WOOD RESEARCH
52 (3): 2007
15-32

USE OF DIGITAL IMAGES IN COMPUTER-ASSISTED DENDROCHRONOLOGICAL ANALYSIS OF DECIDUOUS HARDWOODS

Vila-Lameiro P., Díaz-Maroto I.J.
Department of Agroforestry Engineering, University of Santiago de Compostela,
Campus Universitario s/n, Lugo, Spain

ABSTRACT

Extensive scientific literature on forest modelling provides information about the conditions for the growth and evolution of the stands –natural or not– of the studied species, *Quercus petraea* (Mattuschka) Liebl. (sessile oak). This information derives mainly from field inventories and from data obtained by using different techniques, such as stem analysis. The aim of the present paper is to analyze how to improve the techniques applied in dendrochronology measurement using computer tools. With this objective were digitized and interpreted by using WinDendro™ software images of slow growth hardwoods from *Quercus petraea* because this wood made more difficult the detection and identification of growth rings, what means that the final conclusions result applicables to anyone decidous hardwood species, included tropical hardwood ones.

Using techniques such as sanding, brushing, contrast enhancement by wetting, and digital photography, instead of use scanner, it's possible to obtain a quality image for subsequent processing. In the last part of the present study, the method proposed is applied to a specific tree providing an example of the measurements obtained.

KEY WORDS: digital image, dendrochronology, growth ring, WinDendro™, decidous hardwoods, *Quercus petraea*

INTRODUCTION

Stem analysis was and still is a constant concern in forest research. The first literature on stem analysis dates from more than two centuries ago in the German School of Forestry and deals specifically with studies conducted in Central Europe (Amorini and Fabbio 1988). The purpose of stem analysis is to reconstruct the evolution of the tree, based on tree height and diameter, collecting wood samples at different heights of the tree to analize and analysed in the laboratory in order to know the age and growth rate at each height. If the exact height of the complete tree is known and the previous information is properly structured, it is possible to know a pair of data, which is fundamental for the analysis of evolution in time: the age of a tree when it reached certain height (Amorini and Fabbio 1988, Gadow et al. 1999, Courbet and Houllier 2002).

To perform this analysis, the wood samples must be obtained at different tree heights, in the shape of increment cores (Smelko and Scheer 2000) or wood disks that are more advisable due to provide more reliable information because there is available whole area of the disk for interpretation in case of doubtful analysis (Soille and Misson 2001).

In the first studies, disk analysis was conducted manually for a long time. The direction or directions considered most appropriate for analysis were chosen and measured by direct visual interpretation on the disk surface (Cook and Kairiukstis 1990, Telewski and Lynch 1991, Christy et al. 2005).

The evolution of methodological procedures for data processing and computer implementation of forest research in the last few years demanded the replacement of manual ring measurement with digital methods using computer applications. Digital methods reduce subjectivity in the assessment of age and radial growth (Guay et al. 1992, Simpson and Denne 1997, Bucur 2003, Vila-Lameiro 2003). WinDendro™ 2001b by Regent Instruments Inc. was selected among the products available according to the requirements of the study. This software implements a computer tool for the analysis of wood disks being possible to obtain information about the age and growth of felled trees, individual and/or stand volumes and growths, as well as basic information to describe complete tree stands from the age perspective (Courbet 1999, Regent Instruments Inc. 2002, WinDendro™ 2002).

Multidisciplinary studies conducted in the 20th Century gave evidence of the areas in which dendrochronology can be used as a source of information Guchu et al. 2006. The relation of dendrochronology to climatology was studied at the beginning of the 20th Century by Douglass (1920) and Schulman (1938). Recently, different authors, Rozas (2001), González and Eckstein (2003), Gjerdrum (2003), Vila-Lameiro and Díaz-Maroto (2005), among others, published studies on the same topic. The evolution of dendrochronology can also be analysed in connection with archaeology, geomorphology, glacial processes, etc, (Splechtna et al. 2000, Vila-Lameiro and Díaz-Maroto 2005, Guchu et al. 2006).

Many software were developed in the two last decades of the 20th Century with different works comparing computer and non-computerized methods, or developing methodological procedures to enable practical applicability. (Thetford et al. 1991, Guay et al. 1992, Conner et al. 2000, Soille and Misson 2001, Vila-Lameiro and Díaz-Maroto 2005). The mentioned studies proposed methods to optimize image management for dendrochronological interpretation by using computer tools. The process to obtain and manage images varies largely, ranging from the lack of image support (ring width is determined by moving a mouse connected to a microscope and clicking on it), to the use of digitized images (Schmidt et al. 1996, Conner et al. 2000, Vila-Lameiro 2003).

With this antecedents, the objectives to reach with the present paper is to analyze how to improve the techniques applied in dendrochronology measurement using software images of slow growth hardwoods from *Quercus petraea* as model because of it's more difficult detection and identification of growth rings, being able to extrapolate the final conclusions to anyone decidous hardwood species, included tropical hardwood ones.

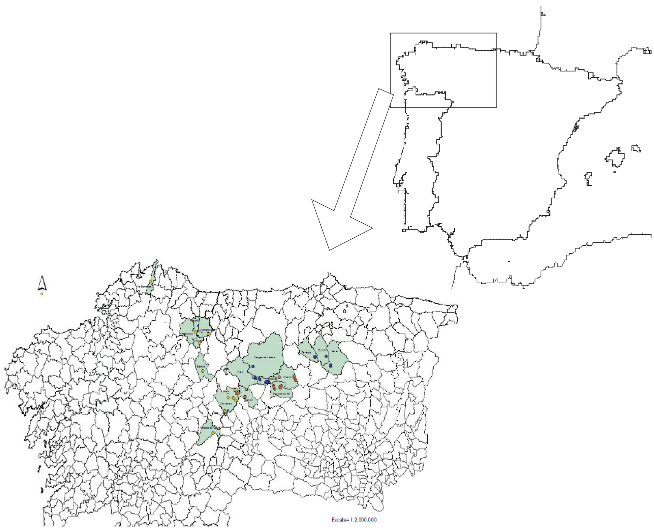
MATERIAL AND METHODS

Description of the study area and fieldwork

The study area for collection of wood samples for the present study is located in northwest Spain covering the most western part of the Orocantabric biogeographical province (Rivas-Martínez 1987, Romero 1993, Fernándes-Parajes et al. 2005). This area extends over zones of three different regions: the eastern of Galicia (Os Ancares and O Courel), the southern of Asturias, and the northern hillside of León (Map 1).

In *Q. petraea* natural stands all over this area were collected the wood disks used in this work obtained following the recommendations contained in the Code of Sample Plot Procedure of the British Forestry Commission (Hummel 1969, Díaz-Maroto et al. 2005). 53 rectangular plots with areas ranging 375 to 1,200 m^2 were remapped without border effect or vast gaps, avoiding the effect and distorsion in growth and ringwith that this situations implies (Madrigal 1992, Díaz-Maroto 1997) selecting the sample points as representative of the stand dominant conditions, what's suitable to obtain the required data for stem analysis (Pita 1991, Ayuga et al. 1998).

Two dominant trees by plot were selected to be felled in order to extract the needed wood disks (Madrigal et al. 1999, Díaz-Maroto 2001, Fernándes-Parajes et al. 2005). The first disk felled was the basal one and the next at dbh height. Then, at every meter of the tree was obtained one disk (Spurr 1952, Zobel and Buijtenen 1989, Zhang et al. 1994, Díez and Fernández-Golfín 1998).



Map 1: Study area in spanish context and inventory plots distribution

WinDendro™ operation outline

The software selected in this study (WinDendro™) is a semiautomatic image analysis system that runs on different computer platforms (Windows XP SP1 in this case) specifically designed for measurement of different parameters related to tree growth rings (Thetford et al. 1991, Cufar and Levanic 1999, Palviainen and Silvennoinen 2001). The use of this software increased over the years because some features made it particularly attractive to research processes. The system allows the operator to control the paths of analysis selected for measurement and can be "taught" how to interpret the boundaries of the growth ring in a specific analysis if detection is difficult as with deciduous hard woods in general and *Quercus* trees particularly, where it is more difficult to obtain the desired results. Because of this problems, Regent Instruments Inc. recommends dispose the disks surface free of irregularities or marks, which is a problem common to every sample (hardwoods or conifers).

Working with Windrendro™ can be based on graphical (exported as a BMP file) or numerical (exported as TXT or PXB files) data, conducting the division between two anual rings by the colour range contrast of the earlywood to latewood transition in accordance with the following process:

Calibrating the program, Acquiring the image (using scanning, digital photography or graphic file imported), Locating start and end of the first path of analysis and identifying the disk, Selecting other paths interesting for analysis, Verifying sensitivity limits in the Profile Area, Revising that Automatic Ring Detection is correct (applying manual correction if necessary, by using a "Teach and Show" method) and Saving graphical and text data.

In this process can emerge different moments of uncertainty whose proposed solutions must enable easy use of the software, not only with conifers, where ring contrast is evident (Abrams et al. 1998, Rittie and Gelhaye 2002), but also with deciduous hardwoods (Smelko and Scheer 2000, Rozas 2003 a and 2003 b).

RESULTS AND DISCUSSION

Image acquisition and management using WinDendro™

The first problem with this software began with the adquisition of the image to manage. As the image must be calibrated prior to measurement of wood samples to guarantee that the dimensions reflected in the results text file are correct and not influenced by a scale error it's advisable to use an object of known dimensions and an image devoted only to this purpose (Schmidt et al. 1996).

The reference element used for calibration was not completely defined until the method for image acquisition was selected. The calibration process was conducted horizontally and vertically and, in order to minimize the possibility of error, the known distance used as standard must be close to the edges of the photograph to be analysed (Guay et al. 1990, Regent Instrumets Inc. 2002, WinDendro™ 2002).

WinDendro™ analyses TIFF and JPEG images, and enables direct acquisition of the image from scanner or from a digital camera what's useful when the particular circumstances do not permit image storage, or when the sample volume is small, but image storing is advisable in order to enable further analysis.

JPEG format is a graphic file format established by the JPEG (Joint Photographic Experts Group), which constitutes an international standard for compressed photographic images with minimal quality loss (20 to 1) and small file size. TIFF format, or Tagged Image File Format, is a file format especially developed for page composition applications, admitted by image edition software. TIFF files can store information in RGB, CMYK and LAB colour modes, but not duotones.

WinDendro™ can analyse images from 12 bits per pixel, but with a 16-bit image works with 65,536 levels of grey (8-bit image recognizes just 256 levels) (Soille and Misson 2001, Bucur 2003, Christy et al. 2005). For example, if a scanner is used, a resolution of 100 or 200 dpi is recommended when the distance between rings exceeds 2 mm. If distance is shorter than 1 mm, very frecuent with not conifers species, a resolution of more than 400 dpi is required. Dendrochronologists normally use images at the highest resolution (Guay et al. 1990, Carter et al. 1999, Regent Instruments Inc. 2002). However, times of analysis and file sizes increase four-fold when the resolution of the image is doubled, or when using a colour image instead of a grey-scale image. The use of colour does not improve analysis accuracy, but variations can be more easily detected by the operator on a colour image than on a grey-scale image. Regent Instruments Inc. recommends scanning just a part of the wood disk and not the whole disk in order to obtain a considerable reduction in the size of the final file. However, working with a portion of the disk reduces the possibilities of comparison with other zones of the section and this reduction constitutes a disadvantage if there are doubts about the number or width of the growth rings on the selected path (Soille and Misson 2001).

Working with hardwoods, this difficulties are emphasized, because the transition or colour change from earlywood to latewood is less contrasted than in conifers (Thetford et al. 1991), and the disk surface becomes uniform after the brief seasoning period that follows cutting (Abrams et al. 1997, WinDendro™ 2001, Vila-Lameiro and Díaz-Maroto 2005). Moreover in this species, the superimposed and/or very narrow rings (growth reductions) is intensified.

Taking into consideration these constraints, the study focused mainly on developing a methodological procedure to provide the program with quality images, appropriate contrast between rings and appropriate file sizes for easy management. Following the recommendations by Regent Instruments Inc., at least one side of all the *Quercus petraea* samples was sanded, removing irregularities and defects caused by field sampling (Regent Instruments Inc. 2001, Soille and Misson 2001).

To start the analysis was used the scanner supplied by Regent Instruments Inc. together with WinDendro™. The best scanner among the different purchase options was an Epson Expression 1680, which is a flatbed colour image scanner, with a maximum read area of 216mm x 297mm. The light source of the scanner is a Xenon gas cold cathode fluorescent lamp, with a scanning resolution of 1,600 x 3,200 dpi and an output resolution of up to 12,800 dpi at 200% zoom (Abrams et al. 1998, WinDendro™ 2001). 12-bit greyscale images (4,096 levels of grey) and 36-bit colour images (68.4 millions of colours) can be generated. That is to say, a comercial scanner that result available to test the quality of the image display and the response of the program to direct scanning of sanded wood disks for acquire the image. The results induced to study how to enhance contrast because the boundaries of growth rings could not be detected with clarity, and the obtained image was too "homogeneous", what means a problem with *Quercus* species and with another decidous hardwoods. Resolutions higher than 800 dpi must be used in order to reach a minimum image quality that enables detection. Too large files were obtained in the initial stage of the study using small and medium sized disks. For example, the smallest file size obtained for disks smaller than 10 cm was 3 Mb, reaching 38 Mb if resolution was increased to 2,400 dpi. Then, use this image acquisition system is unfeasible because a file with the minimum quality for disks a little larger than 15 cm exceeds 20 Mb (Christy et al. 2005). Consequently, two difficulties arouse in research after the first trials: disks required a technique to enhance contrast and the use of the scanner became unfeasible due to the large size of the files obtained if the analysis of the complete disk surface was performed.

To solve the problem of growth ring contrast, previous works that analysed *Quercus petraea* core samples collected by using a Pressler borer were taken into consideration. The mentioned works showed that alternately wetting and drying the samples favoured the occurrence of the desired contrast (Soille and Misson 2001, Vila-Lameiro 2003). Based on this method, a continuous process was developed, which consisted in: brushing of the impurities that resulted from disk polishing and sanding, surface wetting, quick partial evaporation of moisture and image acquisition. By applying this procedure, the image of each sample can be obtained in the most convenient moment of contrast and analysis can be conducted with more ease because the moment is immortalized.

To solve the problem posed by the large size of the generated files, the use of a digital camera was suggested (Benckert 2004). The selected model was Canon PowerShot G1. As in the scanner selection, this camera is a comercial model that allows a maximum resolution of 3.34 million pixels, with three different resolution modes: 2,048 x 1,536; 1,024 x 768; and 640 x 480 pixels, working with ISO sensitivities of 50, 100, 200 or 400. The macro mode covers a focusing range of 6 to 70 cm, which has an equivalent 35mm focal range of 34 to 102 mm. Then any other model could be selected to follow the test.

The first tests using a digital camera were completely satisfactory. Using samples with a diameter of more than 35 cm and applying maximum resolution –2,048x1,536 pixels– files never exceeded 1,200 Kb. The problem related to the size of the resulting image was solved (Guay et al. 1992, Conner et al. 2000).

One of the difficulties of using the digital camera was to determine the most appropriate adjustment option for the proposed test. After several attempts, Macro mode was selected. In this mode, the camera is adjusted to take photographs at less than 70 cm and with constant automatic focusing. Final adjustments included enabling the option of detail enhancement, and disabling the automatic flash in order to avoid the excess of momentary light that caused unwanted glare. Instead, two 500 W halogen light source was placed at a distance of 30 cm from the wood sample. This halogens lights the surface disk indirectly, what means no glare (Conner et al. 2000).

However, the use of the digital camera presented two problems that did not occur when using the scanner: scale problems caused by different zoom levels and possible distortions at the edges of the photograph induced by conic projection.

The distortions induced by conic projection appeared more difficult to solve. A graph with 1 mm spacing between lines was designed (Fig. 1). The graph was printed and photographed using the camera, the resulting file was downloaded to the computer and the relevant measurements were performed, consisting on sets of four points, randomly selected from diferent zones in Fig. 1. The difference between the largest and the shortest measured distances did not exceed two tenths of a millimeter. Any possible distortion caused by the printer on the image was taken into consideration. The printer could alter the screen scale and vary the 1mm-equidistance between the designed lines. However, this fact did not influence the results because scale was known to be uniform over the whole graph. The purpose of measurements was not to compare specific dimensions but to compare variations of a dimension, constant over the whole graph.

The verified absence of variation suggested that the use of a conic projection did not vary the dimensions at any point of the image, what's logical because distortion occurs when different height values are assigned to the image. The highest zones of the image (elevations) display the nearest points, and the lowest zones (depressions) display the most distant points. This effect appears only when working with aerial photographs and, in this case, all the points were measured on the same plane and distortion due to conic projection was not possible (Soille and Misson 2001).

To solve the scale problem we part from the photographs scale was unknown, although scale data must be known in order to calibrate the image using WinDendro™. Allthought, the Canon PowerShot G1 has different zoom levels, as any other camera. The use of a progressive zoom did not enable discrete definition of 'zoom in' and 'zoom out', and made adjustment difficult. Moreover, the camera was automatically disabled to protect the lens and the system if it was not used in a continuous manner. Variations of scale occurred within the same stem disk package because wood disk preparation interfered photograph shooting, and the camera was sometimes disabled.

A system for calibration of photographs was developed to solve the limitations mentioned. As in the case of conic projection problem, a graph of two perpendicular axes was developed to enabled easy calibration of any image both on the horizontal and on the vertical axis (Fig. 2). The graph was printed and attached to the disk holder, and served as reference scale for all the photographs. The first photograph of each tree and the first photograph taken after the disconnection of the camera showed the disk holder with no disk on it, using this image to calibrate WinDendro™ independently of zoom, because the dimensions of the graph scale used were known.

At this point of work, the first objective relative to obtain the perfect image was performed. Then, the photographs of all the disks were obtained in a sequential and mechanical manner, starting from the basal disk of each tree, and up to the moment that the memory card of the camera was full.

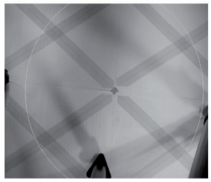


Fig. 1: Graph designed to determine the distortions induced by conic projection

Fig. 2: System developed for calibration of photographs

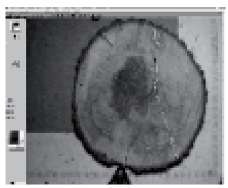


Fig. 3: Perpendiculars to the rings converging at the centre of the disk

Fig. 4: First photograph used to choose the most suitable to use with WinDendro

Fig. 5: Second photograph used to choose the most suitable photograph to use with WinDendro

Selection and analysis of the path using WinDendro™

In order to make detection faster and more accurate, the recommended orientation of the path runs from the pith to the bark (Regent Instruments 2001, Guilley and Nepveu 2003). Yet, if the heartwood is too damaged or if there is no heartwood, it's posible to calculate the location of the pith and estimate the number and dimensions of the rings up to the centre. The heartwood error detection can be corrected by applying the automatic detection system. However, computer-assisted detection of the location of the heartwood and of non-detectable rings at the centre of the disk must be used only as an aid or as the verification of the observations conducted by the researcher (Guay et al. 1990, WinDendro™ 2002). The operational process consists in placing correctly and with the highest accuracy the first rings that are easily visible by using the method of tangent definition of ring boundaries. Then, the first three rings are selected and the program plots the perpendiculars to the rings, which converge at the centre of the disk (Fig. 3). After the heartwood of the disk was calculated, WinDendro™ estimates the mean width of the first five rings, correctly defined, and, by extrapolation, the number of rings between the first detectable ring and the heartwood, wich result requires surveillance and approval of the analysis manager.

When the disk center is clear, the selection of the most suitable path is complex because it requires the combination of a favourable location for image analysis and interpretation, and of a characteristic dimension, representative of the mean radius of the wood sample. The selection of the path is particularly relevant for slow growth species such as genus Quercus and decidous hardwoods, like tropical ones, in general, due to the frequent occurrence of non-circular sections and of a completely off-centre position of the heartwood and, consequently, of the initial point of analysis (Rojo and Montero 1996). This requirement can be met by following the recommendations by Rojo and Montero (1996): in order to know the required dimension, the area of each wood disk is equated to the area of an ellipse. The two characteristic dimensions measured were: the semimajor axis and the semiminor axis, established by drawing a perpendicular line at the centre point of the semimajor axis. Whether each semiaxis crossed the area of the disk at the centre (heartwood) or not was not taken into consideration for selection. Once these two dimensions are known, the area of the analysed ellipse (disk) can be calculated. Equating the area of the ellipse to the area of a circumference of equivalent dimensions, the radius of the circumference can be known. The value of the circumference radius constitutes the representative characteristic dimension required. The process described above can be mathematically described as follows:

Ellipse area $S_e = \pi \cdot a \cdot b$ a, b = ellipse semiaxes

Circumference area $S_c = \pi \cdot R^2$ R = characteristic radius

$$S_e = S_c = \pi \cdot a \cdot b = \pi \cdot R^2 \qquad \Rightarrow \qquad R = \sqrt{a \cdot b}$$

The representative characteristic dimension, which is the radius used in measurements performed with WinDendro™, is equal to the square root of the semiaxes of the ellipse (Rojo and Montero 1996). The case of the ellipse is the least favourable because if the shape is completely regular and equivalent to a circumference, the value of the radius is obtained directly. The selection and dimensioning of the characteristic radius can be performed directly on the digitized image due to the calibrated images enable direct on-screen measurements on the image of the disk, which avoids performing direct measurements on the wood sample that could affect accuracy of measurements.

After the mean radius was calculated for each disk, two paths per disk were selected, starting at the pith on zones where analysis was possible, avoiding branch insertion, alive knots, rotten sections or zones with non-detectable rings. In some disks, finding the two radii under good conditions was not possible. In those cases, exactness of the calculated characteristic radius was sacrificed in favour of working with a path that offered reliable information. When sacrifice in radius selection was excessive (a 5% limit was arbitrarily established), the value of only one radius was taken into consideration, as well as the disk was cancelled when none of the radii could be taken into consideration (Soille and Misson 2001).

Each of the selected paths generated a sequence of data as result that can be exported as a single reference ring (Reference Data) or as a set of paths where the mean value of the sequence of ring widths represented on each active path must be calculated, provided the final ring count coincides for all the paths. This mean value is similar to a "mean ring" (Abrams 1997, Regent Instruments Inc. 2002).

When the paths were defined, the analysis started by applying the process of automatic detection of growth rings (Automatic Ring Detection). This option can be disabled and rings can be defined manually. However, maintaining automatic detection and completing it by using manual correction if necessary, is preferred. The automatic detection depends on sample preparation and ring contrast, and smaller widths require more careful preparation. If the analysed species has a natural low contrast on the ring boundaries and/or high ring density, automatic detection is more difficult and originates unexpected results (Sheppard 1995, Abrams 1997 and 1998). The use of WinDendro™ as a tool for the analysis of hardwoods of slow growth was rejected in several occasions due to improper or inadequate preparation of samples, rather than to impossibility of use. The program tends to define rings in excess and, therefore, detection sensitivity must be conveniently managed, by defining a minimum ring width (0.01 mm is admitted). Automatic analysis can be improved by changing the sensitivity limits of the program modifing the profile area. This area consists of two screen sections: a horizontal and a vertical section. The variations on the colour intensity of the image when crossed by the path and, consequently, the possible boundaries of the growth rings are recorded in these sections. The profile area includes a sensitivity selector that enables the modification of the sensitivity of analysis in those images or parts of images with lower colour contrast and worse automatic detection. Using the manual detection system, the program "learns" the locations where the growth ring markers must be placed. The Teach and show system stores the variations of image colour contrast that the user wants to identify as boundaries between two growth rings (Regent Instruments Inc. 2002). By enabling this option, WinDendro™ detects rings by comparing the current image with a previously analysed image, which becomes the defining image of typical rings (Ivkovich and Koshy 1997).

Respect to path orientation, the boundaries of the ring can be defined perpendicular to the direction of the path. The program does not need to find the ring orientation, and the lines defining the boundaries are perpendicular to the path. This method is faster but less accurate. The second possible method defines the ring boundaries tangent to the ring and independently of the direction of the path (Fig. 7). In that case, the program uses the orientation angle of the ring to perform a more accurate definition of the ring width by applying triangulation adjustments. If the selected orientation is wrong, the ring boundaries must be manually reoriented. This method performs a more accurate definition of ring and of ring density measurements, and it's more consistent with dendrochronological standard procedures (Regent Instruments Inc. 2002). Consequently, a revision of ring detection by the program operator is advisable in all cases.

Other situations can arise that present difficulties for analysis, independently of the detection system used (automatic or manual detection). In the case of deciduous hardwoods, samples often lack a path that is able to connect the heartwood of the disk and the bark because growth rings present irregularities, image faults, etc. (Guay et al. 1992, Guilley and Nepveu 2003). The conventional path is replaced by a path divided into several segments, which allows the program to "avoid" zones of scarce visibility. This is an equivalent situation to trees with some paths cut by holes or seasoning checks. The problem can be solved by defining a Gap Area, which consists in marking the interruption of measurements so that the program stops calculations at that point and resumes calculations at the point defined as the end of the gap area. This measurement problems can be easily solved both by using computer tools such as WinDendro™, and by applying the classical methods for manual measurement, what means an important degree of subjectivity in the estimation of the ring width.

Finally, growth reductions constitute an extremely serious problem in classical methodologies, and were studied by other authors (Martinelli and Pignatelli 1992, Pérez 1995). Growth reductions are the years of minimum or 'zero' growth, and cause a marked confusion between several rows of vessels in earlywood. The use of computer tools allows working with much larger detail in image and zooming magnification than the human eye or conventional magnifying lenses. By using a computer, the number of growth rings/years that coexist in a small portion of disk can be easily determined and translated in practice into a series of very narrow rings or into a superimposition of rings with no growth. In the case of ring superimposition, the confusion can be solved by inserting null rings, so that rings superimpose on other selected rings. Growth reduction or the existence of null rings is considered one of the greatest problems of tree-ring analysis (Schmidt et al. 1996, Conner et al. 2000), and justifies the need of studying the complete image of the disk. By studying the whole surface, it is possible to compare and analyse if growth reduction exists on other radii, what it's not enabled when managing an image slightly wider than the path.

Obtaining results with WinDendro™

The last step, if the analysis of the wood sample on all the marked paths is satisfactory, implicates to export the results as a graphic or a text file. Graphic files enable direct printing of the image on the printer or into a file, as a bitmap (BMP). Exporting numerical data in text format is more useful for several purposes, such as further analysis, information management, compatibility with other applications, and comparison of the resulting information with other information sources. There are two options to export numerical data in text format: based on path pixels (*.pxb) or based on the information obtained from growth rings (*.txt). Text format was chosen for the present study because it can be easily imported by databases, spreadsheets or statistical packages (Regent Instruments Inc. 2002, WinDendro™ 2002).

The information contained in the text file is wide-ranging. First, it contains information about the conditions of analysis: data about the program and version used to create the text file, orientation of data in the file (columns or rows), order of ring analysis (from the centre to the bark, or vice versa), the dimensioning mode of the rings (incremental or cumulative from the heartwood), or the existence or not of data about bark thickness. The text file also contains data resulting from the analysis. The description of each disk is distributed over 10 fields: Ring width in mm with three decimals of accuracy, Earlywood width (mm) Percentage of earlywood according to width of the growth ring, Latewood width (mm), Percentage of latewood according to width of the growth ring, Maximum, minimum and mean ring density, Mean density of rings in earlywood and latewood.

Fig. 6: Photograph of the disk obtained from the selected sample tree at a height of 2.3 m

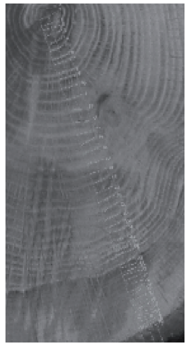


Fig. 7: Example of measurement path created with Windendro™

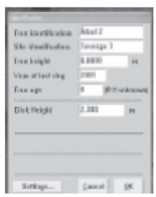


Fig. 8: Example of information provided to Windendro™

Example of measurement using WinDendro™

According to the description of use of WinDendro™, and applying the description to one of the sample trees felled in fieldwork, an account is given of how disks and images were managed, and of the results of the analysis conducted to the selected sample tree. The tree was felled in the most eastern zone of the study area, in South Asturias (sample tree number 2; plot 'Teverga 3'). Selection was made at random because all the sample trees were valid. The first step was brushing each disk of the tree in order to remove the fine dust produced by sanding. Then, the sanded disk surface was wetted in order to enhance contrast between earlywood and latewood. After a brief seasoning period (5 to 10 minutes, depending on the tree), photographs were taken of all the disks.

In the case of the selected tree, 16 photographs were shot from the 15 disks obtained. The first photograph did not fit completely in the image due to the zooming level, which was frequent in the first and second disks. The most suitable photograph was chosen during stem analysis using WinDendro™ (Figs. 4 and 5).

The image on Fig. 6 shows the photograph of the disk that was obtained from the selected sample tree at a height of 2.3 m. In order to calibrate the program, a ‘twin’ image was used. The image was identical to disk images, but it did not contain a photograph of the disk (see Fig. 2).

After calibration of the program, the image of the first disk was imported from WinDendro™, and identified by: name of the plot, tree, disk height, year of last ring growth, tree age (if known), and total tree height. Fig. 8 shows the information provided. The characteristic radius was dimensioned following the method by Rojo et al. (1996). A zone of the disk was chosen in which the two selected paths were defined in order to calculate the mean, and to obtain the definitive path. In this case, the characteristic radius was 26 cm.

As a result, the program offered the two definitive selected paths, as shown in Fig. 3. Tab. 1 shows the results of the analysis, including one example of part of the results for the disk obtained at a height of 2.3 m from the ground. The large quantity of data obtained made it difficult to fit disk information in just one table.

Tab. 1: Obtained results with Windendro for Tree 2 from Plot Teverga 3

Section Height	Ring Count	Data Type	1	2	3	4	5	6	7	8	9	10	11	12
2,3	**48**	*Ringwidth*	1,85	2,42	2,69	2,50	1,60	1,85	2,78	3,13	3,64	2,44	3,95	3,74
2,3	**48**	*Earlywidth*	0,52	2,42	2,69	2,21	1,28	1,26	1,52	2,16	1,37	0,26	3,69	3,74
2,3	**48**	*Latewidth*	1,33	0,00	0,00	0,29	0,31	0,59	1,27	0,96	2,28	2,17	0,27	0,00
2,3	**48**	*Earlywidth*	28,28	100,00	100,00	88,27	80,34	68,15	54,51	69,24	37,50	10,81	93,22	100,00
2,3	**48**	*Latewidth*	71,72	0,00	0,00	11,73	19,66	31,85	45,49	30,76	62,50	89,19	6,78	0,00
2,3	**48**	*Ringdensity*	43,86	63,78	94,60	133,70	151,83	148,29	114,10	94,92	63,50	54,60	53,71	48,63
2,3	**48**	*Earlydensity*	52,00	63,78	94,60	132,67	151,40	151,60	123,00	99,67	65,00	67,50	53,31	48,63
2,3	**48**	*Latedensity*	40,60	0,00	0,00	143,00	154,00	140,00	100,75	80,67	62,38	51,38	60,00	0,00
2,3	**48**	*Maxdensity*	54,00	84,00	136,00	152,00	164,00	158,00	135,00	106,00	70,00	69,00	63,00	58,00
2,3	**48**	*Mindensity*	39,00	41,00	81,00	117,00	139,00	138,00	94,00	73,00	54,00	49,00	45,00	39,00

(continue Tab. 1)

Anillo																	
13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
4,51	5,13	4,71	4,33	4,23	5,82	4,44	4,29	5,49	4,28	5,92	5,35	4,55	5,25	5,27	3,73	3,66	3,95
4,08	4,82	4,38	3,82	3,91	5,31	4,03	3,79	5,03	3,66	4,86	4,09	3,37	2,75	4,07	2,21	2,76	3,56
0,43	0,31	0,33	0,51	0,31	0,50	0,41	0,50	0,47	0,62	1,06	1,26	1,18	2,50	1,21	1,52	0,90	0,38
90,38	93,91	92,93	88,20	92,57	91,33	90,81	88,42	91,50	85,49	82,10	76,44	74,05	52,41	77,13	59,27	75,46	90,29
9,62	6,09	7,07	11,80	7,43	8,67	9,19	11,58	8,50	14,51	17,90	23,56	25,95	47,59	22,87	40,73	24,54	9,71
49,22	51,71	58,00	56,56	53,89	41,77	41,61	40,06	46,95	48,59	45,35	103,70	155,44	172,95	178,60	165,00	169,73	167,88
48,88	51,00	57,44	55,73	53,24	41,48	40,88	39,20	46,00	48,80	45,89	103,56	156,36	176,82	184,50	180,22	173,58	167,67
55,00	66,00	68,00	69,00	65,00	48,00	54,00	53,00	66,00	47,00	42,75	104,25	152,25	168,22	155,00	137,60	154,33	171,00
60,00	73,00	82,00	74,00	76,00	58,00	60,00	61,00	74,00	61,00	63,00	134,00	192,00	191,00	197,00	192,00	183,00	179,00
36,00	42,00	44,00	43,00	43,00	33,00	26,00	25,00	31,00	40,00	34,00	56,00	104,00	148,00	149,00	126,00	149,00	151,00

CONCLUSIONS

1. The use of computer implementations to aid detection and measurement of rings and other related parameters speeds up the process, increases reliability. Future remeasurements can be performed at ease because the wood disks sampled must not be kept.
2. The incorporation of the digitized wood sample to be measured into the computer system enables storing the sample for the time necessary. Working with the complete image of the wood disk constitutes an advantage as compared to disk paths of increment cores.
3. The use of deciduous hardwood samples, especially tropical ones or boreal and temperate species, complicates the process because detection of growth rings is more difficult in these species. Preparation of samples is required prior to analysis: sanding, contrast enhancement and digital image acquisition.
4. WinDendro™ software is easy to use, intuitive and easy to customize to the special circumstances of each research process. One of the main advantages of this software is the interactive system that allows the program to "*remember*" which variation in the image must be interpreted as a growth ring.
5. The use of the scanner provided by Regent Instruments Inc. is restricted to the cases in which working with the complete image of the disk is not necessary, and in which just one path can be used due to lack of irregularities, growth reductions or null rings. In other cases, the use of a digital camera is more suitable. The size of the images obtained with the digital camera can be easily managed by the computer.
6. The common difficulties of tree-ring analysis, such as lack of heartwood, vision problems, presence of gaps or holes, or use of various paths to compare measurements on different zones of the disk, can be easily solved by different program commands.
7. The information exported from the program is wide-ranging and can be adapted to the requirements of each situation. Particularly, text format is especially useful for further statistical processing. Many parameters can be taken into consideration, and not only age and ring width.

ACKNOWLEDGMENTS

This work was funded by the *Dirección Xeral de Investigación e Desenvolvemento of the Consellería de Innovación, Industria e Comercio, Xunta de Galicia*, within the framework of research project PGIDIT02RFO29101PR, developed in the Department of Agroforestry Engineering of the University of Santiago de Compostela.

REFERENCES

1. Abrams, M.D., Orwig, D.A., Dockry, M.J., 1997: Dendroecology and successional status of two contrasting old-growth oak forests in the Blue Ridge Mountains, USA. Can. J. For. Res. 27: 994-1002
2. Abrams, M.D., Ruffner, C.M., Morgan, T.A., 1998: Tree-ring responses to drought across species and contrasting sites in the Ridge and Valley of Central Pennsylvania. Forest Sci. 44 (4): 550-558
3. Amorini, E., Fabbio, G., 1988: Il metodo auxometrico: applicazioni in selvicoltura. L'analisis auxometrica in selvicoltura: il metodo di analisi del fusto. Annali dell'Istituto Sperimentale per la Selvicoltura. XIX: 7-46
4. Ayuga, E., González, C., Martín, S., Martínez, J.E.,, Pardo, M., 1998: Técnicas de muestreo en ciencias forestales y ambientales. Bellisco, Madrid, Spain
5. Benckert, L., 2004: Wood drying studies using white light speckle photography. Measurement. 10 (1): 24-30
6. Bucur, V., 2003: Techniques for high resolution imaging of wood structure: a review. Meas. Sci. Technol. 14 (12): 91-98
7. Carter, R., Leroy, S., Nelson, T., Laroque, C.P., Smith, D.J., 1999: Dendroglaciological investigations at Hilda Creek rock glacier, Banff National Park, Canadian Rocky mountains. Geogr Phys Quatern. 53 (3): 365-371
8. Christy, A.G., Senden, T.J., Evans, P.D., 2005: Automated measurement of checks at wood surfaces. Measurement. 37 (2): 109-118
9. Conner, W.S., Schowengerdt, R.A., Munro, M., Hughes, M.K., 2000: Engineering design of an image acquisition and analysis system for dendrochronology. Opt. Eng. 39 (2): 453-463
10. Cook, E.R., Kairiukstis, A., 1990: Methods of dendrochronology- Applications in the environmental Sciences. Kluwer Academic Publishers and International Institute for Applied Systems Analysis, Dordrecht, Netherlands
11. Courbet, F., 1999: A three-segmented model for the vertical distribution of annual ring area – Applilcation to *Cedrus atlantica* (Manetti). Forest. Ecol. Manag. 119 (1-3): 177-194
12. Courbet, F., Houllier, F., 2002: Modelling the profile and internal structure of tree stem. Application to *Cedrus atlantica* (Manetti). Ann. For. Sci. 59 (1): 63-80
13. Cufar, K., Levanic, T., 1999: Tree-ring investigations in oak and ash from different sites in Slovenia. Phyton-Ann. Rei. Bot. A. 39 (3): 113-116
14. Díaz-Maroto, I.J., 1997: Estudio ecológico y dasométrico de las masas de carballo (*Quercus robur* L.) en Galicia. Doctoral Thesis. Unpublished. E.T.S.I.M, Madrid, Spain
15. Díaz-Maroto, I.J., 2001: Informe final del proyecto de I+DT C-1999. Estudio epidométrico de las masas de *Quercus robur* L. en Galicia y su influencia sobre la calidad de la madera. Inédito, Secretaría Xeral de Investigación e Desenvolvemento, Xunta de Galicia, Spain
16. Díaz-Maroto, I.J., Vila-Lameiro, P., Silva-Pando, F.J., 2005: Autoécologie des chênaies de *Quercus robur* L. en Galice (Espagne). Ann. For. Sci. 62: 737-749
17. Díez, M.R., Fernández-Golfín, J.I., 1998: Influencia de diversos factores en la calidad de la madera de uso estructural de *Pinus sylvestris* L. Rev. Inv. Agr. Ser. Sist. Rec. For. **7** (I): 41-51

18. Douglass, A.E., 1920: Evidence of climatic effects in the annual rings of trees. Ecology 1 (1): 24-32
19. Fernández-Parajes, J., Díaz-Maroto, I.J., Vila-Lameiro, P., 2005: Physical and mechanical properties of rebollo oak (*Quercus pyrenaira,* Wild.) wood in Galicia (Spain). Wood Res. 50(4): 1-15
20. Gadow, K.V., Rojo, A., Álvarez, J.G., Rodríguez, R., 1999: Ensayos de crecimiento. Parcelas permanentes, temporales y de intervalo. Inv. Agr. Sist. Rec. For. Fuera de Serie I. INIA, Madrid, Spain
21. Gjerdrum, P., 2003: Heartwood in relation to age and growth rate in *Pinus sylvestris* L. in Scandinavia. Forestry 76(4): 413-424
22. González, I.G., Eckstein, D., 2003: Climatic signal of earlywood vessels of oak on a maritime site. Tree Physiol. 23 (7): 497-504
23. Guchu, E., Díaz-Maroto, M.C., Díaz-Maroto, I.J., Vila-Lameiro, P., Perez-Coello, M.S., 2006: Influence of the species and geografical location on volatile composition of Spanish oak wood (*Quercus petraea,* Liebl. and *Quercus robur* L.). J. Agric. Food Chem. 54(8): 3062-3066
24. Guay, R., Gagnon, R., Morin, H., 1990: A new automatic and interactive tree-ring measurement system based on a line scan camera. In Proceedings of the International Dendrochronological Symposium: Tree rings and Environment, 3-9 September 1990, Lundqua Report, Ystad, Sweden.
25. Guay, R., Gagnon, R., Morin, H., 1992: A new automatic and interactive tree-ring measurement system based on a line scan camera. Forest Chron. 68 (1): 138-141
26. Guilley, E., Nepveu, G., 2003. Anatomical interpretation of the components of a wood density mixed model in sessile oak (*Quercus petraea,* Liebl.): ring number from the pith, ring width, tree, interannual variation, heartwood formation. Ann. For. Sci. 60 (4): 331-346.
27. Hummel, F.C., 1969: Code of sample plot procedure. Forestry Commission Booklet. 34, London, Great Britain
28. Ivkovich, M., Koshy, P.M., 1997: Wood density measurement: comparison of X-ray, photometric methods. In Proceedings of the 26th Biannual Meeting of the Canadian Tree Improvement Association and International Workshop on Wood Quality: Timber Management Toward Wood Quality and End-Product Value, August 1997, CTIA/IUFRO, Quebec City, Canada. Pp. 55-58
29. Madrigal, A., 1992: Selvicultura de hayedos. Rev. Inv. Agr. Sist.Rec. For. Fuera de serie I (II): 33-60
30. Madrigal, A., Álvarez, J.G., Rodríguez, R., Rojo, A., 1999: Tablas de producción para los montes españoles. Fundación Conde del Valle de Salazar. E.T.S.I.M, Madrid, Spain
31. Martinelli, N., Pignatelli, O., 1992: Tree-ring analysis on oak in northern Italy. *In* Bartholin T.S., Berglund, B.E.
32. Palviainen, J., Silvennoinen, R., 2001: Inspection of wood density by spectrophotometry and a diffractive optical element based sensor. Meas. Sci. Technol. 12 (3): 345-352
33. Pérez, A., 1995: Comentarios sobre la evolución de los bosques gallegos hasta comienzos del siglo XX. Rev. Montes. 41: 5-20
34. Pita, P., 1991: Potencialidad de las estaciones forestales. Curvas de calidad. *In* Proceedings of the Seminario sobre Inventario y Ordenación de Montes, August 1991, ETSIM, Segovia, Spain. Tematic Unit 1: 18-39

35. Regent Instruments Inc., 2002: Manual de Windendro™ 2002. Regent Instruments Inc. Chicoutimi, Quèbec, Canada
36. Rittie, D., Gelhaye, P., 2002: Détermination d'un seuil de séparation pour la mesure des largeurs de bois initial et final sur l'épicéa commun. Piecea abies Karst. Bulletin des techniques de l'Inra
37. Rivas-Martínez, S., 1987: Memoria y mapas de las series de vegetación de España (1:400.000). IONA, Madrid, Spain
38. Rojo, A., Montero, G., 1996: El pino silvestre en la Sierra de Guadarrama. Ministerio de Agricultura, Pesca y Alimentación, Madrid, Spain
39. Romero, M.I., 1993: La vegetación del valle del rio Cabe (Terra de Lemos, Lugo). Doctoral Thesis. Unpublished. Faculty of Biology, Univ. Santiago de Compostela, Spain
40. Rozas, V., 2001: Detecting the impact of climate and disturbances on tree-rings of *Fagus sylvatica* L. and *Quercus robur* L. in a lowland forest in Cantabria, Northern Spain. Ann. For. Sci. 58 (3): 237-251
41. Rozas, V., 2003a: Regeneration patterns, dendroecology, and forest-use history in an old-growth beech-oak lowland forest in Northern Spain. Forest. Ecol. Manag. 182 (1-3): 175-194
42. Rozas, V., 2003b: Tree age estimates in Fagus sylvatica and *Quercus robur*: testing previous and improved methods. Plant Ecol. 167 (2): 193-212
43. Schmidt, R.A., Kaufmann, M.R., Porth L., Watkins, R.K., 1996: Measuring tree-ring increments on tree bole sections with a video-based robotic positioner. Tree Physiol. 16 (10): 865-870.
44. Schulman, E., 1938: Nineteen centuries of rainfall history in the southwest. B. Am. Meteorol. Soc. 19 (5): 211-216
45. Sheppard, P.R., 1995: Reflected-Light image. Analysis of conifer tree rings for dendrochronological research. Doctoral Thesis. Department of Geosciences, University of Arizona, USA
46. Simpson, H.L., Denne, M.P., 1997: Variation of ring width and specific gravity within trees from unthinned Sitka spruce spacing trial in Clocaenog, North Wales. Forestry 70(1): 31-45
47. Smelko, S., Scheer, L., 2000: Dendrochronological analysis of diameter growth and increment of pedunculate oak (*Quercus robur* L.) in Danube floodplain forests. Ekol. Bratislava 19 (2): 125-140
48. Soille, P., Misson L., 2001: Tree ring measurements using morphological image analysis. Can. J. For. Res. 31 (6): 1074-1083
49. Splechtna, B.E., Dobry, J., Klinka, K., 2000: Tree-ring characteristics of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) in relation to elevation an climatic fluctuations. Ann. For. Sci. 57 (2): 89-100
50. Spurr, S.H., 1952: Forest inventory. The Ronald Press Company, New York, USA
51. Telewski, F.W., Lynch A.M., 1991: Measuring growth and development of stems. CRC Press, Boca Raton
52. Thetford, R.D., Darrigo, R.D., Jacoby G.C., 1991: An image-analysis system for determining densitometric and ring-width time-series. Can. J. For. Res. 21 (10): 1544-1549
53. Vila-Lameiro, P., 2003: Estudio epidométrico y xilológico de las masas de *Quercus petraea* (Mattuschka) Liebl. en el noroeste de la Península Ibérica. Doctoral Thesis. Cd-Rom. ISBN: 84-9750-304-X. Santiago de Compostela, Spain

54. Vila-Lameiro, P., Díaz-Maroto, I.J., 2005: Study of the influence of environmental factors on the width of growth rings in *Quercus petraea* (Matts.) Liebl. through interpretation of digital images. Wood Res. 50 (3): 23-36
55. WinDendro™, 2002: Online Regent Instruments Inc. and WinDendro™ support. Available from http://www.regentinstruments.com. Updated June of 2002. Cited June of 2002
56. Zhang, S.Y., Nepveu, G., Eyono R., 1994: Intratree and intertree variation in selected wood quality characteristics of european oak (*Quercus petraea* and *Quercus robur*). Can. J. For. Res. 24: 1818-1823
57. Zobel, B.J., Buijtenen, J.P., 1989: Wood variation: its causes and control. Springer-Verlag, Tokio, Japan

Vila-Lameiro P.
Department of Agroforestry Engineering
University of Santiago de Compostela
Campus Universitario s/n
E–27002 Lugo
Spain
Tel.: +34982285900
Fax: +34982285926
E-mail: pablovl@lugo.usc.es

Díaz-Maroto I.J.
Department of Agroforestry Engineering
University of Santiago de Compostela
Campus Universitario s/n
E–27002 Lugo
Spain
Tel.: +34982285900
Fax: +34982285926
E-mail: diazmaro@lugo.usc.es