radius and small angles (2° and 4°).

- Fresh wood

Seven taxa with different anatomical characteristics (Angiospermae vs Gymnospermae, presence of uniseriate and/or multiseriate rays, ring porous/diffuse wood, etc.) were studied: Gymnosperm: *Pinus halepensis* (uniseriate rays)*;* ring porous Angiosperms*: Quercus petraea* (uni- and multiseriate rays)*, Castanea sativa* (uniseriate rays)*, Fraxinus excelsior* (2-3 seriate rays)*, Ulmus minor* (3-5 seriate rays)*;* diffuse porous Angiosperms*: Fagus sylvatica* (multiseriate)*, Prunus avium* (3-5 seriate rays). As far as it was possible, from one to six wood slices from different trees coming from different locations were analysed for every taxon to record a maximum of variability (excepted for *Ulmus, Prunus* and *Castanea*). Measurements were performed on fresh wood slices after a fine sanding of the surface. A total of 4164 measures were carried out (see the total number of measurements in Table 2).

- Carbonized wood

In order to evaluate the PLT on carbonized wood slices, we measured before and after carbonization two of the studied taxa: *Pinus halepensis* and *Fagus sylvatica* (Table 2). Two wood slices for *Pinus* (R1, R2) and one for *Fagus* (R13) were carbonized in a muffle furnace at 300°C during two hours according to its thickness. The measured shrinkage fluctuates from

14.7% (slice R2, 14,5 x 13 cm) to 15.38% (slice R1, 16,5x 16,4 cm) and is about 20% on *Fagus sylvatica* (R13). In total, 720 measures were carried out on this carbonized material (Table 2).

Data Treatment

The PLT we provide consists in producing an estimation of the real radius (RR) given the calculated radius (CR). For each measure, we registered the real radius (RR), the angle and the distance between the two rays, and the calculated radius by using the trigonometric tool (CR). The relative error (RE) was calculated following the equation: RE= (CR-RR)*100/ RR). Some values of RE are negative due to possible underestimations of CR. In order to have a comparable measure of error (i.e. both negative and positive), we used the Absolute Relative Error: ARE = (|CR-RR|)*100/RR).

While most of the observations follow a straight regression line, for small angles, CR and thus ER show obvious outliers. We tried several methods to identify and remove them in order to provide the user a practical minimum angle (see SM1). Unfortunately, none of these methods allowed us to identify a clear angle limit from which all observations could be included. As we want to perform the regressions on every observations starting from a given angle to include the whole variation of the selected range, we chose 2º as the lower limit, a solution which is reproducible on archaeological charcoal assemblages.

In order to understand the relation between RR and RC, we use our dataset as a training sample in order to establish models suited to estimate the RR on archaeological wood / charcoal fragments based from the CR by using the provided PLT. An eye-check on a bivariate representation of RR over CR (see Fig. 3 in Results) strongly suggests that the relationship between these two variables is linear. We therefore try to model this relationship with a linear model with RR as the response variable and CR as the explanatory variable (*reg*). The variance of RR increases over the range of CR. To take this into account, we performed a weighted regression with the weights of each observation being 1/CR (*wreg*). Secondly, we noticed that the relationship between RR and CR may be piecewise, with a potential important decrease of the slope for highest values of CR (see Fig. 4 in Results). To investigate this issue, we fit a regression model for each species with broken line relationships (*swreg* = segmented weight regression model) using the R package segmented (Muggeo, 2008). This model can be viewed as a linear regression from which we allow the relationships between CR and RR (i.e the slope) to change on each side of a breakpoint represented by the parameter □. Using such a model is of prime importance as the relationship seems stronger for low values of CR. This allows us to test precisely each part of the relationship and to locate on which of those part the prediction are the best. AIC (Akaike, 1973) allows finding the adequate balance between the goodness of fit and the number of parameters. We use it to select the best model for each species (i.e. reg, wreg, swreg; Table 3).

To investigate the effect of carbonization on the relationship between CR and RR, we add to the model swreg an additional discrete variable representing the carbonization (here after called *swregCarb*). We use the approach proposed by Muggeo (2008) to split the values of the explanatory variable (i.e. CR) for the different levels of the factor (i.e. carbonized or not).

Results

Comparison of manual and semi-automatic PLTs on perfect target

The analysis of the manual PLT on perfect target is based on 1320 measurements. The mean of the Absolute Relative Error (ARE) and its standard error is 3.52% ± 0.48. The correlation of the exact and the approximated value of the radius is 0.9953078 (method = Spearman, p-value < 2.2e-16).

The test of the semi-automatic PLT is also based on 1320 measurements. The mean of ARE and its standard error is 2.44% ± 0.3. The correlation of the exact radius and the approximated radius is 0.9958947 (method = Spearman, p-value < 2.2e-16).

A Wilcoxon-Mann-Whitney test between RE from the manual and the semi-automatic PLT indicates a significantly different median. However, the differences are very fine as shown by Figure 1. Indeed, the manual PLT has a slightly negative ER when semi-automatic PLT is centred on zero. Then, the semi-automatic PLT works slightly better than the manual PLT.

Establishment of exclusive criteria

The analysis of the distribution of the Relative Error (RE) on perfect targets, according to angle and distance, indicates that the distribution of RE decrease obviously from angles bigger than 10°. The biggest RE is reached for the smallest angle (2°, ARE = 5.27%, sd= 4.39%) (Fig. 2). The analysis of RE values according to RR indicates that there is no correlation between these two parameters (Pearson correlation coefficient = 0.009, p-value = 0.5).

Thus, exclusive criteria to avoid inexact measurements using the PLT on archaeological charcoal fragments have been established according to the analysis of the referential dataset. Indeed, for all taxa together (fresh wood), and all angles and distances included, the mean of the ARE and its standard deviation are 0.511 ± 5.47.
The analysis of the RE according to distance and angle indicates that the most important RE concerns angle below 2° (Fig. 2, SM2). Most often, these small angles correspond to small distances between rays, less than 2 mm. Integrating these exclusive criteria, the mean of the ARE and its standard deviation are 0.25 ± 0.24. The correlation between the exact values of radius and its approximate values is 0.8832283 (method = Spearman, p-value < 2.2e-16). The following analyses presented include the exclusive criteria.

Comparison between taxa (fresh wood) and modeling of the relation between RR and CR

The bivariate representation of RR over CR (Fig.3) from data measured on fresh wood strongly suggests that the relationship between these two variables is linear. However, the variance of RR increases over the range of CR.
A comparison of the results obtained with the referential analysis was performed in order to compare the results of the PLT on the different taxa and to model the relation between the RR and the CR (Table 4, data treatment). Thus, a regression model for each species with broken line relationships was performed (Fig. 4, Table 4).

The first slopes (lowest CR) are very similar between taxa excepted for *Pinus halepensis*. Indeed, very low CR values corresponding to a wide range of RR values are to be noted without explanation (Fig. 3, *Pinus halepensis*).
Thus, the smallest breakpoint concerns *Pinus halepensis* with a CR of 4.071 cm that means about 8 cm of diameter. Below this breakpoint, the correlation between CR and RR is very strong while above 4 cm, the estimation of RR from CR is no more reliable, characterized by a nearly flat regression line.
The swreg model indicates also a low breakpoint for *Quercus petraea* as for *Pinus*. However, after this breakpoint, CR is still correlated with RR even if the interval of confidence is large.

At the opposite, the highest breakpoint corresponds to *Prunus avium* with a CR = 9.833 cm that means about 20 cm of diameter. In other words the correlation between CR and RR is very strong for diameters less than 20 cm while the estimation of RR for largest diameter is no more reliable, characterized by a downward slope. *Fagus sylvatica* presents similar behavior.

Lastly, *Ulmus minor, Fraxinus excelsior* and *Castanea sativa* are between these two groups with a breakpoint at CR = 5.475, CR =6.958 and CR = 6.043, respectively. Before the breakpoint, the correlation between RR and CR is very strong. After it, the correlation is less accurate but still reliable despite a large interval confidence (the signal is preserved).

Effects of carbonization

In order to evaluate the efficiency of the PLTs on carbonized wood, we repeated the same protocols on carbonized slices for *Pinus halepensis* and *Fagus sylvatica*. (Fig. 5, Table 5). To carry out this comparative analysis, we considered only measurements from fresh wood slices that were charred (i.e. R1 and R2 for *Pinus*, and R13 for *Fagus*).

The effect of carbonization is almost negligible on *Pinus sylvestris*. The breakpoint value is small before carbonization (CR = 4.168 cm). It slightly increases after carbonization (CR = 4.91). In fact, the above-mentioned marginal measures are no longer recorded on carbonized slices, which is the reason why the slope 1 of carbonized wood is slightly less inclined and the breakpoint slightly higher. After carbonization, it is interesting to note that the slope 2 is slightly less flat.

On the contrary, the carbonization induces significant changes in the RR estimation for *Fagus sylvatica* whose breakpoint value was high before carbonization (CR = 7.717 cm) and smaller after carbonization (CR = 4.717 cm). Nevertheless, the slope 1 and the slope 2 before and after carbonization are very similar. That means the signal is preserved.

Interpretation and Discussion

PLTs on perfect targets

A manual technique with 12 landmarks and a semi-automatic technique with 4 landmarks (less time consuming and more suitable for a routine use) using the trigonometric principle were compared on perfect target printed on white paper. The 1320x2 measures developed show quite comparable results even if the statistical test indicates a median significantly different. A previous study showed that Thales' theorem, trigonometry in a right-angled triangle, and trigonometry in an isosceles triangle provide relevant and similar results. They are just more or less adapted to the software used (Paradis-Grenouillet et al., 2013). Two reasons can be given to explain why the semi-automatic PLT works slightly better than the manual one. The first one is the observation equipment. The manual PLT was associated to a binocular stereoscope that is not recommended in morphometry. The second one is the smaller number of landmarks for the semi-automatic PLT (4 landmarks instead of 12 for the manual PLT). Indeed, the recorded relative errors on perfect target are related to handling, i.e. to the operator. Then, the smaller the number of landmarks is, the less the margins of error are important.

PLTs on fresh wood

The values of relative errors on fresh wood slices are significantly higher than on perfect targets. This means that the larger relative errors on fresh wood are related to the anatomy of the wood, as the RE linked to the operator is marginal. It is impossible to escape this margin of uncertainty, which is intrinsic to any living phenomenon, as each characteristic of an organism results from the interaction between its genome and the environment, which is itself greatly variable.

In order to limit the margins of error, an exclusive criterion could be set up for the archaeological application of the PLT: avoid angles $<2°$. In addition, whichever the taxon, RE values increase significantly in relation to the distance from the pith. Observations of the wood slices suggest that this is due to the fact that new ligneous rays are inserted during growth of the stem, the latter not necessarily converging at the level of the pith. In addition, when tension wood occurs during growth, the direction of the rays can change to adapt to the new wood morphology. Also, the observation scale, often limited to a camera field about 1 cm^2, does not allow to assess local deformations or wood rays which can also be a source of error (Fig. 6).

Comparison between taxa

The variance of RR estimations on fresh wood increases for all taxa over the range of CR. The segmented weighted regression model allows comparing different taxa. The slope 1, before the breakpoint, is very similar for all taxa excepted for *Pinus halepensis* due to marginal values.

Then, the model indicates similarities between taxa. For example, *Fagus* and *Prunus*, whose anatomy is very close, are characterized by a high breakpoint (about 10 cm in radius). However, after this breakpoint, the signal is lost (see slope 2). These two species are diffuse porous wood with multiseriate rays. Thus, deformation linked to large vessels in earlywood, as it can be seen in porous wood, is probably limited.

Other similarities can be observed between *Fraxinus*, *Castanea* and *Ulmus*, whose anatomy is also close. Their breakpoint ranges from 5.4 cm to 6.9 cm. The signal is well preserved after it for *Fraxinus*, which is less obvious for *Castanea* and *Ulmus* (see slope 2).
Another group is formed by *Pinus* and *Quercus*. They are both characterized by a small breakpoint (about 4 cm in radius). Nevertheless, the signal is better preserved after this breakpoint for *Quercus* than for *Pinus*, even if their anatomy is significantly different.

According to these results, wood anatomy, especially the ligneous rays and probably their formation, may be an explanation of such variations. However, surprisingly, our understanding of how wood develops, especially wood rays, is far from complete (for a review, see Lev-Yadun and Aloni, 1995). Short radial initials (cells in the cambium) give rise to rays that are essential to the translocation of nutrients between phloem and xylem. As for other wood elements such as vessels, the cellular and molecular processes are controlled by a wide variety of factors both exogenous (photoperiod and temperature) and endogenous (phytohormones) and by interaction between them (Plomion et al., 2001). According to Lev-Yadun and Aloni (1995), a basic aspect of maturation in woody plants is the normal gradual increase in ray size with age, with distance from the pith, and with distance from the young leaves. However, the increase in size and number of rays is not necessarily dependent on the distance between rays. The greater number of rays generally observed in branches, as compared with the stem, no doubt correlates with the reduced width of the rings and the associated reduction in caliber of the tracheids. In *Fraxinus excelsior* and *Castanea sativa* there were more rays per unit area in the wood with wide growth rings than there were in the slower-growth wood. Concerning *Pinus halepensis*, there is no clear, general conclusion that the rate of cambial activity determines the number of rays. Lev-Yadun and Aloni (1995) concludes that the rate of cambial activity is not the only regulating mechanism of ray characteristics, and another explanation for the regulation of ray formation during cambial activity is needed.

Effect of carbonization

The results indicate that the effect of the carbonization is different depending on the two taxa. It is almost negligible on *Pinus*, while on *Fagus* we can observe an obvious decrease of the breakpoint. The slope 1 is very similar before and after carbonization for the both taxa. After the breakpoint, the slope 2 indicates that the signal is not well preserved. However, the reference data is still limited and have to be completed. Xue et al. (2018) analysed the effect of wood rays on the shrinkage of wood during the drying process. The wood is characterized by an anisotropic shrinkage (as well as during the carbonization): the longitudinal shrinkage from the green to the dried condition (and during carbonization) is the smallest and the tangential shrinkage is usually 1.5 to 2.5 times that of radial shrinkage. Their experiments indicate that the larger the rays, the greater the shrinkage of fibers. In addition, fiber shrinkage is clearly dependent on the distance from the wood rays. If this study concerns the wood drying process, it could be assumed that this same process may occur during the carbonization with greater effects. The most important decreasing of the breakpoint value observed on *Fagus* can thus be explained by the numerous and multiseriate rays.

Measurement protocol

Considering the results of this referential study, a measurement protocol can be established in order to provide a ready-to-use PLT to estimate the missing radius with an interval of confidence. According to the results, the semi-automatic PLT using a multizoom microscope is preferred, as it reduces the margins of errors (and measures) and is less time-consuming. Accordingly, the following protocol is established in order to obtain reliable estimations of the charcoal-pith distance for archaeological wood and charcoal fragments and to estimate the original diameter of the wood used:

1- Each charcoal fragment to measure have to present at least one preserved ring (this is two ring boundaries) in a transverse section of at least 2 mm length is needed in order to provide a reliable assemblage to be measured. A limit inherent to the size of archaeological charcoal, especially for fragments smaller than 4 mm, is noticeable. This limit is directly related to the minimum angle that must be exceeded to obtain a reliable measurement (2°). Thus, the maximum missing radius that can be measured on transversal section smaller than 4mm*4 mm is 11.5 cm (23 cm diameter) (Nocus, 2014).

2- Orientate each wood/charcoal fragment under the multizoom microscope in order to verify that the rays are not divergent. Do not measure fragments presenting deformed wood anatomy. As far as possible, take measurements on the last ring boundary preserved. Eliminate the measurements with angles <2º.

3- Repeat 3 to 5 times the measure on the same ring boundary and with different rays. Discard the two extreme values (largest and smallest measurements of the missing radius) and calculate a mean value with the three remaining measures.

4- An R function and the swreg model with a user guide can be downloaded on the DENDRAC website in the section Dendro-anthracological tools (https://dendrac.mnhn.fr/spip.php?rubrique71). The function allows to obtain, from the CR, a RR with margins of error following the model presented in the paper. The result can be improved considering each taxon independently and/or the state of carbonization. If the taxon are not referenced in the database, the estimation of RR is given taking into account all the taxa.

5- If the analysed material is carbonized, correct the shrinkage due to carbonization. At the state of the art, we assume a mean of 20% in open domestic fireplace. The value can reach 40% in charcoal kilns. A more precise reference was conducted on *Quercus* and *Castanea* at different temperatures and taking into account sapwood and heartwood (Paradis-Grenouillet and Dufraisse, 2018)

6- (optional) Double the CR final value and locate it into one of the diameter classes proposed for angiosperms and gymnosperms (this is the actual value that will allow discussing the composition of the assemblage in relation to diameter). Considering the accuracy of the RR estimated and the standards used in dendrometrical plans by foresters (Gaudin, 1996; Deleuze et al., 2014), the values of estimated RR can be ordered into diameter classes as following for Angiospermae: [0-2] cm, [2-4] cm, [4-7] cm, [7-10] cm,-[10-20] and >20 cm; and as following for Gymnospermae: [0-2] cm, [2-4] cm, [4-7] cm, [7-10] cm, [10-14] cm, [14-20] cm and >20 cm (Dufraisse et al., 2018). However, taking into account the segmented weighted regression models, data must be interpreted with caution between [10-14] cm, [14-20] cm. It is also important to note that referential studies for other Gymnospermae should be considered in order to strength the model for these taxa.

Contributions of the use of the trigonometric PLT on archaeological charcoal assemblages.

The PLT has been tested on archaeological charcoal analysis to approach wood management strategies on different contexts. García-Martinez and Dufraisse (2012) analysed charcoal fragments at the Argaric Bronze Age site of Barranco de la Viuda, South-Eastern Iberia. In this case, charcoal-pith distance for diameter restitution has been performed on Aleppo pine (*Pinus* *halepensis*) charcoal fragments from three different assemblages. Small diameters (>10 cm, mainly 2-5 cm) were exploited to provide firewood for different dwelling and craft activities performed at the site. The occurrence of saproxylophagous in some of the branches suggested that firewood provisioning at the site focused on the gathering of Aleppo pine dead branches.

Aleppo pine charcoal fragments have also been analysed in Late Bronze Age and Iron Age sites of Mallorca (Balearic Islands, Western Mediterranean, Picornell-Gelabert and Dufraisse 2018). Assemblages of dispersed charcoal fragments from two different sites abandoned after fire events were analyzed in order to suggest the original use of pinewood before the firing of the buildings. At Ses Païsses site the occurrence of diameters >7 cm was minor, while at Son Fornés site the occurrence was significantly more important. Such results allowed the authors to suggest that at Son Fornés pine trunks would have been used as constructive material (timber for beams), while in Ses Païsses Aleppo pine charcoal fragments would mainly represent the residues of the use of branches as firewood during the occupation of the building before the final abandonment after the fire event.

Charcoal-pith distance has been measured on charcoal fragments from historical charcoal kilns in order to interrogate forest resources management and the exploitation of woody vegetation to produce energy sources. In this sense, Paradis-Grenouillet et al. (2015) identified the continuous sustainable exploitation of *Fagus sylvatica* forests at Mont Lozère (France) during four hundred years (11^{th} to 15^{th} centuries AD), based on beech coppicing practices by the Medieval charcoal burners in relation to the metallurgical industry.

Finally, charcoal-pith distance has been measured on charcoal fragments associated with tree-ring width and heartwood/sapwood (anthraco-typology) in four Neolithic sites located in northern France (Houplin-Ancoisne in Deûle's Valley) and Alpine arc (Chalain 4 and Chalain 21 on Lake Chalain, Jura, France) (Coubray and Dufraisse, in press). These tools were combined with the biological and ecological traits of the woody taxa identified for a systemic approach to forest space. Two forest management systems are thus detected. The sites on Lake Chalain are characterized by the exploitation of oak branches, probably from the hinterland, and ash tree shoots from fragmentary woodland areas. In the Deûle Valley, it is the crown of trees, such as ash and alder, which were exploited, whereas oak came mainly from the felling of large trees. These data are integrated coherently into the paleoeconomic syntheses proposed for these sites, namely, in a mountain context, semi-permanent habitats associated with a shifting agriculture system in the forest where deer hunting played a predominant role, and in the valley bottom a system of permanent habitats, structured within a densely occupied territory where the share of livestock was dominant.

Conclusion and perspectives

The estimation of missing radius (CR, this is the charcoal-pith distance) by using the trigonometric method, and the constitution of a reference dataset composed of 7 taxa allow moving forward in the establishment of a reliable and less time-consuming PLT. This study allows establishing a predictive model and estimating the missing radius and its interval of confidence. This PLT, thus, allows a rapid and reliable measurement of the charcoal-pith distance and, subsequently, an estimation of the original diameter up to 20 cm. Beyond this diameter size, the margins of error detected increase considerably due to the insertion of new rays during the growing of the tree and the creation of new rings.

In this sense, this study shows that carbonization is also a factor to be taken into account to obtain reliable diameter estimations. In order to solve this, this experimental dataset allows establishing correction factors of the wood shrinkage during carbonization to be applied to the CR values obtained with the trigonometric semi-automatic PLT.

However, the access to specific equipment (multizoom microscope combined with a software image analysis) is not always possible due to logistic reasons. We are therefore creating a printed calibrated target based on the trigonometric principle; this means without taking into account the tree-ring curvature but based on the angle and the distance between ligneous rays. The target will be made freely available online (https://dendrac.mnhn.fr/spip.php?article239) and can be printed out on different supports (rigid/soft). This target is ready to use under a binocular stereomicroscope as a PLT to easily estimate a class of charcoal-pith distance (and not a strict value) on charcoal fragments big enough.

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Supplementary material 1:

We know from figure 2a that the relative error of the reconstructed diameters is really high for small angles. We tried to find a quantitative justification to set a lower limit under which the method should not be used because of too important errors.

Our first try was to identify outliers from the RE distribution as being outside 1.5 times the interquartile range above the upper quartile and below the lower quartile. The range of “normal data” was then [-0.825, 0815]. We would then select only the data which angles are higher to the last observation being consider as outlier.

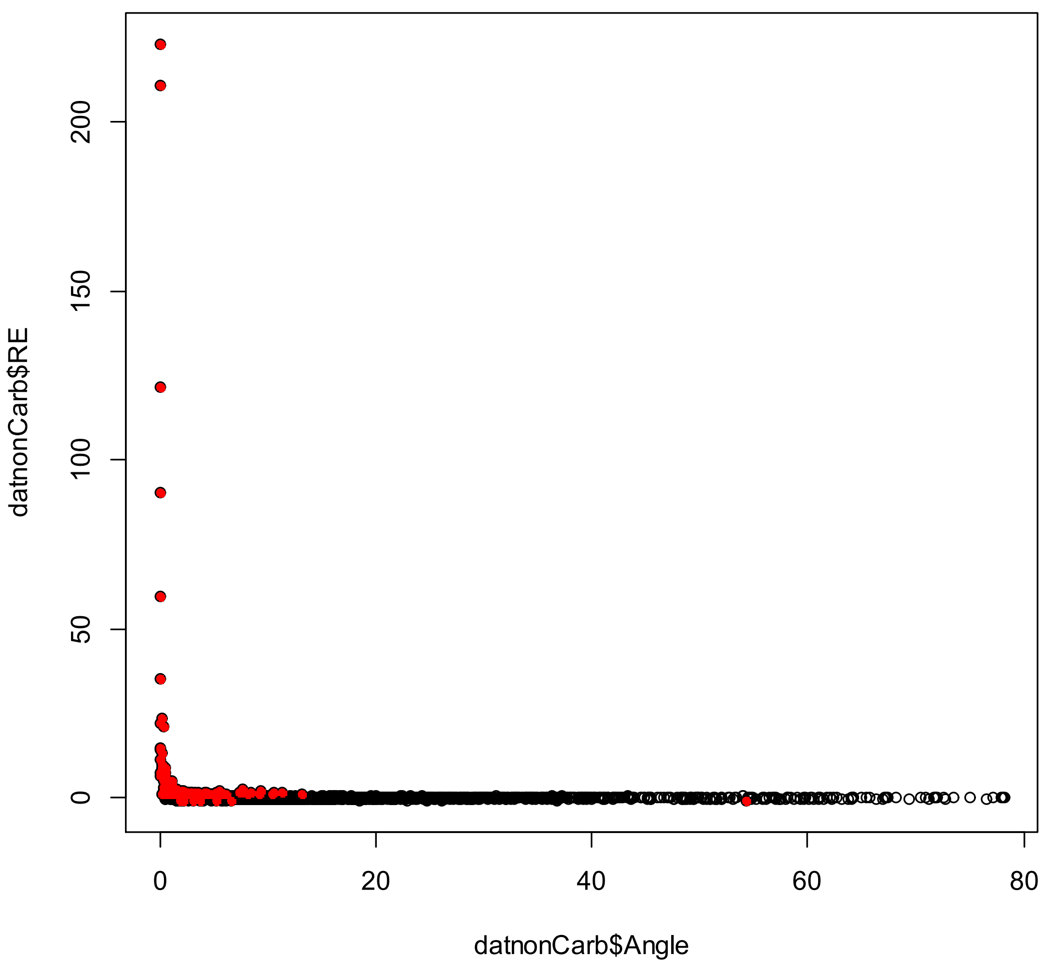

Figure SM1.1. Scatter plot of the relative errors of diameters estimations and angles. Red dots indicated data which are outside 1.5 times the interquartile range above the upper quartile and bellow the lower quartile { -0.825, 0.815}.

Unfortunately, an outlier appeared at an angle of 54.28 with an RE negative which was not what we expected to remove. Even by ignoring this point, the next limit was at 13.2 and we knew that linear regression was quite good even for smaller angles. We then tried to include values inside a range of 99% around the median.

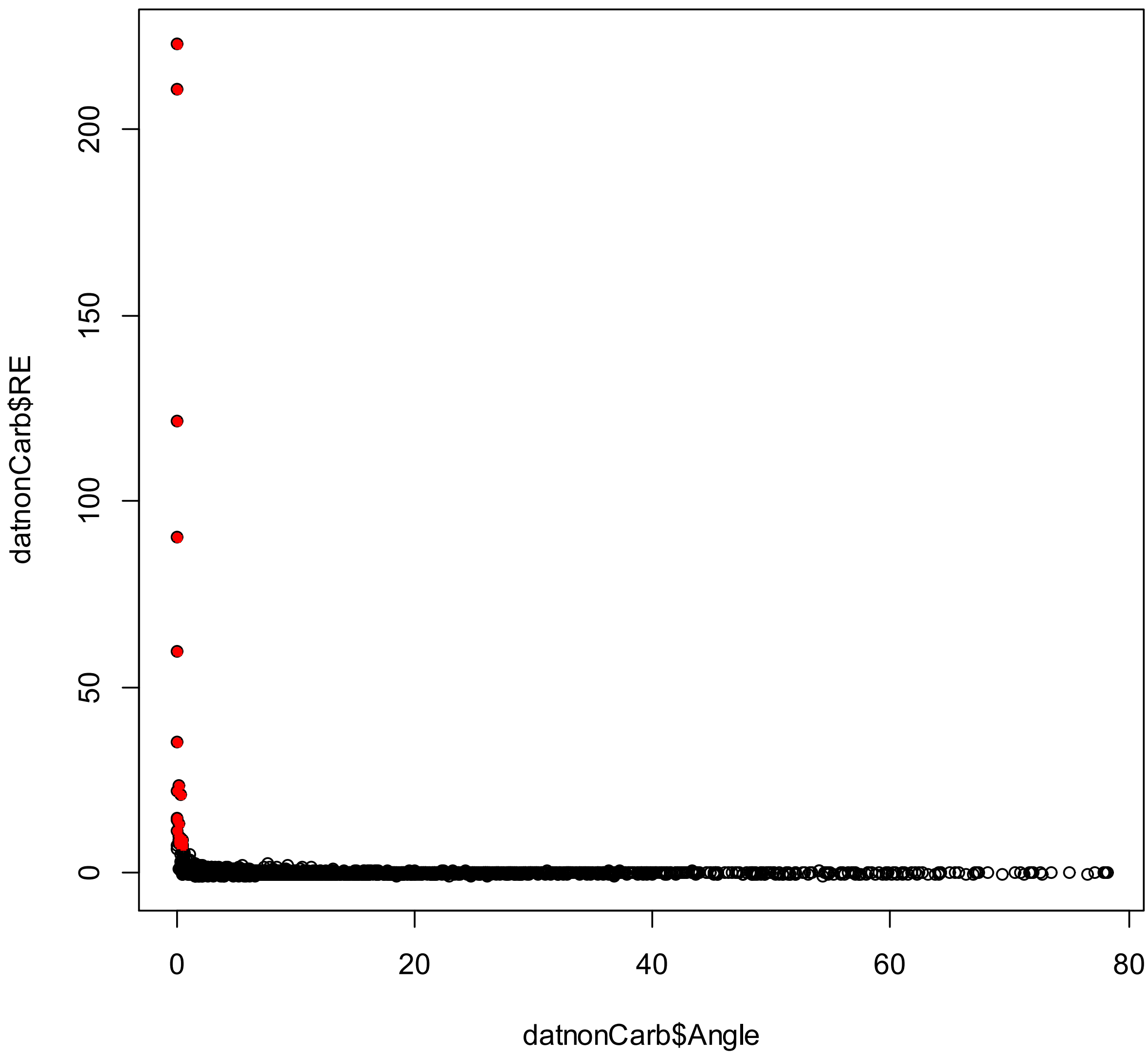

Figure SM1.2. Scatter plot of the relative errors of diameters estimations and angles. Red dots indicated data which are outside the 0.99 quantiles range {-0.99000, 7.50295}.

This time too many observations were kept and would have biased models very much at small angles. We finally considered that looking for outliers had some subjectivity in the quantile we would have selected to recognize the lower angle limit.

We then switched to Cook's distances (Cook & Weisberg, 1980) to identify points that would influence the regression too much in comparison to the others. The usual limit is 4 times the mean of the cook's distances of all the observations. This operation identifies four observations that are outside the limit (Fig. SM1.3).

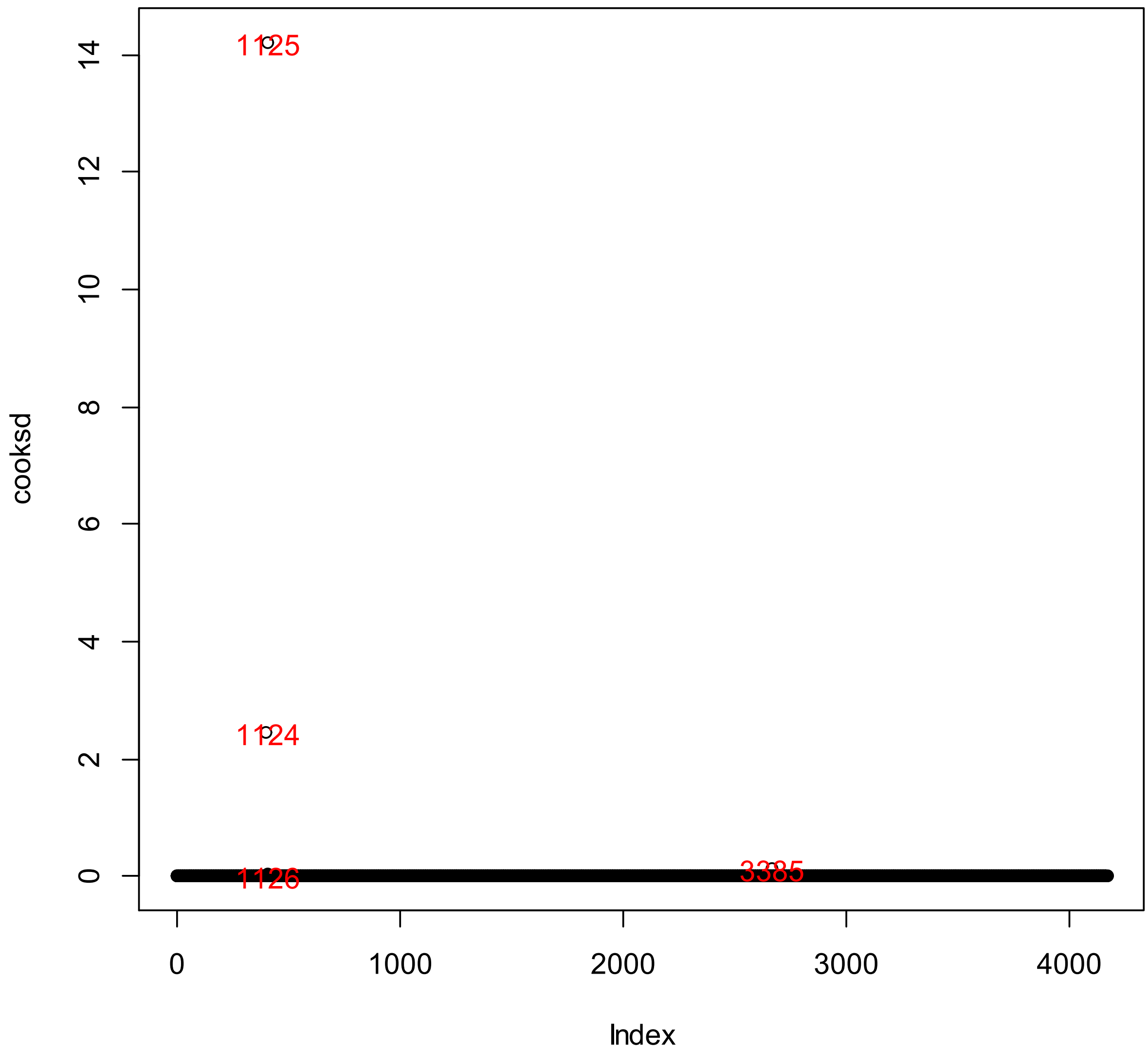

Figure SM1.3. Cook's distance of every point from the regression RR = a * CR + b.

We thus still have an important bias at small angles. We decided to try an iterative procedure by using a loop on the previous procedure and to run it until no points where outside the range. 46 runs were computed until it stabilized leaving only 983 points over the 4164 from the original dataset. This reduction of the dataset would have too much weakens the study and the regressions would be artificially good.

We finally decided to compute moving average and dispersion intervals to recognize the point where the variability was reasonably small and the successive means centered on 0 (Fig.SM1.4, SM1.5). These two conditions are necessary to both have a good precision and resolution in our models. The value of 2 degrees appeared as the good balance between these properties and the number of points considered to build the models. We hope to find a more robust procedure in the future.

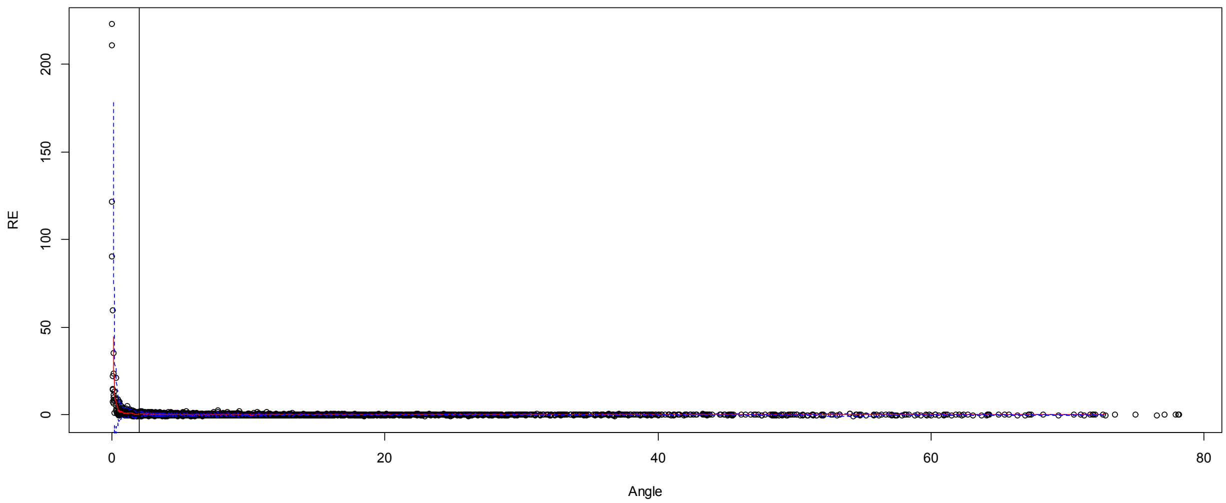

Figure SM1.4. Scatterplot of the Relative Errors and angles. Red line represents the moving average and blue dashed lines the moving average +/- 2 standard deviations. Windows of 20 consecutive points. The vertical bars is angle = 2.

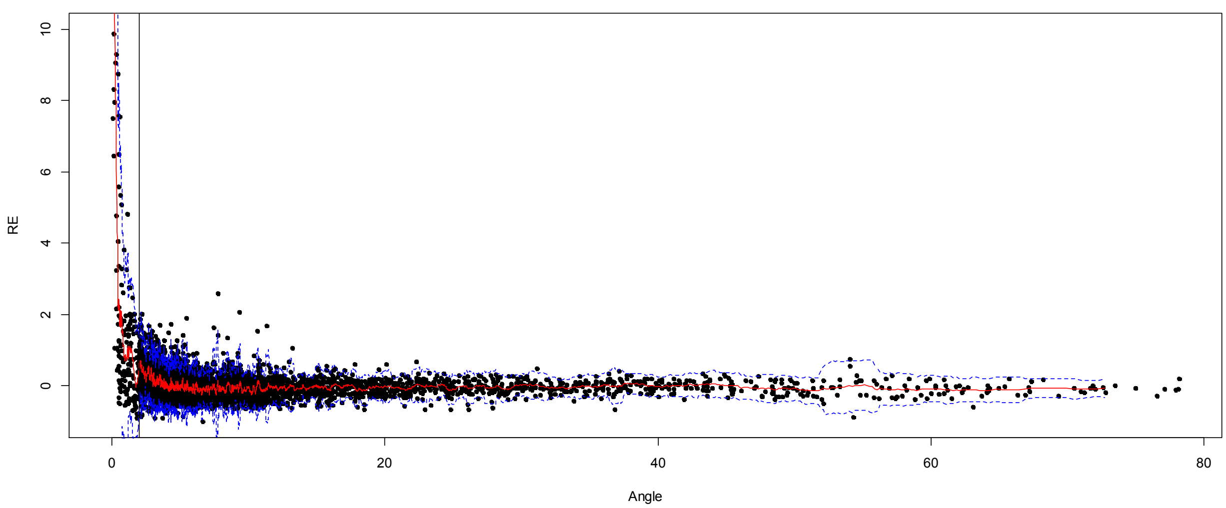

Figure SM1.5. Idem as fig.SM3.4 but limits of the y axis set to {-1, 10}.

Script:

```
# a common way to identify outliers is to consider as an outlier a value which is
    # outside 1.5 times the interquartile range above the upper quartile and bellow the
    # lower quartile.
# in our example lets check the variability of RE
    qu<-quantile(datnonCarb$RE)
# so the range is
    rangeQ<-c(qu[2]-(1.5*(qu[4]-qu[2])),qu[4]+(1.5*(qu[4]-qu[2])))
# we can remove lines which RE is outside {-0.825 , 0.815}
    datnonCarbNoOut<-datnonCarb[datnonCarb$RE<rangeQ[2]&datnonCarb$RE>rangeQ[1],]
    datnonCarbOut<-datnonCarb[datnonCarb$RE>rangeQ[2]|datnonCarb$RE<rangeQ[1],]
# check graphically
    plot3d(datnonCarbNoOut$Distance,datnonCarbNoOut$RE,datnonCarbNoOut$Angle)
# which angles are related to these outliers
    angleIn<-datnonCarb$Angle[datnonCarb$RE<rangeQ[2]&datnonCarb$RE>rangeQ[1]]
    angleOut<-datnonCarb$Angle[datnonCarb$RE>rangeQ[2]|datnonCarb$RE<rangeQ[1]]
    hist(angleOut)
    hist(angleIn)
# many good RE are for small angles (~1400 for {0,5})
    plot(datnonCarb$Angle,datnonCarb$RE)
    points(datnonCarbOut$Angle,datnonCarbOut$RE, pch= 20,col="red")
# lets say now we want 99%
    rangeQ<-quantile(datnonCarb$RE, probs = c(0,0.995))
    datnonCarbNoOut<-datnonCarb[datnonCarb$RE<rangeQ[2]&datnonCarb$RE>rangeQ[1],]
    datnonCarbOut<-datnonCarb[datnonCarb$RE>rangeQ[2]|datnonCarb$RE<rangeQ[1],]
    plot(datnonCarb$Angle,datnonCarb$RE)
    points(datnonCarbOut$Angle,datnonCarbOut$RE, pch= 20,col="red")
    abline(v=2)
    plot(datnonCarb$Angle,datnonCarb$RC)
    points(datnonCarbOut$Angle,datnonCarbOut$RC, pch= 20,col="red")
## test avec cooks distances
    mod <- lm(RR~RCtrigo, data=datnonCarb)
    cooksd <- cooks.distance(mod)
    plot(cooksd)
    abline(h = 4*mean(cooksd, na.rm=T), col="red")  # add cutoff line
    text(x=1:length(cooksd)+1, y=cooksd, labels=ifelse(cooksd>4*mean(cooksd, na.rm=T),names(cooksd),""), col="red")  # add
labels
    datnonCarbCD<-datnonCarb[cooksd<4*mean(cooksd, na.rm=T),]
    plot(RR~RCtrigo, data=datnonCarbCD)
    # test loop cooks distance
        isCD<-0
        datnonCarbCD<-datnonCarb
        count<-0
        while (isCD!=1) {
            mod <- lm(RR~RCtrigo, data=datnonCarbCD)
            cooksd <- cooks.distance(mod)
            datnonCarbCD<-datnonCarbCD[cooksd<4*mean(cooksd, na.rm=T),]
            if(all(cooksd<4*mean(cooksd, na.rm=T))) {isCD<-1}
            plot(RR~RCtrigo, data=datnonCarbCD)
            count<-count+1
        }
        plot(RR~RCtrigo, data=datnonCarb)

## moving average on RE / Angle
width<-10
meansRE<-running(datnonCarb$RE[order(datnonCarb$Angle)],fun=mean,width=width,by=1)
```

```
meansAngle<-running(datnonCarb$Angle[order(datnonCarb$Angle)],fun=mean,width=width,by=1)
sdRE<-running(datnonCarb$RE[order(datnonCarb$Angle)],fun=sd,width=width,by=1)
plot(RE~Angle, data=datnonCarb),ylim=c(-1,10),pch=20)
lines(meansAngle,meansRE,col="red")
lines(meansAngle,meansRE-2*sdRE,col="blue",lty=2)
lines(meansAngle,meansRE+2*sdRE,col="blue",lty=2)
abline(v=2)
```

Additional references.

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Legend

Table 1 – Number of measurements on perfect target performed with each PLT (manual and semi-automatic)

Table 2 – Number of measurements taken for each taxon. The reference number of the wood slices corresponds to that given for the dendro-anthracological reference collection, available to researchers (UMR 7209, Paris)

Table 3. Akaike Criterion Information (AIC) for the three models tested and R^2 of the best one for each taxon. reg: classic regression, wreg: weighted regression, swred: segmented weighted regression. Values in bold represents the lowest AIC (the best model) corresponding for all taxa to swreg.

Table 4. Details of the swreg model for all taxa. The first slopes (lowest CR) are very similar between taxa. Notable differences are the breakpoints. Bold values indicate p-values lower than 0.05. P-values for breakpoints and slope 2 are not currently available; we use std.error to estimate the confidence in the results. The swreg model indicates significant differences between taxa regarding the breakpoints.

Table5. Estimations, standard errors of the parameters and R^2 of the swregCarb model for *Pinus halepensis* (A) and *Fagus sylvatica* (B).

Figure 1: Kernel density of the relative errors (RE) measured on perfect targets. Comparison of manual and semi-automatic PLTs.

Figure 2: Biplots of angles between ligneous rays and relative errors (RE). A: representation of all the data, the vertical bar corresponds to an angle of 2° that is the threshold recommended in this paper. B: Boxplot of the data from which angles inferior to 2° have been removed and organized into classes.

Figure 3 – Scatter plot of the real radii (RR) over the calculated radii (CR), each panel corresponds to a taxon (fresh wood).

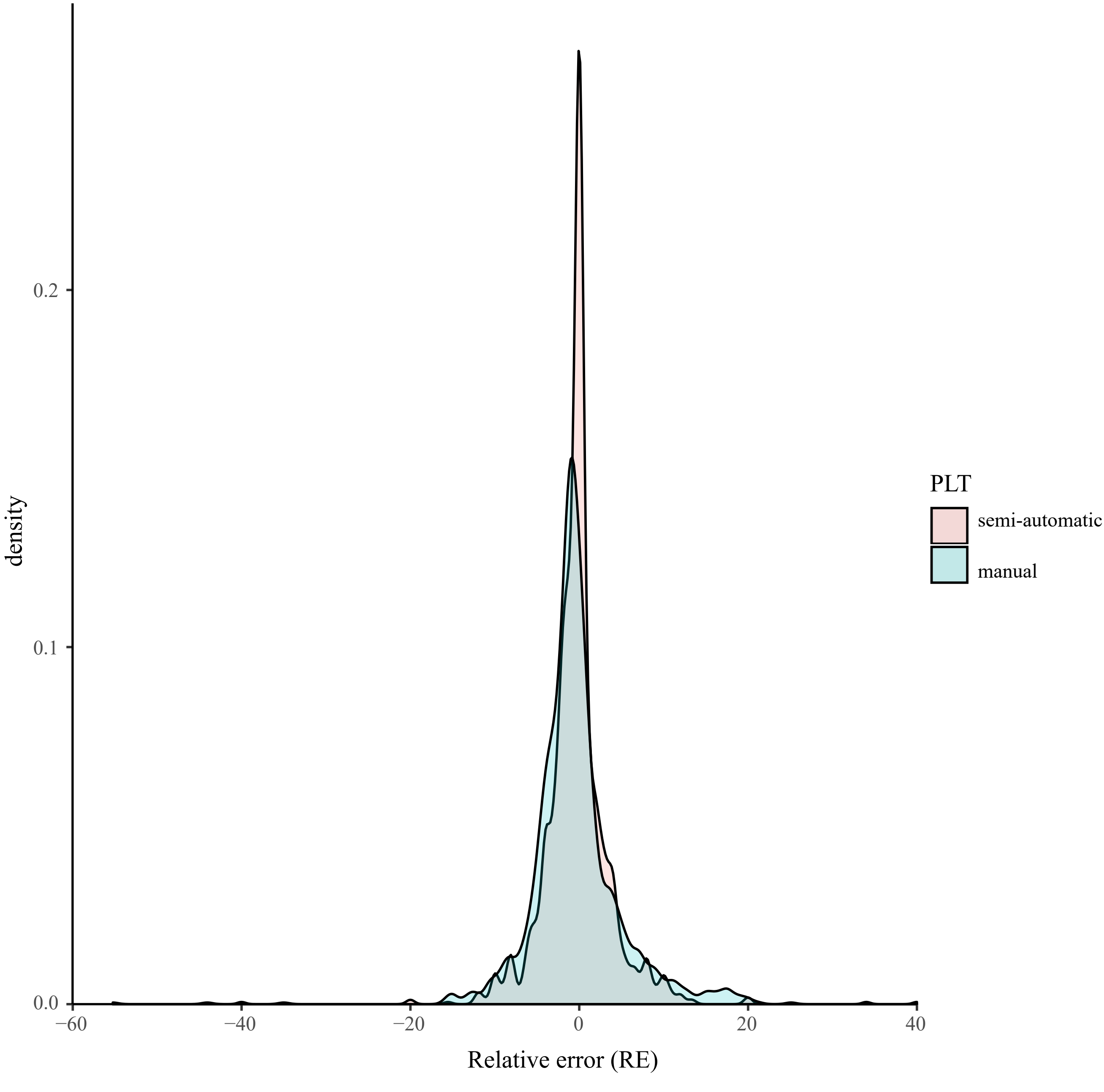
Figure 4 – Fitted lines corresponding to the swreg model for all taxa. The solid lines represent the estimation, the dashed lines represent the 0.95 prediction interval, and horizontal bars represent the 0.95 confidence interval around the estimation of the breakpoints represented by circles

Figure 5_ Fitted lines corresponding to the swregCarb model for *Pinus halepensis* and *Fagus sylvatica* whether or not carbonized. The solid lines represent the estimation and the dashed lines represent the 0.95 prediction interval.

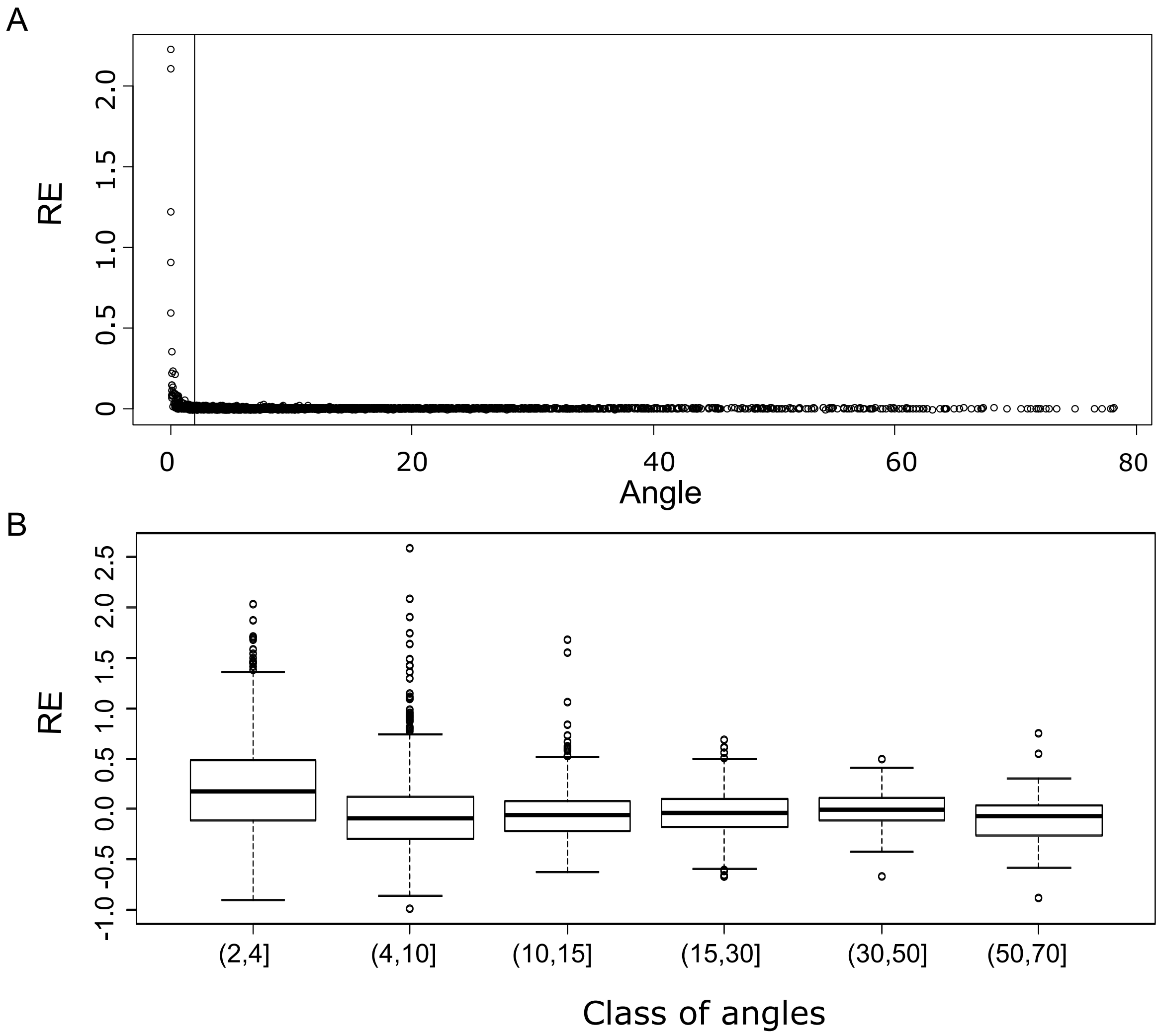
Figure 6 -a- Fresh wood of *Quercus petraea*, without tension wood. All the wood rays converge to the pith. b- Fresh wood of *Quercus petraea*, with tension wood. The direction of the rays changes to adapt to the new morphology of the wood.

SM 1 - the different statistical methods tried in order to provide the user a practical minimum angle

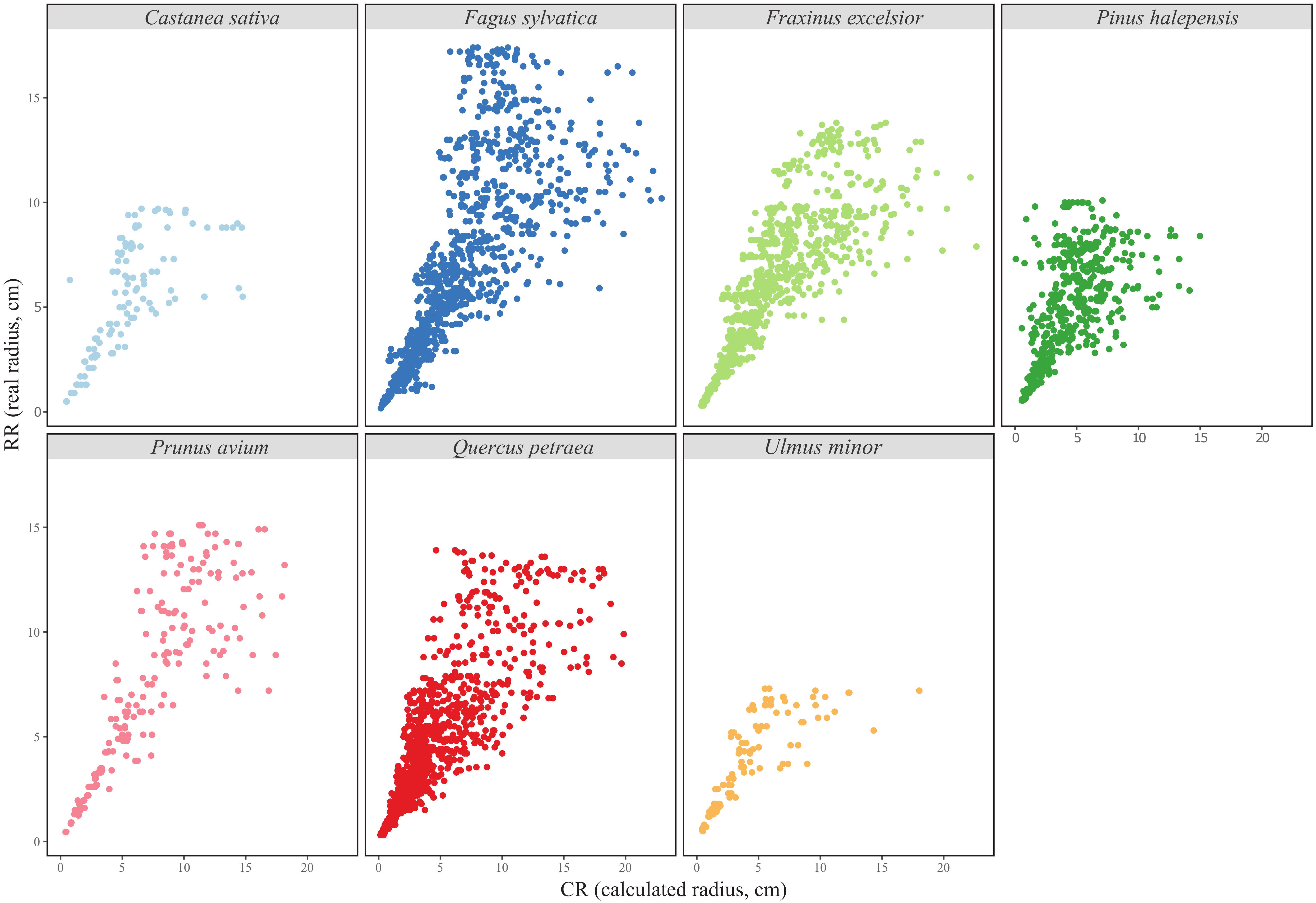
SM 2 – Boxplot of the relative errors (RE) on perfect targets depending on the distances between rays. A: Boxplot of all the data B: Boxplot of the data from which angles inferior to 2° have been removed.

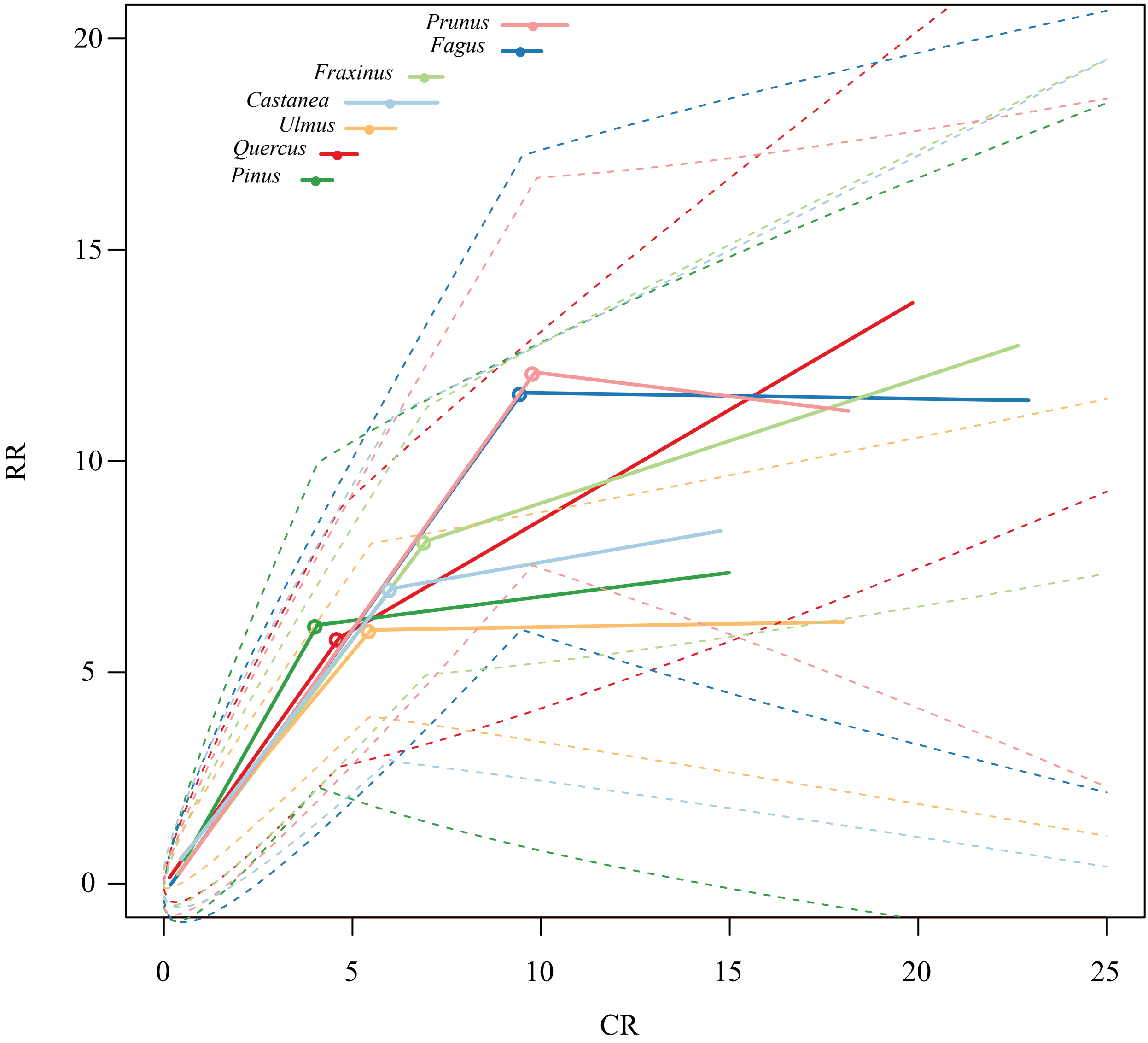


density
0.2
0.1
0.0
−60
−40
−20
0
20
40
Relative error (RE)
PLT
semi-automatic
manual

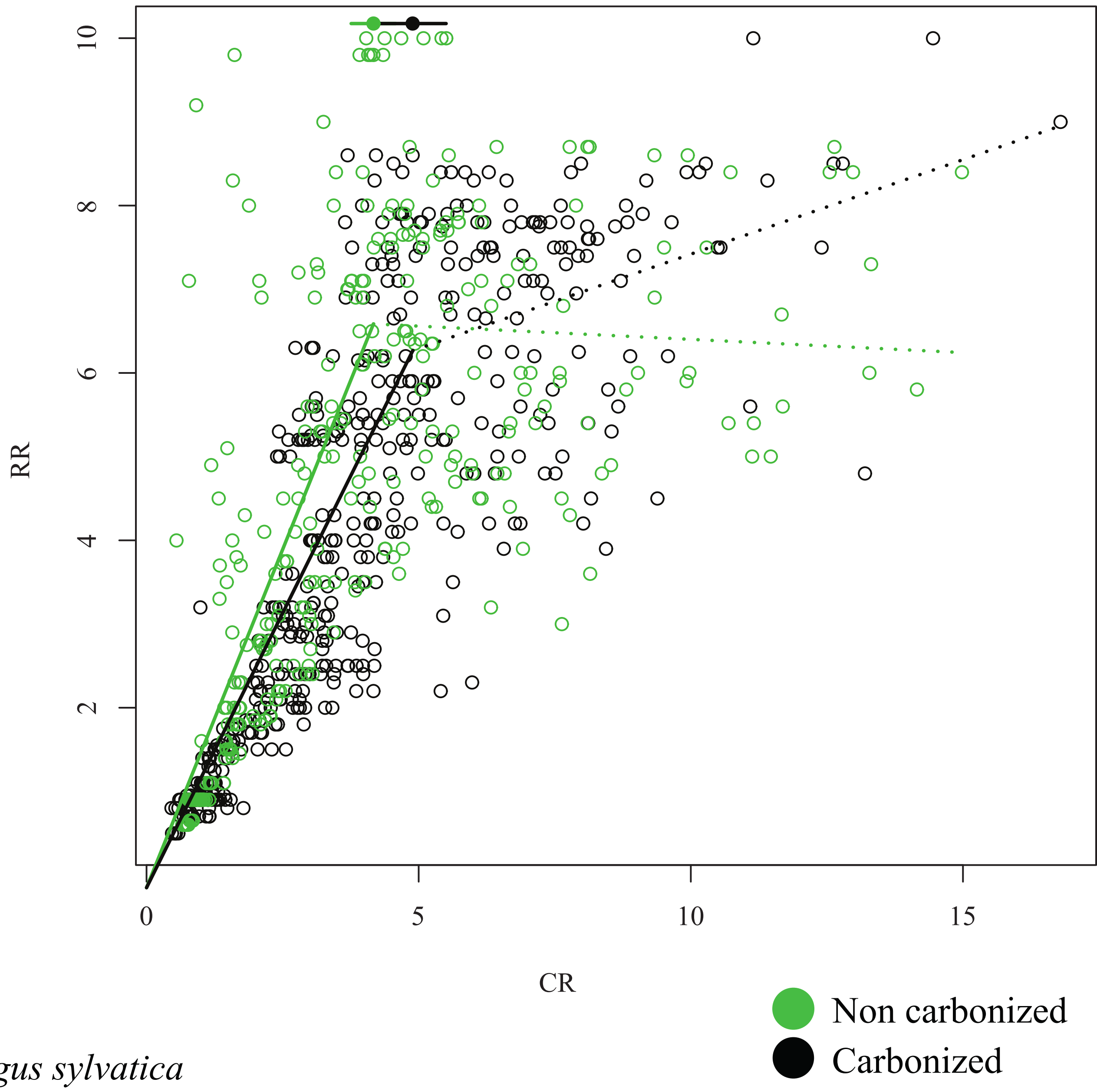


A
RE
0
0.5
1.0
1.5
2.0
0
20
40
60
80
Angle
B
RE
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
(2,4]
(4,10]
(10,15]
(15,30]
(30,50]
(50,70]
Class of angles

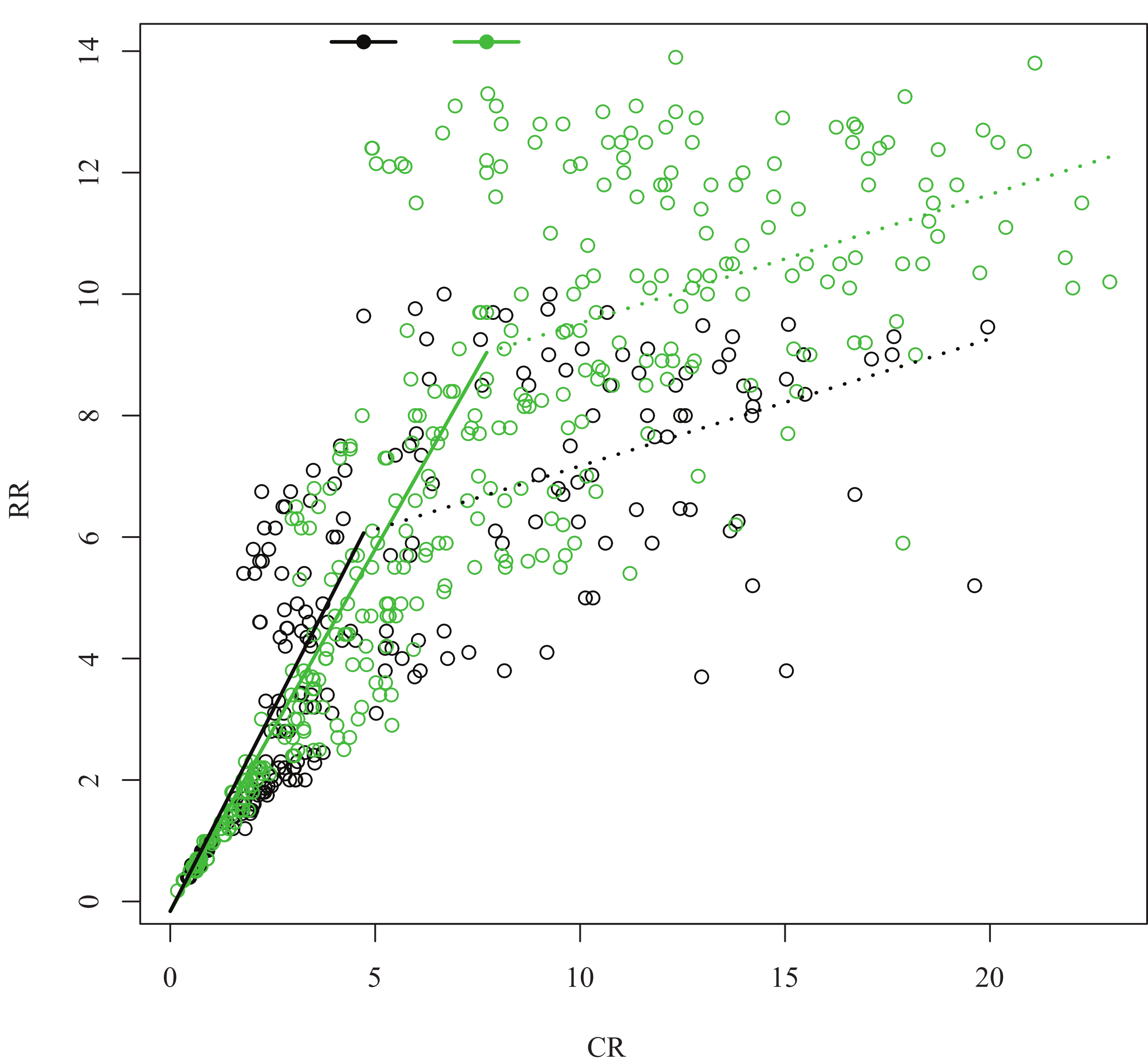

Castanea sativa
Fagus sylvatica
Fraxinus excelsior
Pinus halepensis
Prunus avium
Quercus petraea
Ulmus minor
RR (real radius, cm)
CR (calculated radius, cm)
0
5
10
15
20

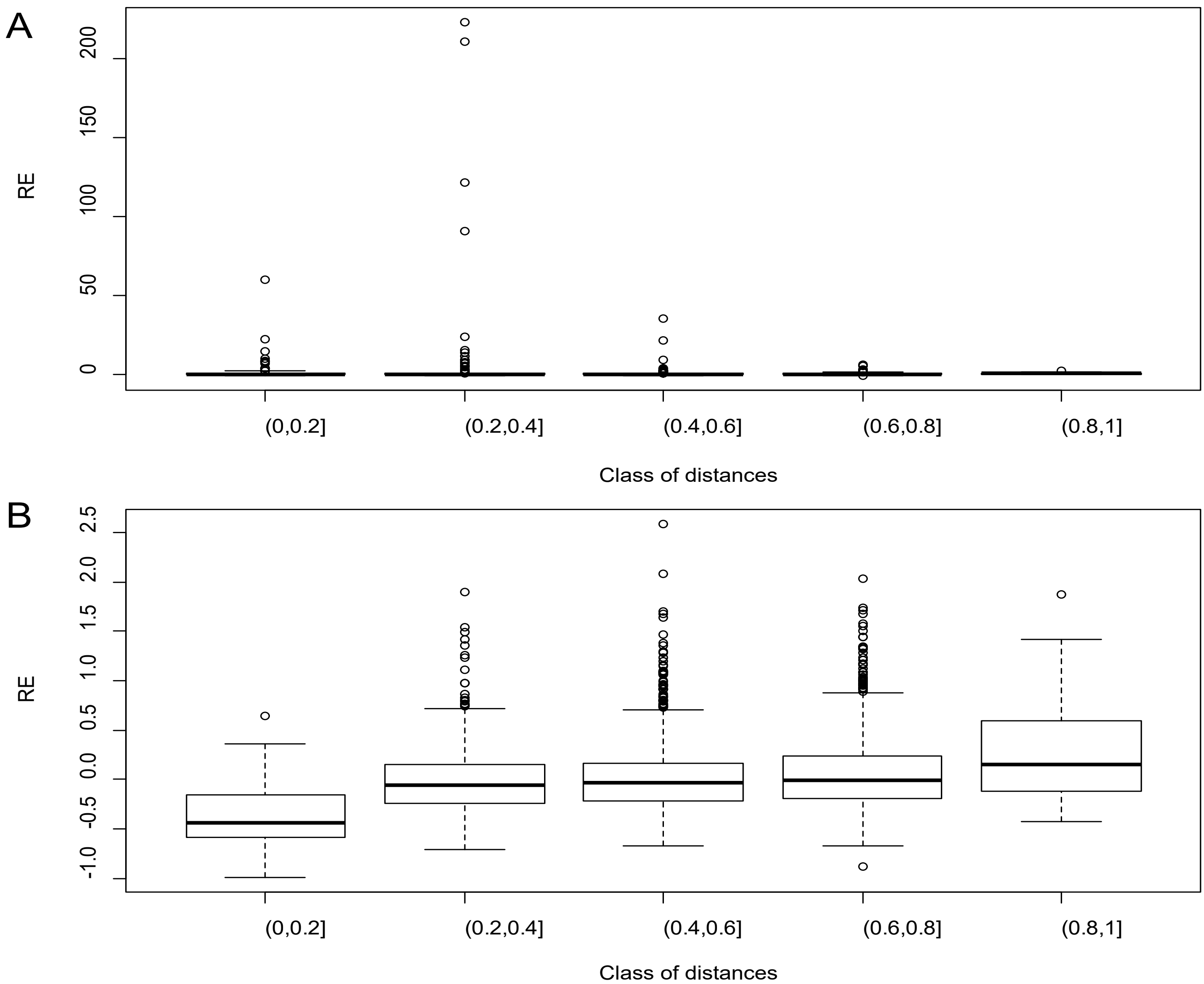

Prunus
Fagus
Fraxinus
Castanea
Ulmus
Quercus
Pinus
RR
CR
0
5
10
15
20
25

Pinus halepensis



Fagus sylvatica




A
RE
0
50
100
150
200
(0,0.2]
(0.2,0.4]
(0.4,0.6]
(0.6,0.8]
(0.8,1]
Class of distances
B
RE
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
(0,0.2]
(0.2,0.4]
(0.4,0.6]
(0.6,0.8]
(0.8,1]
Class of distances

Author statement

Alexa Dufraisse : Conceptualization, Methodology, Archaeological data curation

, Writing- Original draft preparation, Supervision

Jérémie Bardin : Statistical treatment and modelisation

Llorenç Picornell-Gelabert : Archaeological data curation

Sylvie Coubray : Archaeological data curation

Maria Soledad Garcia-Martinez : modern reference data curation

Michel Lemoine : technical supervision

Silvia Vila Moreiras : modern reference data curation