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Programa de doctorado de Biociencias y ciencias agroalimentarias

Analysis of methodologies to evaluate juvenile wood with regard to wood quality

Análisis de metodologías para la evaluación de la madera juvenil en la calidad de la madera

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Mención de Doctorado Internacional

La presente Tesis cumple con los requisitos establecidos por la Universidad de Córdoba en relación a la obtención de la Mención de Doctorado Internacional, que se exponen a continuación:

- Estancia de 3 meses en el grupo de "Wood Chemistry" del departamento "Material Sciences and Process Engineering (MAP)", de la "University of Natural Resources and Life Sciences (BOKU)" (Viena, Austria), bajo la supervisión de la Ao.Univ.Prof.Mag. Dr. Barbara Hinterstoisser y el Dr. Andreas Ziteck, en la que se realizó parte del trabajo del Capítulo 6 y en el que también se intentó, durante la estancia, en el "Institute of Physics and Materials Science (IPM)" de la mano de la Ao.Univ.Prof.Mag. Helga Lichtenegger y el Dr. Harald Rennhofer, realizar el escaneo del ángulo de microfibrillas anillo a anillo de madera de primavera y verano de muestras mediante difractómetro
- Estancia de 3 meses en el "Department of Economics Business and Statistical Sciences (Scienze Economiche Aziendali e Statistiche- DSEAS)", de la Università degli Studi di Palermo (Italia), bajo la supervisión de Vito Michele Rosario Muggeo, en la que se realizó el análisis de los datos correspondiente al Capítulo 2.
- Evaluación previa de dos doctores con experiencia investigadora acreditada, pertenecientes a centros de investigación o instituciones de educación extranjeros.
- Un miembro del Tribunal pertenece a un centro de investigación o institución de educación superior extranjero.

TÍTULO DE LA TESIS: ANÁLISIS DE METODOLOGÍAS PARA LA EVALUACIÓN DE LA MADERA JUVENIL EN LA CALIDAD DE LA MADERA

DOCTORANDO/A: ANTONIO RUANO SASTRE, DNI: 53623372E

INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

La presencia de madera juvenil en las producciones de maderas de coníferas es un problema de calidad de gran trascendencia, que se pone de manifiesto no solo en menores propiedades elastomecánicas sino, también, en mayores tasas de deformación en el proceso de secado. Por dicho motivo la normativa internacional (EN 14081-1) cita este defecto como de obligada evaluación en las normas nacionales de clasificación (UNE 56544), exigencia que se queda en la práctica sin aplicar por no existir método alguno para su evaluación.

La mayor o menor presencia de madera juvenil en las producciones forestales de coníferas es también una variable de desconocido manejo para la Selvicultura y la mejora genética, ya que, aunque parecen existir indicaciones sobre la posibilidad de minimizar su presencia mediante prácticas selvícolas adecuadas y/o procesos de mejora genética, la verdad es que al no existir método aceptado para su evaluación no es posible afirmar si una determinada metodología tiene o no efecto real.

Por todo lo citado anteriormente la presente tesis doctoral aborda una temática de gran trascendencia científica y económica y sus hallazgos han de impulsar no sólo un mejor conocimiento de la fisiología de los árboles (coníferas) sino, también, un avance sobre los métodos para la determinación de su cuantía en los troncos.

El doctorando ha utilizado diferentes técnicas e instrumentación analítica, así como avanzadas herramientas estadísticas para desarrollar la presente tesis, lo que ha potenciado sus capacidades y habilidades en el conocimiento de la fisiología de los árboles, así como en el de la evaluación de las propiedades físico-mecánicas de las maderas. Adicionalmente el doctorando ha realizado estancias en Centros internacionales de muy alto nivel (BOKU en Austria, en la facultad de Estadística de Palermo, Italia, así como en la Universidad de Stellenbosch en Sudáfrica).

La metodología empleada ha sido consistente y los resultados obtenidos soportan las conclusiones extraídas, las cuales tienen una evidente relevancia científica.

La Tesis se presenta como un compendio de cuatro artículos de los que uno ya ha sido publicado y los otros tres restantes han sido enviados a revistas de impacto en el área de conocimiento en el que se desarrolla el presente trabajo. También se ha añadido en un capítulo una comunicación a un congreso y un último capítulo de análisis de contracciones que se publicará juntamente con los resultados de contracciones del pino radiata, que están siendo estudiados.

Los artículos citados anteriormente son los siguientes:

- Ruano A, Zitek A, Hinterstoisser B, Hermoso E (2019) *NIR hyperspectral imaging (NIR-HI) and µXRD for determination of the transition between juvenile and mature wood of Pinus sylvestris L*. Holzforschung 73(7), 621-627 doi:10.1515/hf-2018-0186. Impact Factor (SJR): 0.83. Q2 Biomaterials, rank 43 / 77.
- Ruano A, Ruiz-Peinado R, Fernández-Golfín J, Hermoso E (n.d.) *Height growth for assessing juvenile-mature wood transition on Pinus sylvestris and Pinus nigra Spanish stands*. Wood Science and Technology (Submitted). Impact Factor (SJR): 0.97. Q1 Forestry, rank 15 / 129.
- Ruano A, Hermoso E (n.d.) *Distribution of juvenile wood along the bole considering the influence of silvicultural treatments*. European Journal of Wood and Wood Products (Submitted). Impact Factor (SJR): 0.58. Q1 Forestry, rank 41 / 129.
- Ruano A, Muggeo VMR, Fernández-Golfín J, Hermoso E (n.d.) *Estimating transition between juvenile and mature wood in two Spanish Pinus species: an approach based on segmented mixed modelling*. Wood Science and Technology (Submitted). Impact Factor (SJR): 0.67. Q1 Forestry, rank 26 / 129.

Por otro lado, el candidato ha colaborado durante el desarrollo de la tesis en un artículo publicado en una revista científica indexada en el JRC, relacionado con la calidad de la madera y su uso en estructuras expuestas a la intemperie:

- Fernandez-Golfin J, Larrumbide E, Ruano A, Galvan J, Conde M (2016) Wood decay hazard in Spain using the Scheffer index: Proposal for an improvement. Eur J Wood Wood Prod, 74(4), 591–599. Impact Factor (SJR):0.56. Q2 Materials Science, rank 185 / 439.

Adicionalmente, el candidato ha realizado 4 comunicaciones a congresos, tanto nacionales como internacionales:

- Antonio Ruano Sastre, Juan Ignacio Fernández-Golfín Seco, Eva Hermoso Prieto, Marta Conde García (2016) Efecto de las prácticas selvícolas en la calidad madera. V Congreso Científico de Investigadores en Formación de la Universidad de Córdoba. Córdoba, Andalucía, España
- Ruano A, Hermoso E, Grau JM (2017) *Near infrared spectroscopy (NIRS) for determining of juvenile wood to mature wood transition point.* II Congreso Latinoamericano de Estructuras de Madera y II Congreso Ibero-Latinoamericano de la Madera en la Construcción (CLEM+CIMAD) (UNNOBA, 2017), Ref. T3-09, 78-83. Junín, Buenos Aires, Argentina.
- Ruano Sastre A, Hermoso Prieto E, Ruiz-Peinado R, Montero G, Grau JM (2017) Estimación de la transición entre madera juvenil y adulta de *Pinus sylvestris* L. Mesa 9, Productos e industrias forestales, 7º Congreso Forestal Español. Plasencia, Cáceres, España
- Ruano A, Ruiz-Peinado R, Hermoso E (2018). Variation of juvenile-mature wood transition year along the bole of *Pinus nigra* arn. between two silvicultural treatments. New Frontiers in Forecasting Forests (NFFF 2018). Stellenbosch University, Sudáfrica.

Por último, el candidato realizó una estancia corta de dos meses en la universidad de Stellenbosch de Sudáfrica, dentro del marco de colaboración con el proyecto 778322-CARE4C H2020 (Carbon smart forestry under climate change), en el que se estudiaban crecimientos y el efecto de la selvicultura en plantaciones de pino radiata, cuyos resultados que se compararán los datos obtenidos en España de crecimientos de radiata.

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, 5 de julio de 2019

Firma del/de los director/es

Fdo.: Juan I. Fernández-Golfin Seco　　　Fdo.: Eva Hermoso Prieto

Fdo: Marta Conde García

All models are wrong, but some are useful.

George E.P. Box

Agradecimientos

Repasando los años empleados en realizar la tesis, te das cuenta de la cantidad de gente involucrada directa o indirectamente en este proyecto. En primer lugar, quisiera dar las gracias a mis directores de tesis, Eva Hermoso Prieto, Juan Ignacio Fernández-Golfín y Marta Conde García, por confiar en mi para llevar a cabo esta investigación y por el apoyo recibido.

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Summary

On conifer species, when growing, on the inner part of the log closer to the pith they produce wood with different characteristics, which show rapid and progressive changes in the rings outward from the pith in a transverse direction until a point is reached where the properties are stabilized. The area closer to the pith is called juvenile wood (JW) to distinguish it from the mature wood (MW). The JW is characterized by having a cellular structure with smaller tracheid length, lumen diameter, wall thickness, transverse shrinkage, stiffness and cellulose/lignin ratio. Other properties are lower, such as density and mechanical properties but others, such as spiral grain and microfibril angle (MFA) are higher. One phenomenon sometimes related to JW is the presence of wider growth-rings and high levels of compression wood, although these last two relationships are not mutually exclusive. The transition year (TY) between JW and MW can be found by analyzing all these different properties. The boundary tends to change according to the wood property studied with variable patterns from pith to bark. All of these characteristics have undesirable effects on the physical-mechanical and technological properties of the material for solid dimension lumber. Also, the higher the proportion of JW, the greater incidence of different drying distortions such as spring, bow, crook and twist resulting in diminished prospects for profitable end use and economic return for solid wood products.

Different explanations to the presence of these variations have been proposed and different names have been given to these two areas that can be differentiated in transversal direction of the tree at any height. When considering the longitudinal variation, the nomenclature usually employed is corewood (CW) and outerwood (OW). But in this Thesis, we will use the JW/MW nomenclature as the Spanish industrial sector still uses it.

There are several studies assessing the importance of juvenile wood for solid dimension lumber in Spain. But not much studies have been carried out on Mediterranean conifers regarding the effect of the silviculture on the amount of JW present on the bole. Basic specific gravity, MFA and densitometry have been extensively used as indicators of JW presence. In this Thesis different methodologies are studied for JW determination on *Pinus nigra* and *Pinus sylvestris* with different silvicultural management and those results are compared with the ones obtained from densitometry.

The influence of silviculture on the TY in black pine and Scots pine stands in Spain using densitometry, is studied. This analysis is done using a segmented linear mixed model including the analysis of the different covariate effects, included in the models, on density. Also, the variations on the JW volume and tree taper produced depending on the silvicultural practices using latewood (LW) density radial variation, is considered.

Other objective was to see if at basal height it is possible to estimate a TY, by means of the accumulated yearly height growth that can be related to the one obtained for yearly LW and medium density on Scots pine and black pine.

It is assessed the feasibility of using multipoint near infrared spectra (NIRs) to differentiate between JW and MW. On the same way, the potential of the near infrared

hyperspectral imaging (NIR-HI) for semi-automatic identification of JW and MW moieties carried out in Scots pine is also assessed.

Finally, it is done a study of radial and angular shrinkage patterns in the transversal direction along different heights of the bole. Based on the results on shrinkages, the JW/MW areas obtained, are related to the ones obtained through densitometry.

When assessing the JW area on a log, micro X-ray densitometry is a suitable method for its study, results showed that the best density trait for automatization of the process is LW density. If assessing the TY by increment cores, which can be done on standing trees, the pith needs to be in the extracted core in order to assess the boundary correctly.

The function developed for segmented mixed models, provides a powerful and more stable tool to predict the TY in a large number of samples using LW density profiles. Drought index is relevant for the modelling affecting LW density, on the slope on the MW or the density in TY determination. Up to a height of 9 meters TY was reached prior to the implementation of any silvicultural treatment, so further sampling is necessary to assess whether any treatment could influence or shift the transition year outside the part influenced by the crown. However, within the crown and in the case of PN, pruning was found to affect the TY because the LW density required to reach it increased, thus delaying the TY and increasing LW density. In both pine species, thinning seems to have a significant albeit slight negative effect on LW density, while the thinning and pruning combined seemed to have a small positive effect on it, compared to the control group. These results presented here may vary depending on the intensity and the timing of thinning, as well as on the amount of green pruning carried out. The growth response after silvicultural treatments show that the amount of JW is reduced in percentage as total volume increases with any silvicultural treatment applied, for both species, in Mediterranean forests.

The TY calculated using Chapman-Richards growth functions on the accumulated height increments, does not fit the estimation of the TY obtained through density for the Spanish provenances studied of Scots and black pines.

The calibration between measurements obtained with multipoint NIRs and density data derived from micro X-ray densitometry has been found difficult to obtain good enough results. On the other side NIR-HI can be calibrated with µXRD results and the JW, MW and transition point (TP) between both, can be determined on the transversal section of the tree. The results are independent from the silvicultural treatment applied in the Scots pine plantations studied. The principal component analysis was a useful and easy way to provide additional information on the presence and location of compression wood. The partial least squares discriminant analysis approach was the best procedure for detecting the TP between JW and MW, when the EW and LW were evaluated separately. Every strip was classified within ±1 annual ring difference compared with the LW. The biggest margin was ±2 annual rings. A previous automatic classification, by combination with a partitional k-means unsupervised classification, between EW and LW, would probably improve the results and could lead to a better automation of the process.

Radial shrinkage tends to be in the first rings, up to the first 8 rings near the pith, between 4 and 9 %, decreasing until it stabilizes around 3%. Regarding the angular shrinkage, is close to 0% or even negative near the pith and increases until a certain ring (9-11) when it becomes more or less stable at around 2 %. These results are valid all along the bole, being greater and the transition produced earlier in radial shrinkage than in the angular one in each height studied. No general patterns can be seen along the same tree at the different heights sampled. Applying silvicultural treatments seems not to have any significance on the radial and angular shrinkage variation. If density is not an issue for the strength grading of solid dimension timber, the volume regarding the area where the shrinkage is stable suggest that, if the longitudinal shrinkage follows a similar pattern, the area that could be segregated for higher quality is bigger than the one provided by latewood density radial variation.

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Resumen

En las distintas especies de coníferas, en la parte interna del tronco más cercana a la médula se genera, al crecer, madera que presenta cambios rápidos y progresivos en los sucesivos anillos hacia la corteza en dirección transversal, hasta que se alcanza un punto donde las propiedades se estabilizan para el resto de los anillos. El área más cercana a la medula se llama madera juvenil (JW) para distinguirla de la madera madura (MW). La JW se caracteriza por tener una estructura celular con menor longitud de traqueidas, diámetros de lúmenes, espesor de pared, contracción transversal, rigidez y relación celulosa/lignina. Unas propiedades que también son más bajas serían la densidad y las propiedades mecánicas, pero otras, como el grano en espiral y el ángulo de microfibrillas (MFA), son mayores. Un fenómeno a veces relacionado con la JW es la presencia de anillos de crecimiento más amplios y altos niveles de madera de compresión, aunque estas dos últimas relaciones no son mutuamente excluyentes. El año de transición (TY) entre JW y MW se puede encontrar mediante el análisis de todas estas diferentes propiedades que caracterizan a la JW. El límite tiende a cambiar según la propiedad de madera estudiada con patrones variables de la médula a la corteza. Todas estas características tienen efectos indeseables en las propiedades físico-mecánicas y tecnológicas de la madera aserrada para uso estructural. Además, cuanto mayor sea la proporción de JW, mayor incidencia de diferentes distorsiones de secado como el curvado de canto, curvado de cara y alabeo lo que resulta en una disminución en las perspectivas de renta de uso final y retorno económico de los productos aserrados estructurales.

Se han dado diferentes nombres a estas dos áreas, las cuales se pueden diferenciar en la dirección transversal del árbol a cualquier altura. También se han expuesto diferentes explicaciones al porqué de dichas variaciones. Si se considera la variación longitudinal, la nomenclatura generalmente empleada es madera interior (CW) y madera exterior (OW). Pero en esta Tesis, utilizaremos la nomenclatura JW/MW, ya que en el sector industrial español es la nomenclatura que se utiliza.

Hay varios estudios que evalúan la importancia de la madera juvenil para la madera aserrada estructural en España. Pero no se han realizado muchos estudios sobre las coníferas mediterráneas sobre el efecto de la silvicultura en la cantidad de JW presente en el tronco. La gravedad específica, el MFA y la densitometría se han utilizado ampliamente como indicadores de presencia de JW. En esta Tesis se estudian diferentes metodologías para la determinación de JW en *Pinus nigra* y *Pinus sylvestris* con diferente gestión selvícola y esos resultados se comparan con los obtenidos mediante densitometría.

Se estudia la influencia de la silvicultura en el TY, en masas de pino laricio y pino silvestre en España, obtenido mediante densitometría. Este análisis se realiza utilizando un modelo mixto lineal segmentado que incluye el análisis de los diferentes efectos, de las covariables incluidas en los diferentes modelos, sobre la densidad. También se estudian las variaciones en el volumen JW y la conicidad de árbol producidas en función de las prácticas selvícolas utilizando la variación radial de densidad de la madera de verano (LW).

Otro objetivo de la tesis es la comprobación de si a la altura basal es posible estimar un TY, por medio de la curva de crecimiento acumulado en altura anual y que éste esté relacionado con el obtenido mediante densidad media y de LW anual.

Se evalúa la viabilidad de utilizar espectroscopía de infrarrojo cercano (NIR) multipunto, para diferenciar entre JW y MW. Del mismo modo, se evalúa el potencial de las imágenes hiperespectrales de infrarrojo cercano (NIR-HI) para la identificación semiautomática de las áreas de JW y MW en el pino silvestre.

Finalmente se estudian los patrones de contracción radial y angular en la dirección transversal a lo largo de diferentes alturas del tronco. En base a los resultados sobre las contracciones, las áreas de JW y MW obtenidas, se relacionaron con las obtenidas a través de la densitometría.

Cuando se evalúa el área de JW en un tronco, la micro densitometría de rayos X es un método adecuado para su estudio, los resultados mostraron que la mejor característica de densidad para la automatización del proceso es la densidad de la LW. Si la determinación del TY se realiza mediante datos de cores, que se pueden extraer sobre los árboles en pie, es necesario que la médula necesita esté en el core para evaluar el límite correctamente.

La función desarrollada para la realización de los modelos mixtos segmentados proporciona una herramienta potente y más robusta para predecir el TY en un gran número de muestras, en vez de hacerlo individualmente, utilizando perfiles de densidad de LW. El índice de sequía es relevante para el modelado ya que afecta a la densidad de la LW, a la pendiente de la MW o a la determinación del TY. Hasta una altura de 9 metros el TY se produjo antes de la implementación de cualquier tratamiento silvícola, por lo que es necesario hacer otro muestreo en otra masa en la que se hubiesen hecho los tratamientos antes, para evaluar si algún tratamiento pudiera influir o cambiar el TY fuera de la parte del tronco bajo influencia de la copa. Sin embargo, dentro de la copa y en el caso de PN, se demustra que la poda afecta al TY porque la densidad de la LW a la que se alcanza aumenta, retrasando así el TY y aumentando la densidad de la LW. En ambas especies de pino, las claras parecen tener un efecto negativo significativo, aunque pequeño, sobre la densidad de la LW, mientras que los clareos y la poda combinados parecen tener un pequeño efecto positivo en ella, en comparación con el grupo de control. Estos resultados presentados aquí pueden variar dependiendo de la intensidad y el momento de la clara, así como de la cantidad de poda verde llevada a cabo. La respuesta al crecimiento después de los tratamientos silvícolas muestra que la cantidad de JW se reduce en porcentaje, ya que aumenta el volumen total del tronco con cualquier tratamiento selvícola aplicado, para ambas especies, en los bosques puros mediterráneos.

El TY calculado utilizando las funciones de crecimiento Chapman-Richards en los incrementos de altura acumulados, no se ajusta a la estimación del TY obtenido a través de la densidad para las procedencias españolas estudiadas de pino silvestre y laricio.

Respecto a la calibración entre las mediciones obtenidas con NIR multipunto y los datos de densidad derivados de la micro densitometría de rayos X, ha sido difícil y no se han obtenido resultados lo suficientemente buenos. Por otro lado, el NIR-HI se puede calibrar con los resultados de la micro densitometría de rayos X y la JW, MW y el punto de transición (TP) entre ambos, se puede determinar en la sección transversal del árbol. Los resultados son independientes del tratamiento silvícola aplicado en las plantaciones de pino silvestre estudiadas. El análisis de componentes principales resultó ser una manera útil y fácil de proporcionar información adicional sobre la presencia y ubicación de la madera de compresión. El uso de regresiones de mínimos cuadrados parciales, en nuestro caso, fue la mejor solución para la detección del TP entre JW y MW, cuando la madera de primavera (EW) y la LW se evaluaron por separado. Cada laminilla se clasificó con una diferencia de ±1 anillo en comparación con la obtenida mediante densidad de la LW. Las mayores diferencias fueron de ± 2 de anillos. Una clasificación automática mediante una combinación con una clasificación no supervisada de k-medias anterior entre la EW y la LW, probablemente mejoraría los resultados y podría conducir a una mejor automatización.

La contracción radial tiende a ser mayor en los primeros 8 anillos cercanos a la médula, generalmente entre 4 y 9% en los primeros anillos disminuyendo hasta que se estabiliza alrededor del 3%. En cuanto a la contracción angular, es cercana al 0% o incluso negativa cerca de la médula y va aumentando hasta un cierto anillo (9-11), cuando se vuelve más o menos estable alrededor del 2%. Estos resultados son válidos a lo largo del tronco, siendo mayores y la transición producida antes en la contracción radial que angular para cada altura estudiada. No se observan patrones generales a lo largo del mismo árbol en las diferentes alturas muestreadas. La aplicación de los tratamientos silvícolas parece que no tienen ninguna influencia en las variaciones de contracción radial y angular. Si la densidad no es un problema para la clasificación de resistencia de la madera aserrada de uso estructural, el volumen con respecto al área donde la contracción es estable sugiere que, si la contracción longitudinal sigue un patrón similar, el área que podría ser segregada para una mayor calidad es más grande que la proporcionada por la variación radial de densidad de madera de verano.

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Chapter 1. Introduction

1.1 Spanish forestry sector

Since ancient times, wood has been by far the most used building material. Neolithic long houses in Europe, for example, date from 5000 to 6000 BC. Due to its natural origin it has considerable strength in relation to its relatively light weight (although this varies depending on the type and direction of the force applied). It is also a highly workable material (even with a stone axe), and it is readily available, although there are less forested areas today than in the stone and bronze ages. In Europe, forested areas have been recovering since the XX century.

Although wood has been replaced in the construction industry by new materials, none of these materials ticks as many boxes as wood in terms of sustainability, since wood is renewable, recyclable, and has the lowest carbon footprint associated with its processing. Furthermore, wood provides a means of carbon sequestration, since trees sink atmospheric CO2 while they are growing, and this carbon is retained over the lifecycle of the wood. Moreover, reforestation and afforestation form part of the negative emission technologies (NETs) proposed under the objectives of the Paris Agreement. Additionally, this NET contributes to increasing biodiversity, mitigates erosion and provides socioeconomic benefits.

However, harvesting without taking sustainability into consideration can lead to problems such as deforestation and forest degradation. Hence, in the European Union (EU), efforts have been made to regulate the obligations of operators who place timber and timber products on the market (the EU Timber Regulation). Thus, marketing of illegal timber in the EU is prevented, the supply of legal timber has been improved and the demand for timber sourced from responsibly managed forests has increased.

As Spain is part of the EU, the government is obliged to implement and enforce laws aimed at ensuring ecological and social sustainability of forested areas. Hence, any forest operation must be carried out according to these laws, which means using practices which encourage forest sustainability. Furthermore, two recognized certification systems coexist in Spain: F.S.C. (Forest Stewardship Council) and P.E.F.C. (Program for the Endorsement of Forest Certification Schemes), both backed by international and European organizations. The two systems certify the sustainability of forest management in a given forest area and also certify the chains of custody of the wood processing industries, verifying that the wood used comes from forests managed sustainably.

The three National Forestry Inventories (NFI) conducted in Spain have allowed several aspects of the forest to be monitored since the first NFI was carried out (1966-1975). According to the most recent NFI, 29% of the national territory comprises forested land and 23% is deforested forest areas. Of the forested areas, 39% are pure conifer stands and 26% are mixed conifer and hardwood stands. The total amount of forested areas has increased since the last NFI (MITECO 2018)

As regards conifers, the species most commonly used in Spain are Scots pine (*Pinus sylvestris*), black pine (*Pinus nigra*), radiata pine (Pinus radiata), maritime pine (*Pinus pinaster*) and Aleppo pine (*Pinus halepensis*). Annual growth slightly exceeds 30 million cubic meters, mostly located in the northern part of the country. Only half of this annual increment is harvested, again mostly in the north of the country, so this resource is well managed with a view to meeting the future needs of the wood market.

However, it is important to point out that only a relatively small amount of conifer wood can be used or ends up being used for structural purposes. Furthermore, the import-export balance for sawn wood is negative, at almost a third of the consumption. Specifically, 1429 m^3 are produced of which 185 m^3 are exported and 929 m^3 imported (MAPA 2017). Figure 1.1. shows the evolution of sawn timber in recent years (MAPA 2017).

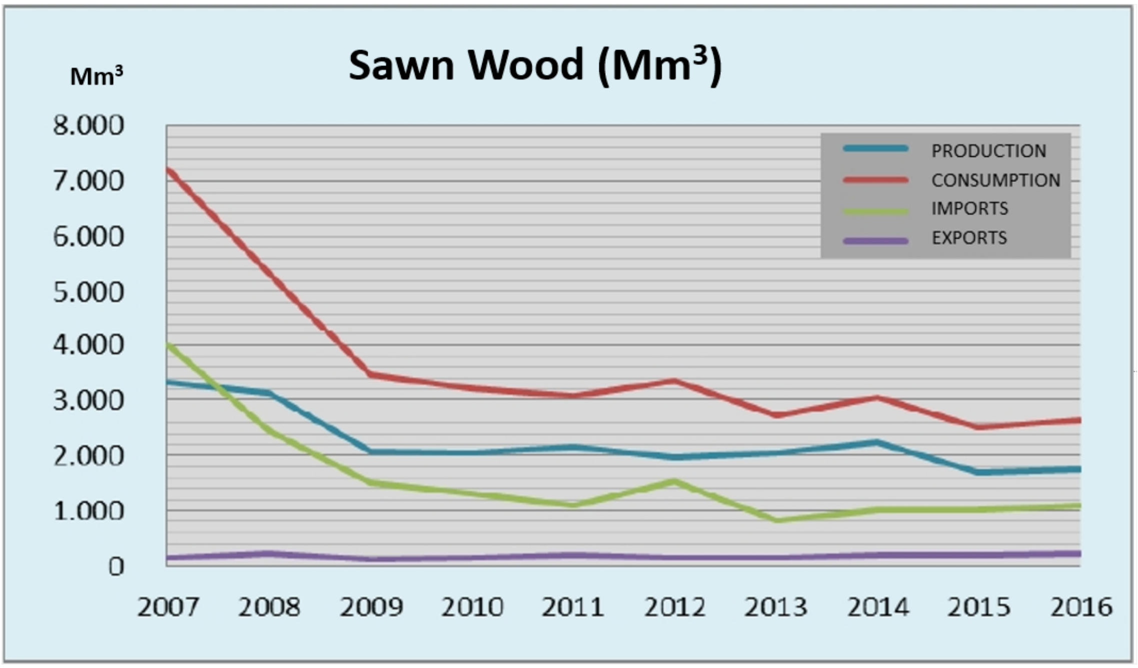

Figure 1.1. Evolution of sawn timber in the last 10 years for which data is available.

A negative balance of 158 337 € reveals the potential for incrementing the amount of high-quality wood, bearing in mind the wide availability of this resource and the fact that the use of wood in construction will increase in the coming years (MAPA 2017).

1.2 Wood for structural purposes

Wood used in construction is regulated by European standards in order to assess the mechanical properties of the material. In Spain, as in the rest of the EU, UNE-EN 338:2016 is the standard that defines wood strength classes. Strength and other mechanical properties can only really be determined when the wood sample is tested to destruction. Therefore, reliable predictors of mechanical properties must be employed to assess the properties of the wood without testing the wood samples (Fernández-Golfín et al. 2003). Wood density is one of the variables that correlates well with mechanical properties and therefore with wood quality (Rodríguez and Ortega 2006, Gutierrez-Oliva et al. 2006, Fernández-Golfín and Díez 1996, Auty et al. 2014). Also, the UNE-EN 338:2016 establishes minimum density values for each strength class.

Wood is a hygroscopic, anisotropic and heterogeneous material. Because of these characteristics, its physical, chemical and mechanical properties vary among species, within the same species and even in each tree. Inside a tree, substantial changes occur across the stem in the radial direction (pith to bark) as well as along the stem in the vertical (axial) direction. Furthermore, there are differences between earlywood and latewood within a ring and even in the same ring along the length of the tree. Wood harvested for structural use requires certain characteristics as a raw material in order to obtain high quality end products for the wood industry (Fernández-Golfín et al. 1998). In this regard the more homogeneous the properties of the bole, the better.

The heterogeneity of the material is an area which has been subject to much research in order to improve its quality. Knottiness, spiral grain, resin pockets, density, stem straightness, microfibril angle (MFA), compression wood and juvenile wood among others are characteristics which foresters have been trying to improve to obtain better quality wood.

This variation in wood properties is complex as they are affected by climatic, site, silvicultural, age and genotype factors, among others (Larson 1969, Larson et al. 2001, Baldwin et al. 2000, Burdon et al. 2004).

In the case of conifers, during the first years of growth, the properties of the wood formed near the pith are different from those of the wood formed towards the end of the life of the tree (Larson 1969, Zobel and Sprague 1998, Ilic et al. 2003, Burdon et al. 2004). During these first years of growth near the pith the wood usually has lower density and elastomechanical properties than normal, along with higher shrinkage, which will result in less strength and a greater tendency to warp. This part of the trunk also produces shorter cells which have very thin walls with more inclined fibrillar and micro fibrillar orientations as well as exhibiting differences in the chemical composition (Larson 1969, Ilic et al. 2003, Ivković et al. 2009). Therefore, two different areas inside the cross section of a stem are commonly considered; the juvenile wood (JW) and the mature wood (MW) (Larson et al. 2001, Ilic et al. 2003, Burdon et al. 2004). Some studies even split the stem cross section into three areas termed JW, transition wood and MW (Groom et al. 2002, Alteyrac et al. 2006). In this study, however, based on the densitometry results and those of other analyses and also to simplify the boundary estimation and volume calculation, only two areas were considered as it was not possible to differentiate three areas on most of the samples.

The JW can be defined as ‘still imperfect wood’, present in the inner part of the bole near the pith, where the characteristics of the wood undergo rapid, progressive changes in successively older growth rings (Larson et al. 2001). Although this definition is employed by end users and the industrial sector, the scientific community has agreed to use the more appropriate term ‘corewood’ (CW) for this inner part of the bole, and the outer part outerwood (OW) (Zobel and Sprague 1998). This terminology allows us to explain the fact that the juvenile wood in the upper part of the bole differs from that in the lower part due to the “physiological aging” (Burdon et al. 2004). Furthermore, the hydraulic and mechanical demands along the tree will change during its life as it grows (Lachenbruch et al. 2011).

Since this study focuses on conifer wood, from now on when we refer to wood it should be interpreted as conifer wood, unless otherwise indicated. Also, we will use JW/MW to refer to the radial variation in the property studied at a given height, which could be extrapolated to the CW/OW terminology. The internal variations can occur over a span of several years, mostly depending on the physical, mechanical or chemical characteristic studied (Bendtsen and Senft 1986); each characteristic displaying a variable pattern from pith to bark (Ilic et al. 2003, Bendtsen and Senft 1986, Larson et al. 2001, Burdon et al. 2004).

All the variations due to JW have undesirable effects on the physical-mechanical and technological properties of the material (Larson 1969, Burdon et al. 2004, Hermoso et al. 2016). The higher the proportion of JW, the greater the incidence of different drying distortions such as spring, bow, crook and twist (Ilic et al. 2003), resulting in lower strength classification as well as lower economic return for most products in the wood industry. However, some studies have suggested that different end products will be affected differently. Solid dimension lumber and Kraft pulp are those most affected by the amount of JW, although certain positive traits have been reported in the case of oriented strand board, medium density fiberboard and some types of mechanical pulp (Moore and Cown 2017).

Due to the problems caused by the presence of large amounts of JW on solid dimension lumber, several approaches have been employed, some of which are implemented while the tree is growing and others at the time of harvesting. While the trees are growing, one strategy focuses on reducing the area where JW is present in the trunk and another on improving the characteristics of the wood in that area. When harvesting the trees, in order to send them to the best processing streams two different approaches can be employed. Firstly, in situ segregation of logs by, for example, the Hitman PH330 (https://www.fibre-gen.com/hitman-ph330) harvester head or secondly, the segregation of logs at the timber yard using equipment such as ultrasonic and sonic timers, resonance frequency or even the more advanced computed tomography, like the Microtec CT Log 360° X-ray CT (https://microtec.eu/es/catalogue/products/ctlog/). In all cases, the financial benefits should compensate the costs of implementation.

Both in the case of segregation or when attempting to improve the raw material, the traits which are usually tried to improve are density, modulus of elasticity (MOE) and MFA when the aim is to improve wood quality for structural purposes. Density is used for strength class grading and can also be related with stiffness. It also tends to be a good predictor of MOE. In turn, MOE, which can also be related with MFA, is an estimation of log stiffness. Finally, MFA is related to shrinkage distortions as the wood dries and is partially related to stiffness.

Several avenues of research have been explored to either improve the characteristics of JW or reduce its area. Research has included genetic improvement of the traits of interest and their heritability (Louzada 2003, Cown et al. 2004, Gapare et al. 2006) along with studies addressing silvicultural practices such as fertilization, irrigation, pruning and thinning to control stand density as well as plantation spacing (Moore at al. 2004, Lundgren 2004, Amarasekara and Denne 2002, Ulvcrona and Ulvcrona 2011,Watt et al. 2010, Moore et al. 2009, Moore et al. 2015, Alteyrac et al. 2006, Vincent et al. 2011, Mörling 2002, Erasmus et al. 2018), and their effects on certain properties of the wood. Hence it was considered to be of interest to assess the influence of thinning and pruning regimes on the TY as different silvicultural practices might bring it forward or result in a delay.

End use of timber for structural purposes is the most profitable for the industrial sector. In order to obtain a high-quality product, it is necessary to take care of forests, which at the same time implies improving sustainability.

Furthermore, the bio economy and circular economy strategies favor increased use of wood products in our society given the clean production characteristics and recyclability.

1.3 Juvenile wood determination

As commented above, basic specific gravity, MFA and density have been extensively used as indicators of JW presence. The suitability of other techniques to assess the JW area in the trees will also be tested with the aim of implementing these techniques on *in situ* standing trees. Some of the methods used are described below.

1.3.1 Estimation through densitometry

When assessing the area of JW, the most commonly used method is micro X-ray densitometry as it is a relatively cheap and easy way to obtain the data. It also has the advantage that it provides a lot of extra information with regard to ring growth width and other yearly characteristics of the tree, as well as allowing cross-validation of dating from the sample profiles. It should be considered that density alone explains a lot of the MOE variance present in the samples (Auty et al. 2014, Rodríguez and Ortega 2006, Gutierrez-Oliva et al. 2006). Several tests revealed (Chapter 4) that the most stable density trait for use in the analysis was latewood density, as reported in previous studies (Sauter et al. 1999, Gapare et al. 2006).

Studies focusing on Spanish black pines (Rodríguez and Ortega 2006, Gutierrez-Oliva et al. 2006) as well as other pine species (Larson et al. 2001) have stressed the need to eliminate extractives for JW assessment. Thus, for the purposes of this study they were removed before the densitometry analysis.

Furthermore, recent studies have emphasized the importance and influence of drought under the Mediterranean climate on annual density variations (Arzac et al. 2018), highlighting differences among the Atlantic, oceanic and continental climates present in Europe, where most of the studies have been conducted. Moreover, some studies suggest that climate has a more direct effect on some wood traits than silviculture (Cregg et al. 1988). Because of this, the effect of climate was included in the study in Chapter 2.

1.3.2 Estimation through MFA

Another characteristic widely studied due to its importance in the quality of the final products is MFA, given its relationship with shrinkage and unexplained variance in the MOE of the JW part (Erasmus et al. 2018). Unfortunately, in our study, estimation using this approach, as it has to be done per ring, is more complicated than through densitometry.

There are basically three methods for measuring MFA in the cell walls of wood, all of which employ a destructive sampling methodology. The first two methods involve either employing variations on polarized light techniques, or through other techniques visualizing directly or indirectly the orientation of the microfibrils themselves, and a third approach, which measures bulk wood samples instead of individual tracheids or fibers, involves the use of an X-ray diffractometer (Donaldson 2008). This latter approach can also be a non-destructive method, using a mobile measurement table like the one used in SilviScanTM. However, the costs of performing such an analysis are prohibitive for a large initial study of the problem.

Nevertheless, during a secondment research period in Vienna at BOKU university to determine the feasibility of studying the MFA using a Small angle X-ray scattering (SAXS), a test was carried out on a small set of *Pinus sylvestris* samples at different heights, considering each silviculture treatment. This equipment has a moving surface so is able to scan the sample in any bidimensional direction. This study aimed to map the MFA variation in the earlywood and summerwood of each ring.

Unfortunately, after several trials during which different settings of the equipment were tested as well as the conditions and thickness of the samples, it was not possible to derive a clear cross-scattering pattern. The study has recently begun again using a new approach, but so far, no results have been reported.

1.3.3 Estimation through shrinkage

As MFA is related with shrinkage, it was decided to study the transversal shrinkage patterns on the felled trees. For this reason, the discs extracted where wrapped in plastic laminated film immediately after felling to avoid any humidity lose and then marked and study in each ring the position variation (Chapter 7). If obtained the MFA per ring as well, the idea would have been to study its relation on the different species considered in this Thesis.

1.3.4 Estimation through NIRs

In this study, the potential of Near Infrared Spectroscopy (NIRS) for identifying juvenile and mature wood zones on the densitometry samples was assessed. Once calibrated, the NIRs techniques are able to provide a reliable classification almost instantaneously. In this thesis the calibration has been attempted using a multipoint approach (Chapter 5) and a hyperspectral (Chapter 6) approach.

1.3.5 Other possibilities for estimating the JW

Several options were assessed for estimating JW without the need to fell the tree, most of which were found in the bibliography reviewed.

In the first place, 5 mm increment borers were used to extract cores at two heights on 5 trees per plot including the felled trees. After analyzing the micro X-ray densitometry results it was found that cores which did not reach the pith were mostly useless. This was because it was not possible to determine how many years had been left out. Moreover, perhaps just a couple of juvenile rings were present on the samples, which were insufficient for the statistical analysis to correctly detect the boundary between JW and MW. Also, in the outermost rings, where ring growth was very small, any angle of the increment borer, however small, led to overlapping LW and EW areas, masking the real densities. In these cases, considering the maximum density variable worked better than LW density variable.

Another approach studied was to relate the sigmoid curve produced by accumulated increment heights to the transition year between both areas. For species like radiata pine this was not possible as radiata pine can develop more than one whirl per year and so the data collected made no sense. The method was studied, however, for *Pinus nigra* and *Pinus sylvestris* in Chapter 4.

The use of the RESISTOGRAPH® technique in radiata pine for JW/MW determination was also studied. However, as the inner area of wood on the tree is not extracted when drilling, it was only possible to detect the ring density and its variations close to the bark and the heartwood area. This technique would require further analysis if aimed at determining the area of JW, but for densitometry as well as ring width analysis of the outer part of the bole, seems that it is a promising technique.

In this study we also analyzed grafted pines to determine whether grafting pines from buds from the upper and supposedly more mature part of plus trees could result in higher quality JW. In this regard we were only able to find plots of Scots pine potentially suitable, but the trees in the plots were still too young to be included in the study. (In Spanish, see A.I.2:.

1.4 Study locations

This study forms part of the Project RTA2014-00005-00-00 and the locations studied for the three conifer species that were considered in the project can be seen in the list below. A more detailed map can be seen in Figure 1.2.

- *Pinus nigra* Arnold subsp. *nigra* (black pine) (PN), Zarzuela de Jadraque (Guadalajara, Spain) (41°1´N, 3º4´W).
- *Pinus sylvestris* L. (Scots pine) (PS) La Morcuera Forest (Madrid, Spain) (40º50´N, 3º5´W).
- *Pinus radiata* D.Don (radiata pine) Balmaseda (Bilbao, Spain) (43º12´N, 3º12´W)

Figure 1.2. Sampling location areas of the Project RTA2014-00005-00-00 in Spain.

1.5 Thesis objectives and structure

1.5.1 General objectives of the thesis

This research is focused on analyzing the interaction between the silviculture applied and the amount of JW present along the bole of a tree. Several methods for reliably and suitably determining the JW have been studied.

For this purpose, three general objectives were established:

1. To evaluate the different, robust models that can be fitted to estimate the TY calculated using densitometry to identify radial variation.
2. To determine the effect of different silvicultural treatments on the TY.
3. To study the different characteristics of wood associated with JW and alternative methods for its determination.

These three general objectives have been widened and the specific objectives studied are explained in Chapter 2 to 7 of this Thesis. A summary of them can be found in next page.

1.5.2 Thesis structure

To present the results corresponding to each of the objectives in this thesis, it has been structured into nine different chapters:

Chapter one provides a starting point as an introductory section for the arguments set out in the thesis. The main results of published scientific work focusing on JW and radial variation in wood properties have also been reviewed in this section.

Chapter two addresses the influence of silviculture on the TY in black pine and Scots pine stands in Spain using LW densitometry. This analysis is carried out using a segmented linear mixed model including the analysis of the different covariate effects included in the density models.

Chapter three deals with the variations in the volume of JW depending on the silvicultural practices employed, using radial variation in LW density, taper will also be studied.

In the fourth chapter we study the use of height growth to assess juvenile-mature wood transition in black pine and Scots pine. The objective was to determine whether it is possible to estimate TY at basal height through the yearly length of the accumulated whirl, which can be related to that obtained for yearly LW and mean density.

The objective of the fifth chapter is to assess the feasibility of using multipoint near infrared spectra (NIRs) to differentiate between JW and MW.

Similarly, the objective of the sixth chapter is to assess the potential of near infrared hyperspectral imaging (NIR-HI) for semi-automatic identification of JW and MW moieties in Scots pine.

The seventh chapter addresses the study of radial and angular shrinkage in the transversal direction at different heights along the bole. Based on the results for shrinkages, it will be determined whether the areas of JW/MW obtained can be related to those obtained through densitometry.

Chapter eight provides a synthesis and a general discussion of the results obtained in the different parts of this thesis document, including considerations and future lines of research lines in this field.

Finally, chapter nine provides a list of conclusions derived from the research work comprising this PhD Thesis.

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Chapter 2. Estimating the transition between juvenile wood and mature wood by densitometry profiles and a segmented mixed model approach

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Abstract

Wood use for structural use has increased in the last decade. Knowledge about the influence of wood quality by silviculture treatments on Mediterranean forests it's important to forest managers.

In Spain, two of the main wood species used in construction, *Pinus nigra* and *Pinus sylvestris*, have been studied in order to determine the juvenile-mature wood boundary (transition year) along the bole. Also, the effect of several silvicultural treatments on the transition year as well as on latewood density has been analyzed.

The transition year was calculated using segmented linear mixed models annual on latewood density, obtained through micro X-ray densitometry, and as covariates silvicultural practices, distance to the crown and a drought index.

The results show how the transition year is distributed along the bole, how it is influenced by the crown as well as how the different silvicultural treatments affect the LW density.

2.1 Introduction

Although straight, cylindrical trees may appear to have homogeneous wood at first sight, not only do they present variations in the axial direction, some of which can be observed on the outside by differences on the bark depending on tree age (Spiral grain, knottiness), but also in the radial direction, even in the growth rings of each year between springwood and summerwood.

When wood is harvested for structural use, the wood industry requires certain characteristics in the raw material in order to obtain high quality end products. In this regard the more homogeneous the properties of the bole the better. Properties such as strength can only be determined when the sample is tested, which implies destruction. Therefore, reliable predictors of mechanical properties must be employed, and the ones most widely used are those which provide good correlations and are easier to obtain without damaging the samples. Clear wood density is one of the variables that correlates well with mechanical properties and therefore, with wood quality (Rodríguez and Ortega 2006; Auty et al. 2014).

A characteristic of conifers is that during the first years of life the properties of the wood formed are different to those of the adult wood (Larson 1969; Zobel and Sprague 1998; Burdon et al. 2004). During these first years the wood usually has lower density and elasto-mechanical properties than normal, along with higher contraction, which will result in less strength and a greater tendency to warp. This part of the trunk also produces shorter cells which have very thin walls with more inclined fibrillar and micro fibrillar orientations and even exhibit differences in the chemical composition.

This area is known as Juvenile Wood (JW), which Larson (1969) defined as “still imperfect wood, present in the inner part of the bole near the pith, where wood characteristics undergo rapid and progressive changes in successively older growth rings” until it stabilizes and becomes ‘Mature Wood’ (MW). Although the term JW is still in use by operators, in the scientific community the term corewood (CW) is now used and the outer part is referred to as outerwood (OW). This latter terminology allows us to explain the variation that occurs along the bole due to physiological aging, as well as the changes in the hydraulic and mechanical demands throughout the life of the tree (Burdon et al. 2004; Lachenbruch et al. 2011). In this paper, the terms JW/MW will be used to differentiate between the two areas of the density radial pattern at each height along the bole. The JW will be defined as the area where density increases rapidly until it reaches a point further towards the bark where the density values more or less stabilize (MW).

Thus, basic specific gravity, microfibril angle (MFA) and density have been extensively used as indicators of JW presence. As density can be measured easily at high resolution using micro X-ray densitometry, this study was carried out using this methodology, considering as a variable the yearly radial ring Latewood density (LW) variation (Sauter et al. (1999) and Gapare et al. (2006)).

Several methods have traditionally been employed to determine the transition year using densitometry measurements. These methods include visual determination of the average density (Zobel et al. 1959; Clark and Saucier 1989), transformed variables (Vargas-Hernández and Adams 2007) and linear regression (Bendtsen and Senft 1986). However, these procedures have been displaced by linear / non-linear segmented regression models (Di Lucca 1989; Bendtsen and Senft 1986; Tasissa and Burkhart 1998; Sauter et al 1999; Mutz et al. 2004; Mansfield et al. 2007) as well as linear-quadratic fitting for final density in Scots pine (Sauter et al. 1999) or cubic-linear fitting for all density variables in Laricio pine (Rodríguez and Ortega 2006).

The main objective of this work is to assess the possibility of calculating the transition year (TY) from Juvenile to Mature wood in *Pinus sylvestris* L. and *Pinus nigra* Arnold subsp. *nigra* trees using the definition of Linear Mixed Segmented Models, based on the attained stability in Latewood density (LW) of successive growth rings.

Additional objectives include analyzing whether TY is influenced by the silvicultural treatments applied and whether taking into account droughts that affect tree density improve the estimation.

These results form part of a wider national research project in which different and varied techniques have been analyzed in order establish their suitability and reliability for juvenile wood ratio determination in logs, thus contributing to improve our understanding of wood quality. Some of the conclusions obtained have been published previously (Ruano et al. 2019).

2.2 Material and methods

2.2.1 Sampling

Two different thinning and pruning trials established by the INIA-CIFOR in several plots at the end of the last century were used to obtain the wood samples.

The first of these sites is a pure plantation of *Pinus nigra* Arnold subsp. *nigra* (Black pine) (PN) with different experimental thinning and pruning regimes and located in the municipality of Zarzuela de Jadraque (Guadalajara, Spain) (41°1´N, 3º4´W) at an altitude of 1,005 m.a.s.l.. The site is more or less flat with a 1–10 % North-West facing slope. In this area, the average annual rainfall is 489 mm, and the average annual temperature is 10.9 ºC (AEMET 2017).

For the PN, 12 trees were felled. Discs at basal height and every 3 meters were then extracted up to the point where the diameter was less than 7.5 cm. Another two discs were extracted at 1.3 meters and at 4.3 meters.

Two strips of 2 mm width were then cut from the cross section of each disc, attempting to avoid compression wood. This was done by extracting the strips perpendicular to the slope and visually checking for compression wood. Once the stripes had been obtained, they were immersed in n-Pentane for 48h to eliminate extractives (Gapare et al. 2006, Rodríguez and Ortega 2006, Gutierrez-Oliva et al. 2006). Once extracted, the samples were stored in a climatic chamber at 20ºC and 65 % RH to reach a moisture content of 12%. They were then scanned with an X-ray to assess the microdensity of the strip using the equipment as described in Rodríguez and Ortega (2006). The images were processed using LIGNOVISION™ and TSAP-Win™ software (http://www.rinntech.de), with a fixed boundary between earlywood and latewood of ½ of each ring density, averaged values for each growth ring: ring width, mean ring density, earlywood width, earlywood density, latewood width, latewood density and texture were obtained. The dating was verified using COFECHA software. For the analysis, after some trials the characteristic with a clearer breakpoint on all samples was latewood density.

The second site is located in a pure plantation of *Pinus sylvestris* L. (Scots pine) (PS) located in the Guadarrama mountain range at La Morcuera Forest (Madrid, Spain) (40º50´N, 3º5´W). This forest stand is of plantation origin and different experimental thinning regimes and pruning trials have been carried out. It is located at an altitude of 1,550 m.a.s.l. on the Northern face of the mountain with a NE orientation and a 10–50 % slope in the trial area. In this area, the average annual rainfall is 1,062 mm, and the average annual temperature is 7 ºC (AEMET 2017).

In this case, 15 trees were felled and no discs were extracted at heights of 1.3 m and 4.3 m, but otherwise the procedure for obtaining the data was the same as that described above for black pine.

2.2.2 Climatic data

Daily data was obtained from all climatic stations surrounding each study site. Using the “meteoland” (De Caceres et al. 2018) package in R (R Core Team 2017), the daily climatic data was modified for the area where the plots were established. The data included precipitation as well as maximum, minimum and mean temperature. Results were obtained from the information provided by the State Meteorological Agency (AEMET), Ministry of Agriculture, Food and Environment of Spain.

A monthly Standardized Precipitation Evapotranspiration Index (SPEI) value was then calculated per month for periods of 1, 3, 5, 6 and 12 months using the “SPEI” (Beguería and Vicente-Serrano 2017) package in R (R Core Team 2017). A correlation was then performed to assess the best SPEI predictor with yearly LW, as described by Navarro-Cerrillo et al. (2018) for radial growth to determine which monthly SPEI provides the best predictions.

Using the “bootRes” (Zang and Biondi 2013) package in R (R Core Team 2017) for this purpose, the results showed that SPEI 6 was the SPEI index most closely related to the LW density. Furthermore, a very high monthly variation in the correlation between different monthly SPEI 6 was found for both species. The “bootRes” (Zang and Biondi 2013) package in R (R Core Team 2017) was again used to analyze these variations in monthly SPEI 6 values, per tree, per treatment and average LW density for each height, pointing to variations in the results depending on the species. In the end, three different SPEI 6 were selected to be tested for inclusion the model: two of the most correlated monthly ones and the yearly average one.

2.2.3 Mixed-models

In order to model longitudinal profiles of tree growth and to obtain an estimate of the transition year (TY) from juvenile to adult status, we made use of the segmented mixed model framework wherein the response growth variable (LW) is expressed as a piecewise linear function of year along with additional covariates understood to modify the parameters of the segmented relationship: silvicultural treatments (Plots with any silviculture vs control group (SILVIC), plots with thinning vs control group (THIN), plots with pruning and thinning vs plots with only thinning vs control group (TREAT) and plots with pruning vs the other (PRUN)), three different SPEI, slope (SLO), tree, distance from the crown (DIST_C), being inside the crown or not (I_C) and distance relative to the top (DT).

To assess the TY through LW at each different height, a two-step procedure was carried out. First, the average LW from both strips of the disk (one on each side of the pith) was obtained and a first TY assessed with the “segmented” (Muggeo 2008) package in R (R Core Team 2017), attempting to relate yearly LW at each height with all the aforementioned covariates, excluding the treatment. The best model selected was the one which included all significant covariates and had the lowest AICc, namely the classical Akaike Information Criterion (AIC) with a correction for small sample sizes (Hurvich and Tsai 1989). The best model obtained was then run through the function developed in R for segmented mixed models with random change points using maximum likelihood, as described in Muggeo et al. (2014) and Muggeo (2016). The aforementioned covariates were included to test for their influence on the shape of the segmented relationship, namely slopes and transition point. The four best models at each height where compared to determine the variability of the TY depending on the covariates selected to fit the model.

Regarding the model selection in the first step, after analysis it was concluded that if instead of trying to relate the density per year for each height, the year covariate was transformed into age, the fit was better and the results easier to interpret. Thus, in the end a transition age (TA) at each height was calculated and then transformed into (TY) to obtain a continuous time series result along the bole for each tree.

2.3 Results and discussion

The outputs from one of the several segmented linear mixed models fitted can be observed on Figure 2.1. The different regressions fitted per tree are plotted for a height of 3 meters on black pine using the best model (See Annex I). Dashed lines represent the population (fixed effects) fitted model and the solid line is the final regression taking into account the random part.

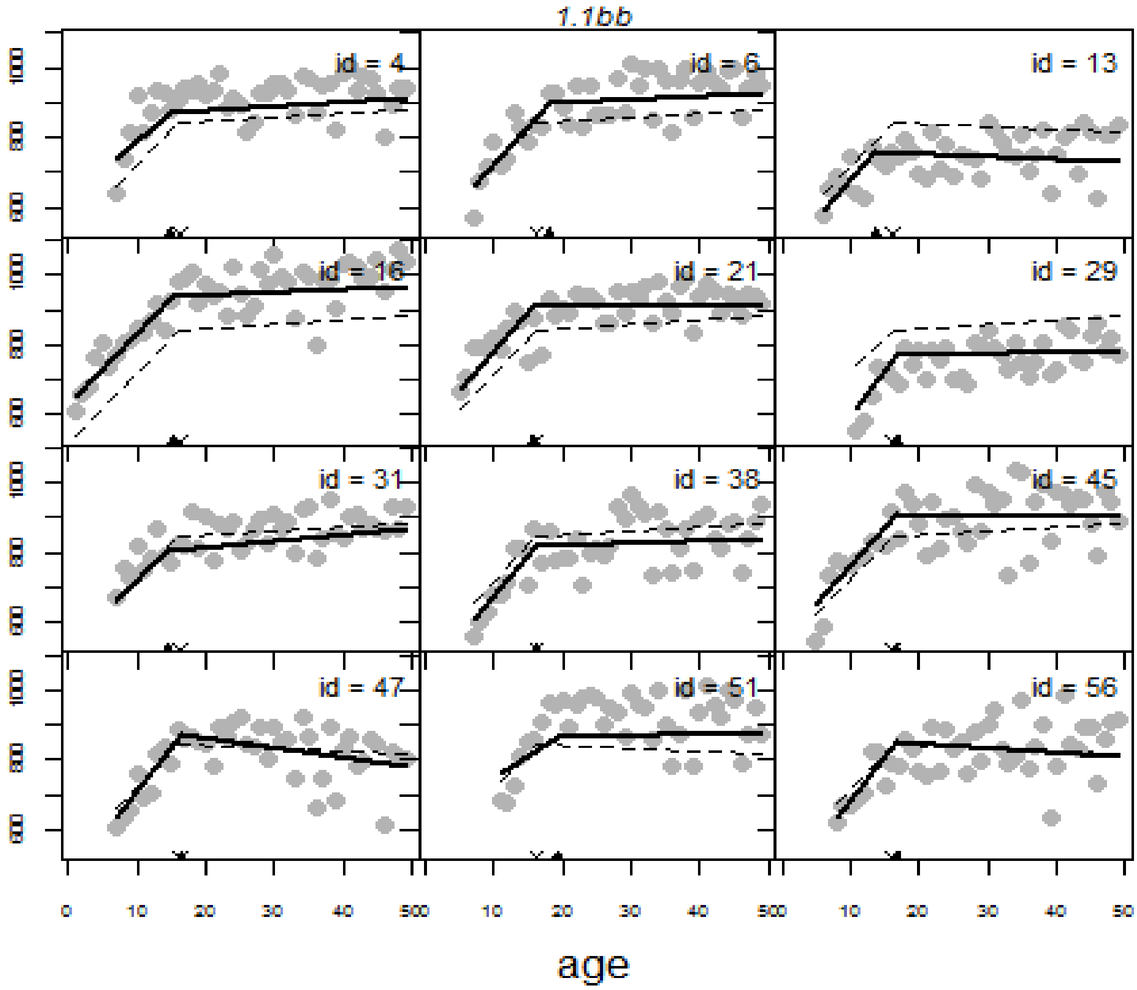

Figure 2.1. Segmented linear mixed model of Pinus nigra stands at a height of 3 meters (H2)

Individual trees can be distinguished and the original data vs the fitted data can be visualized. An example of this can be observed in Figure 2.2., with the same model and height data used in Figure 2.1. The grey dots are the original data and the red crosses and lines represent the fitted data of the model. Overall, the fixed effect model is shown by dashed lines and the model for the tree (random part) as a solid line.

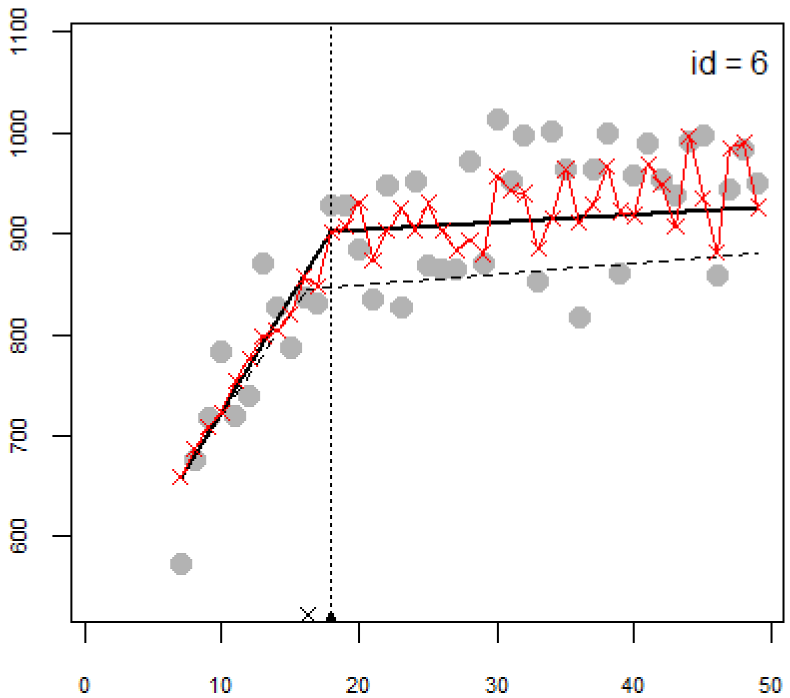

Figure 2.2. Original data vs fitted and fitted model on tree 6 at a height of 3 meters

Equation 2.1 is an example of the fitted model used for Figure 2.1.:

$$DENS_{ij} = \beta_0 + \beta_{1i}AGE_{ij} + \delta_i(AGE_{ij} - \psi_i) + \epsilon_{ij}$$

Equation 2.1. Example of the segmented mixed model

Where *j* stands for the measurement and *i* for the tree.

The parameters of the segmented equation are expressed via fixed and random parameters.

$$\beta_{0i} = \beta_0 + b_{0i} \quad \beta_{1i} = \beta_1 + \beta_2 SPEI\_M \quad \delta_i = \delta_0 + \delta_1 THIN_{ij} + d_i \quad \psi_i = \kappa_0 + \kappa_1 SPEI\_N_{ij}\kappa_i$$

Equation 2.2. Fixed and random parameters modifying the segmented equation

The random effects (b_{0i}, d_i, κ_i) are assumed to come from a multivariate zero-mean Gaussian distribution with proper covariance matrix.

A summary of all the TA, the TY and year differences between the results obtained from the different segmented linear mixed models (diff) for each species and height can be observed in Table 2.1. for black pine and in Table 2.2. for Scots pine.

Table 2.1. Pinus nigra average transition age (TA), year (TY) and the difference between the results of all the models in Annex I per tree and height

HEIGHT	Variable	Tree ID											
		56	**51**	**47**	**45**	**38**	**31**	**29**	**21**	**16**	**13**	**6**	**4**
H0: 0 m	TA	27.9	29.2	22.7	18.4	21.1	19.1	13.1	24.3	21.7	12.0	21.9	21.6
	TY	1988.9	1990.2	1983.7	1978.4	1984.1	1980.1	1974.1	1986.3	1981.7	1975.0	1983.9	1981.6
	diff	0.9	0.8	0.5	0.9	4.3	3.7	2.4	2.3	0.6	1.0	4.9	2.0
H1: 1.3 m	TA	9.2	8.8	10.9	11.5	9.5	12.6	10.5	14.6	12.0	8.7	12.1	9.4
	TY	1978.2	1978.8	1975.9	1976.5	1974.5	1978.6	1980.5	1978.6	1976.0	1976.7	1977.1	1974.4
	diff	1.0	1.1	0.8	1.2	1.3	2.3	3.0	1.1	1.4	1.3	1.4	1.4
H2: 3 m	TA	9.4	9.5	10.5	12.2	10.0	10.5	7.3	14.0	15.2	8.9	11.5	8.8
	TY	1982.4	1985.5	1982.5	1982.2	1982.0	1982.5	1983.3	1984.0	1981.2	1979.9	1983.5	1980.8
	diff	1.1	0.2	0.8	0.9	0.7	2.2	1.6	2.9	1.3	1.8	1.7	1.4
H3: 4.3 m	TA	7.9	8.3	10.7	10.5	9.5	8.3	6.9	9.3	12.3	8.2	8.2	7.3
	TY	1983.9	1986.3	1984.7	1982.5	1983.5	1982.3	1985.9	1981.3	1982.3	1981.2	1983.2	1982.3
	diff	1.2	1.6	1.4	2.3	1.6	1.9	0.9	2.8	3.0	1.5	2.0	0.8
H4: 6 m	TA	7.6	7.0	9.1	8.9	7.4	8.0	4.8	8.7	8.5	7.7	8.6	7.3
	TY	1986.6	1990.0	1987.1	1984.9	1985.4	1986.0	1988.8	1983.7	1983.5	1985.7	1986.6	1985.3
	diff	1.3	1.2	1.7	1.4	1.9	1.7	1.0	1.4	1.7	1.1	2.9	1.0
H5: 9 m	TA	6.9	7.4	8.4	8.7	7.0	7.4	5.7	9.2	9.2	7.0	8.8	7.3
	TY	1993.9	1997.4	1993.4	1989.7	1994.0	1990.4	1994.7	1989.2	1990.2	1990.0	1994.8	1991.3
	diff	0.6	0.7	1.1	1.7	0.8	1.1	0.7	1.7	0.8	1.8	0.8	0.6
H6: 12 m	TA	5.6	7.5	9.6	7.4	9.0	11.0	7.3	8.4	8.9	8.3	10.6	5.8
	TY	2000.6	2004.5	2000.6	1995.4	2004.0	2000.0	2003.3	1995.4	1995.9	2000.3	2003.6	1997.8
	diff	1.1	2.1	1.8	0.7	1.8	2.1	1.9	0.9	1.8	1.6	1.9	1.3

Table 2.2. Pinus sylvestris average transition age (TA), year (TY) and the difference between the TY of all the models in Annex II per tree

ID	HEIGHT											
	H0: 0 m			H2: 3 m			H4: 6 m			H5: 9 m		
	Age	Year	diff	Age	Year	diff	Age	Year	diff	Age	Year	diff
4	17.1	1980.1	0.3	7.9	1979.9	0.8	10.2	1989.2	0.4	6.3	1994.3	0.3
7	16.0	1981.0	2.5	7.1	1980.1	0.3	6.4	1986.4	0.6	12.1	2001.1	0.2
14	20.6	1980.6	0.9	11.8	1981.8	0.8	8.2	1987.2	1.5	6.1	1994.1	1.1
16	22.6	1982.6	2.0	9.2	1975.2	0.6	8.6	1982.6	1.1	6.9	1985.9	0.6
20	17.3	1981.3	2.0	9.7	1981.7	0.6	9.4	1987.4	1.9	7.3	1994.3	0.5
26	21.8	1980.8	1.1	7.9	1976.9	0.7	7.8	1984.8	0.9	5.4	1993.4	2.3
34	17.1	1978.1	0.2	12.2	1983.2	0.3	9.2	1989.2	0.2	7.7	1993.7	0.8
35	12.4	1976.4	1.2	8.3	1980.3	0.3	8.0	1987.0	1.1	8.9	2003.9	0.5
40	23.3	1983.3	0.8	13.5	1983.5	1.7	10.8	1986.8	1.4	5.5	1989.5	0.6
48	20.0	1982.0	1.4	11.6	1980.1	0.4	7.9	1985.9	1.3	4.7	1990.7	0.1

ID	HEIGHT											
	H0: 0 m			H2: 3 m			H4: 6 m			H5: 9 m		
	Age	Year	diff	Age	Year	diff	Age	Year	diff	Age	Year	diff
52	16.9	1976.9	2.6	12.7	1980.7	1.3	7.3	1982.3	1.1	5.0	1987.0	0.8
55	19.9	1978.9	0.7	11.6	1978.6	0.9	10.8	1983.8	0.8	7.1	1990.1	0.6
61	25.6	1988.6	0.9	11.9	1981.9	0.6	11.8	1988.8	0.5	6.6	1992.6	0.5
66	19.1	1981.1	0.9	9.3	1980.3	0.4	7.5	1984.5	0.7	6.3	1990.3	0.4
74	17.2	1980.2	1.5	10.1	1981.1	0.8	9.4	1986.4	0.9	7.7	1997.7	0.1

Table 2.1. and Table 2.2. also show that there is usually less than 2 year variation for the models with the best fit, presented in Annex I and Annex II. Thus, this methodology is shown to be a fast, reliable predictor for assessing the TY or TA in big datasets as long as climatic data is available.

If we analyze the transition age for black pine it can be seen from Table 2.1. that for most of the trees, the higher the sampling point on the stem, the earlier this transition appears or at least becomes more or less stable. There are two exceptions; at 1.3 m (H1) and 12 m (H6), the latter possibly being influenced by its position inside the crown and shorter ring time-series, which may make it more difficult to determine the exact TA than if a longer time-series were available for this height.

In the case of Scots pine, it can be seen from

Table 2.2. that the disks at the controversial height, 1.3m (H1), were not extracted, so no information was available for that height. Neither for height 4.3m (H4). Additionally, at 12 meters (H6) some of the trees had insufficient rings to allow for stable fitting of the model, the breaking point being almost at the end of the time series in most cases and where sorted out of the study.

The next step is to analyze the parameters in each model and for each height to attempt to determine which influence the mixed linear model obtained. All the models fitted can be seen in Annex I for PN and Annex II for PS.

2.3.1 Parameter analysis of segmented linear mixed models for *Pinus nigra*

As previously stated, in the case of black pine, the SPEI most correlated with the LW was the SPEI 6. The mean for all months per year was calculated (SPEI), and the SPEI 6 for May (SPEI_M) and November (SPEI_N) were the chosen covariates, presenting the highest correlation with density over the years.

It should be pointed out with regard to the results that since each SPEI 6 covariate in the models has a positive value for the year with no drought and a negative value for years with drought, from now on when referring to the positive influence of this covariate the meaning is that the greater the drought the higher the density and vice versa.

A segmented linear mixed-model was computed for each height following the procedure described in the methodology. Annex I presents the fitted models that best described the results for each height.

Across all the heights, the older the tree ring the higher the LW density until the TY is reached, at which point other covariates also come into play and the slope changes abruptly (see Figure 2.2.). Based on the results analyzed, this effect is less important in the case of the basal strips than higher up (around 15-20 kg/m^3 less). It can also be seen from Table 2.1. that the age at which the tree reaches TY takes more than 20 years in most cases. However, in the upper part of the bole the TY is reached in around 6-12 years maximum, with the general tendency being that the higher up the bole the earlier TY is reached. There may be two underlying reasons for this difference at basal height. The first is that basal height is where most of the gravitational torque is produced when wind or snow change the equilibrium of the tree (Vargas 2017), so this area may have a different growth pattern and properties from the rest of the tree. Secondly, it may be related to a mixture of tree maturation (Burdon et al. 2004) and to the variation on hydraulic and mechanical demands trough the life of the tree (Lachenbruch et al. 2011).

From the results from Annex I it can be observed, that in the juvenile part, at 0 meter, the models differ from those higher up the trunk. At this height, on the left-hand side of the regression no SPEI 6 significantly affects the slope although a slight negative influence can be observed in the relationship between age and SPEI_M in the LW density. From 1,30 meters upwards and before the proximity of the crown begins to have an effect (6 meters), the juvenile part is affected by age and also by SPEI_M, both having a positive influence, and the relationship between age and SPEI_M shows a slightly negative influence.

If we analyze what affects the TY and the slope on the right-hand side (MW) of the models with the best fit, we can generalize to some extent. When the SPEI_M is significant in the baseline model, then the slope on the right part of the model (MW) is affected positively by SPEI_N.

At 9 meters, where being inside or close to the crown has an influence, the baseline significance covariate to SPEI_N changes, and then the slope on the right-hand side of the model is affected negatively by the SPEI_M. In the models where the SPEI_N affects the TY; it was either delayed or the density was higher. In contrast, in the models where SPEI_M affects the TY, it occurs more rapidly in the drier years, possibly when the covariate was not included in the base model.

As regards the silvicultural treatments applied to the plot, it can be seen from Annex I that until the effect of crown proximity becomes important to the density, treatments only affect the slope on the right-hand side of the regression. That makes sense since up to height 6 no TY is reached after plot treatments were carried out.

As regards the effect of thinning on latewood density, reports in the literature vary from no effect (Peltola et al. 2007; Ulvcrona and Ahnlund 2011; Vincent et al. 2011) to negative effect (Mörling 2002; Barbour et al. 1994) or even a positive effect depending on height (Paul 1958). From this review, it should be taken into account that the results differ depending on whether they refer to early thinning or late thinning, as well as to ring density or LW density.

The different analyses carried out for the silvicultural treatments were:

1. THIN (Plots with thinning vs control group)
2. PRUN (Plots with pruning vs the others)
3. TREAT (Plots with pruning and thinning vs plots with just thinning vs control group)

1. As regards the first group, the LW density slope for the MW of the thinned trees was affected negatively in comparison to the control group. This result is in line with that of Mörling (2002) and Gutierrez-Oliva (2006), who reported that ring growth increased and wood density decreased after thinning. In the latter case water availability was a limiting factor, so LW will tend to grow wider and thus the density will probably be reduced, although other studies such as Larson et al. (2001) suggest that there is no appreciable decrease in density after thinning. The results depend on whether the studies focused on ring density, as this effect may not have been significant for ring density as a whole. The results of the present study reveal that there is a reduction in LW density in thinned plots, although quantitative analysis shows that the reduction is barely significant. This result was found for all heights except at 12 meters, which is due to the fact that the disks were extracted from within the crown, where no effect of thinning was detected.

2. The second group was not significant for any of the models model as regards the slope on the right-hand side of the regression (MW). However, at heights of 9 and 12 meters pruning seems to have delayed the TY, as the LW density needed to reach it was higher. When the pruning was performed, those heights were inside the crown, which may be why the results differ from those of Larson et al. (2001) with regard to the effect of pruning just below the newly formed crown.

3. In the case of the third group, when compared with the control group up to a height of 9m, the results on the slope on the right-hand side of the regression show a decrease in LW density for the thinned trees. For thinning and pruning this slope increases, so there would appear to be a positive relationship with pruning, although both are of scarce significance. Larson et al. (2001) pointed to similar results for specific gravity after thinning and pruning respectively.

The effect of the crown meant that model fitting differed from that for lower heights. At 9 meters, two more variables were tested on the models, namely, distance from the crown DIST_C) and whether inside the crown or not (I_C). Furthermore, at 9 and 12 meters in the juvenile part the density is not influenced directly by the SPEI. Hence, it seems that either before maturity has been reached or due to the different needs on hydraulic and mechanical demands, the LW density in the juvenile part of the tree within the crown tends to be less affected by drought.

At 9 meters, a slight positive effect can be seen on the left hand-side of the model with regard to the relationship between age and SPEI_N. At 12 meters there is a negative effect on the relationship between age and SPEI. It is certain that the crown affects density and wood formation (Larson 1969), since the models fitted at these two heights vary from the rest of the heights. It is possible that by adding other covariates related to the crown the model fitting could be improved, although even with the covariates already included the model fits were good.

2.3.2 *Pinus sylvestris* parameter analysis for segmented linear mixed models

In the case of the Scots pine, the SPEI showing the closest correlation with LW density in the segmented linear mixed models was also the SPEI 6. The mean SPEI 6 for all months per year was calculated (SPEI) and March (SPEI_MC) and September (SPEI_S) were selected because the covariates displayed higher correlation with density throughout the years.

Regarding the results for *Pinus sylvestris* it can be seen from Annex II that they differ from those of black pine in terms of model complexity. This may be due to the altitude at which they are found, as the growing period is different and also, they are less resilient to droughts. The vegetation periods also differ. The drought index is also important for fitting the model. In this case, the best drought index influencing the left-hand side of the regression (Juvenile one) for almost all heights is the average monthly SPEI 6 per year. SPEI presents a positive correlation with LW density and the interaction of SPEI and age is also positive (the older the tree and the drier the year the higher the LW density).

In models where the SPEI_MC positively affects the right-hand side of the slope (MW), the SPEI_S affects it negatively. This may be due to the use of SPEI when fitting the initial model and is the consequence of the interaction between both. In the models that use the SPEI_MC, as this has an effect on the TY, it is delayed or at least the density is higher. The opposite occurs in the case of models using SPEI_S, as with PN.

As occurs with black pine, there seems to be a negative correlation affecting the right-hand side of the slope (MW) between the LW densities of the control group vs the thinned group (THIN). The same happens with regard to the difference between the thinned trees, showing a negative correlation, and a positive correlation in the case of the thinned and pruned trees up to 5 meters (PRUN). The effect on the pruned trees up to a height of 3 meters is the same as that of only thinning on the LW density, probably because no green pruning was carried out, only removal of the dead branches.

The effect of the crown, as with PN, meant that model fitting differed from that of lower heights. At 9 meters two more variables were tested in the models, namely, the distance from the crown (DIST_C) and whether inside the crown or not (I_C). This was significant on two of the fitted models. Being closer to the crown or further within is a factor that delays the TY.

Additionally, at 9 meters, the density in the juvenile part is not influenced by the SPEI directly. Hence, it seems that either once maturity has been reached or due to the different needs on hydraulic and mechanical demands, the LW density in the juvenile part of the tree within the crown tends to be less affected by drought.

2.4 Conclusions

The function developed for segmented mixed models provides a useful tool to predict the TY in a large number of *Pinus sylvestris* and *Pinus nigra* trees using LW density profiles. These models achieve more stable results than by applying segmented regressions to each tree individually, where densitograms, mostly at lower heights, are not really clear.

Covariate data needed for model fitting was obtained. The drought index is relevant to LW density in both species, affecting the slope on the MW or the density in TY determination. Moreover, depending on the moment at which the drought index is calculated during the growing season, the effect changes. Prior to the start of the year's LW growth, a negative effect on LW density is observed, whereas at the end there is a positive effect.

Up to a height of 9 meters TY was reached prior to the implementation of any silvicultural treatment, so further sampling is necessary to assess whether any treatment could influence or shift the transition year outside the part influenced by the crown. However, within the crown and in the case of PN, pruning was found to affect the TY, because the LW density required to reach it increased, thus delaying the TY and increasing LW density.

At heights where the bole of some trees was within the crown and others not, the crown delayed the TY.

In both pine species, thinning seems to have a significant albeit slight negative effect on LW density, while the thinning and pruning combined seemed to have a small positive effect compared to the control group.

As reported in previous studies, the results presented here may vary depending on the intensity and the timing of thinning, as well as on the amount of green pruning carried out. Further studies are required to confirm these results.

Conflicts of interest

The authors declare that they have no conflict of interest.

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2.6 Annex

2.6.1 Annex I

Table 2.3. Best models fitted for Pinus nigra at each height

PN mixed models fitted												
HEIGHT	0											
Parameter	1.1bb			6aa.1			1.1aa			11.1 (ELIMINAR?)		
	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value
β_0	698.95	11.60	<0.001	695.04	12.19	<0.001	696.10	11.80	<0.001	699.14	12.06	<0.001
AGE_{ij}	7.61	0.40	<0.001	8.03	0.44	<0.001	7.95	0.43	<0.001	7.52	0.38	<0.001
$\beta_2SPEI\_M_{ij}$												
$\beta_{1i}AGE_{ij}$	0.66	0.06	<0.001	0.64	0.06	<0.001	0.65	0.06	<0.001	0.66	0.06	<0.001
δ_0	-6.98	0.48	<0.001	-6.72	0.51	<0.001	-6.79	0.49	<0.001	-6.48	0.50	<0.001
κ_0	24.20	2.21	<0.001	22.20	2.03	<0.001	22.74	2.08	<0.001	24.63	2.17	<0.001
$\kappa_1SPEI\_N_{ij}$	-4.44	0.80	<0.001				-4.18	0.78	<0.001			
δ_1THIN_{ij}	-1.04	0.26	<0.001									
$\delta_2SPEI\_N_{ij}$				-1.44	0.25	<0.001				-1.55	0.28	<0.001
$\delta_3TREAT1_{ij}$				-1.42	0.34	<0.001	-1.50	0.34	<0.001			
$\delta_4TREAT2_{ij}$				1.23	0.31	<0.001	1.25	0.31	<0.001			
HEIGHT	1.3											
Parameter	1.1bb			1.1aa			6aa.1			6bb.1		
	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value
β_0	671.43	16.88	<0.001	606.33	22.96	<0.001	614.40	22.65	<0.001	610.39	22.69	<0.001
AGE_{ij}	13.08	0.86	<0.001	23.35	1.77	<0.001	21.93	1.67	<0.001	22.81	1.73	<0.001
$\beta_2SPEI\_M_{ij}$	-7.54	3.73	0.04	-10.24	4.60	0.026	-13.21	4.51	0.004	-13.22	4.51	0.004
$\beta_{1i}AGE_{ij}$	1.02	0.16	<0.001	1.07	0.15	<0.001	1.15	0.15	<0.001	1.15	0.15	<0.001
δ_0	-12.93	0.93	<0.001	-22.24	1.80	<0.001	-20.80	1.71	<0.001	-21.97	1.75	<0.001
κ_0	16.70	1.03	<0.001	11.27	0.77	<0.001	11.66	0.80	<0.001	11.32	0.79	<0.001
$\kappa_1SPEI\_N_{ij}$	-2.47	0.54	<0.001	-1.28	0.25	<0.001						
δ_1THIN_{ij}	-1.10	0.34	0.003							-0.98	0.26	<0.001
$\delta_2SPEI\_N_{ij}$							-1.42	0.21	<0.001	-1.41	0.20	<0.001
$\delta_3TREAT1_{ij}$				-0.94	0.32	0.003	-0.99	0.32	0.002			
$\delta_4TREAT2_{ij}$				1.21	0.31	<0.001	1.24	0.31	<0.001			
HEIGHT	3											
Parameter	1.1bb			1.1aa			6aa.1			6bb.1		
	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value
β_0	512.58	24.98	<0.001	513.90	25.50	<0.001	480.24	28.36	<0.001	502.86	26.25	<0.001
AGE_{ij}	20.78	1.30	<0.001	20.67	1.41	<0.001	24.26	1.65	<0.001	21.85	1.49	<0.001
$\beta_2SPEI\_M_{ij}$	-2.12	1.07	0.048	-2.11	1.07	0.049	-6.12	2.83	0.03	-3.86	1.82	0.033
$\beta_{1i}AGE_{ij}$	0.82	0.19	<0.001	0.82	0.19	<0.001	0.92	0.19	<0.001	0.86	0.19	<0.001
δ_0	-20.01	1.36	<0.001	-19.57	1.46	<0.001	-22.83	1.69	<0.001	-20.86	1.54	<0.001
κ_0	16.89	0.74	<0.001	16.93	0.73	<0.001	15.43	0.81	<0.001	16.30	0.77	<0.001
$\kappa_1SPEI\_N_{ij}$	-1.74	0.32	<0.001	-1.72	0.30	<0.001						
δ_1THIN_{ij}	-1.01	0.31	0.001							-0.99	0.30	0.001
$\delta_2SPEI\_N_{ij}$							-1.62	0.27	<0.001	-1.69	0.29	<0.001
$\delta_3TREAT1_{ij}$				-1.29	0.40	0.001	-1.28	0.38	<0.001			
$\delta_4TREAT2_{ij}$				0.90	0.40	0.023	0.94	0.38	0.013			
HEIGHT	4.3											

Parameter	6aa.1			6bb.1			1.1bb			1.1		
	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value
β_0	431.69	39.20	<0.001	485.78	32.73	<0.001	506.30	30.28	<0.001	524.24	27.85	<0.001
AGE_{ij}	36.81	2.59	<0.001	29.54	2.06	<0.001	26.94	1.76	<0.001	25.05	1.69	<0.001
$\beta_2 SPEI\_M_{ij}$	-5.39	2.37	0.023	-2.14	1.05	0.041	-0.84	0.49	0.088	-1.42	0.75	0.06
$\beta_{1i} AGE_{ij}$	1.06	0.22	<0.001	0.98	0.23	<0.001	0.94	0.23	<0.001	0.96	0.23	<0.001
δ_0	-35.53	2.64	<0.001	-28.83	2.14	<0.001	-26.48	1.85	<0.001	-24.36	1.78	<0.001
κ_0	11.86	0.79	<0.001	13.23	0.77	<0.001	13.92	0.73	<0.001	14.35	0.66	<0.001
$\kappa_1 SPEI\_N_{ij}$							-1.53	0.28	<0.001	-1.66	0.28	<0.001
$\delta_1 THIN_{ij}$				-0.78	0.39	0.046	-0.83	0.42	0.05			
$\delta_2 SPEI\_N_{ij}$	-1.91	0.29	<0.001	-2.00	0.32	<0.001						
$\delta_3 TREAT1_{ij}$	-0.90	0.42	0.034									
$\delta_4 TREAT2_{ij}$	0.91	0.48	0.059									
HEIGHT	6											
Parameter	1.10			1.1c			11.10					
	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value
β_0	484.67	31.66	<0.001	528.59	27.08	<0.001	512.17	29.63	<0.001			
AGE_{ij}	32.91	2.43	<0.001	26.54	1.92	<0.001	28.75	2.30	<0.001			
$\beta_2 SPEI\_M_{ij}$	-2.14	0.97	0.026	-2.27	1.09	0.037	-2.12	1.09	0.05			
$\beta_{1i} AGE_{ij}$	1.08	0.26	<0.001	1.11	0.27	<0.001	1.08	0.27	<0.001			
δ_0	-31.36	2.49	<0.001	-25.29	1.99	<0.001	-27.25	2.38	<0.001			
κ_0	11.18	0.69	<0.001	12.11	0.71	<0.001	11.96	0.73	<0.001			
$\kappa_1 SPEI\_N_{ij}$	-1.50	0.22	<0.001	-1.82	0.30	<0.001						
$\kappa_2 PRUN_{ij}$				1.18	0.57	0.04						
$\delta_2 SPEI\_N_{ij}$							-2.40	0.37	<0.001			
HEIGHT	9											
Parameter	1.2bb			1.2aa			6bb.2			6aa.2		
	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value
β_0	445.65	36.18	<0.001	450.04	35.57	<0.001	446.15	36.05	<0.001	422.20	38.94	<0.001
AGE_{ij}	30.91	2.38	<0.001	30.37	2.33	<0.001	31.31	2.49	<0.001	34.04	2.53	<0.001
$\beta_2 SPEI\_N_{ij}$												
$\beta_{1i} AGE_{ij}$	-1.40	0.26	<0.001	-1.40	0.26	<0.001	-1.40	0.27	<0.001	-1.42	0.26	<0.001
δ_0	-31.23	2.45	<0.001	-30.26	2.38	<0.001	-30.42	2.57	<0.001	-32.70	2.57	<0.001
κ_0	13.15	0.87	<0.001	13.26	0.86	<0.001	12.33	0.91	<0.001	12.01	0.92	<0.001
$\kappa_1 SPEI\_M_{ij}$	0.99	0.14	<0.001	1.01	0.14	<0.001						
$\delta_1 THIN_{ij}$	-1.41	0.51	0.006				-1.02	0.52	0.052			
$\delta_2 SPEI\_M_{ij}$							1.82	0.26	<0.001	1.79	0.25	<0.001
$\delta_3 TREAT1_{ij}$				-1.82	0.67	0.007				-1.28	0.57	0.029
$\delta_4 TREAT2_{ij}$				1.32	0.63	0.037				1.00	0.53	0.058
Parameter	1.2c_dist			1.2b_dist								
	Estim.	S.E.	P-value	Estim.	S.E.	P-value						
β_0	466.13	33.64	<0.001	467.03	33.43	<0.001						
AGE_{ij}	28.76	2.25	<0.001	28.66	2.33	<0.001						
$\beta_2 SPEI\_N_{ij}$												
$\beta_{1i} AGE_{ij}$	-1.39	0.26	<0.001	-1.39	0.26	<0.001						
δ_0	-28.51	2.33	<0.001	-28.47	2.43	<0.001						
κ_0	14.14	0.90	<0.001	15.57	1.20	<0.001						
$\kappa_1 SPEI\_M_{ij}$	1.08	0.15	<0.001	1.07	0.15	<0.001						
$\kappa_2 PRUN_{ij}$	2.06	0.61	<0.001									
$\kappa_3 DIST\_C_{ij}$	0.90	0.40	0.025	0.95	0.49	0.054						
$\kappa_3 THIN_{ij}$				1.85	0.76	0.016						

HEIGHT	12											
Parameter	1.1			1.1c			1.2					
	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value			
β_0	472.18	34.93	<0.001	490.65	31.74	<0.001	487.03	30.59	<0.001			
AGE_{ij}	25.81	1.85	<0.001	23.83	1.68	<0.001	23.85	1.51	<0.001			
$\beta_2 SPEI_{ij}$												
$\beta_{1i} AGE_{ij}$	2.90	0.43	<0.001	2.86	0.43	<0.001	-0.65	0.30	0.029			
δ_0	-23.25	2.03	<0.001	-21.81	1.92	<0.001	-26.09	1.99	<0.001			
κ_0	13.12	1.09	<0.001	13.01	0.96	<0.001	15.84	1.04	<0.001			
$\kappa_1 SPEI\_N_{ij}$	-1.97	0.39	<0.001	-2.05	0.46	<0.001						
$\kappa_2 SPEI\_Mij$							1.51	0.25	<0.001			
$\kappa_3 PRUN_{ij}$				2.07	0.83	0.013						

2.6.2 Annex II

Table 2.4. Best models fitted for Pinus sylvestris at each height

PS mixed models fitted												
0												
Parameter	1.2aa			9e			6ee.2			6aa.1		
	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value
β_0	624.34	13.77	<0.001	619.29	14.11	<0.001	622.41	13.75	<0.001	620.78	14.07	<0.001
AGE_{ij}	6.56	0.49	<0.001	6.98	0.45	<0.001	6.72	0.43	<0.001	6.84	0.44	<0.001
$\beta_2 SPEI_{ij}$	-66.13	7.28	<0.001	-54.22	7.82	<0.001	-67.77	7.86	<0.001	-54.28	7.86	<0.001
$\beta_{1i} AGE_{ij}$	2.81	0.25	<0.001	1.68	0.26	<0.001	2.70	0.27	<0.001	1.68	0.26	<0.001
δ_0	-5.88	0.62	<0.001	-8.60	0.66	<0.001	-7.13	0.63	<0.001	-7.64	0.61	<0.001
κ_0	21.72	1.74	<0.001	22.07	1.45	<0.001	22.16	1.77	<0.001	22.14	1.42	<0.001
$\kappa_1 SPEI\_MC_{ij}$	-3.30	0.55	<0.001									
$\delta_1 SILVIC_{ij}$				-1.53	0.40	<0.001	-1.45	0.42	<0.001			
$\delta_2 SPEI\_S_{ij}$				1.09	0.16	<0.001				1.09	0.16	<0.001
$\delta_3 SPEI\_MC_{ij}$							-0.70	0.15	<0.001			
$\delta_4 TREAT1_{ij}$	-2.04	0.51	<0.001							-2.14	0.50	<0.001
$\delta_5 TREAT2_{ij}$	1.68	0.50	<0.001							1.74	0.48	<0.001
3												
Parameter	1.2aa			1.2			9.2			9e		
	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value
β_0	537.03	20.08	<0.001	549.54	18.79	<0.001	548.11	20.2	<0.001	540.7	21.11	<0.001
AGE_{ij}	20.93	1.16	<0.001	19.33	1.12	<0.001	20.582	1.44	<0.001	21.12	1.389	<0.001
$\beta_2 SPEI_{ij}$	-21.74	7.44	0.004	-21.70	7.70	0.005	-23.75	8.58	0.006	-20.04	8.33	0.018
$\beta_{1i} AGE_{ij}$	2.56	0.30	<0.001	2.54	0.31	<0.001	1.2056	0.33	<0.001	1.093	0.326	<0.001
δ_0	-20.58	1.27	<0.001	-18.78	1.23	<0.001	-21.89	1.53	<0.001	-23.09	1.48	<0.001
κ_0	13.40	0.80	<0.001	14.06	0.75	<0.001	13.768	0.71	<0.001	13.84	0.751	<0.001
$\kappa_1 SPEI\_MC_{ij}$	-1.37	0.15	<0.001	-1.46	0.17	<0.001						
$\delta_1 SILVIC_{ij}$										-0.949	0.33	0.005
$\delta_2 SPEI\_S_{ij}$										1.335	0.142	<0.001
$\delta_3 SPEI\_MC_{ij}$							1.3385	0.14	<0.001			
$\delta_4 TREAT1_{ij}$	-1.17	0.46	0.011									
$\delta_5 TREAT2_{ij}$	0.36	0.16	0.027									

	6											
Parameter	1.1			9.1			1.2			9.2		
	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value
β_0	546.7	19.9	<0.001	545.87	20.32	<0.001	533.15	19.73	<0.001	544.4	20.29	<0.001
AGE_{ij}	18.16	1.49	<0.001	18.37	1.50	<0.001	19.71	1.33	<0.001	18.67	1.512	<0.001
$\beta_2 SPEI_{ij}$	-32.3	9.85	0.001	-25.37	9.82	0.01	-33.07	9.33	<0.001	-38.21	10.02	<0.001
$\beta_{1i} AGE_{ij}$	1.883	0.43	<0.001	1.81	0.43	<0.001	3.16	0.43	<0.001	3.164	0.458	<0.001
δ_0	-18.9	1.64	<0.001	-19.53	1.65	<0.001	-19.40	1.47	<0.001	-18.58	1.647	<0.001
κ_0	13.62	0.82	<0.001	13.92	0.87	<0.001	13.45	0.93	<0.001	13.78	0.89	<0.001
$\kappa_1 SPEI\_MC_{ij}$							-0.90	0.17	<0.001			
$\kappa_2 SPEI\_S_{ij}$	1.10	0.19	<0.001									
$\delta_1 SPEI\_S_{ij}$				1.19	0.18	<0.001						
$\delta_2 SPEI\_MC_{ij}$										-0.88	0.17	<0.001
	9											
Parameter	6			9			9_a			9_b		
	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value	Estim.	S.E.	P-value
β_0	338.87	41.07	<0.001	320.80	44.24	<0.001	320.99	43.99	<0.001	319.42	44.05	<0.001
AGE_{ij}	27.63	1.18	<0.001	29.47	1.75	<0.001	29.39	1.72	<0.001	29.55	1.73	<0.001
$\beta_2 SPEI\_S_{ij}$												
$\beta_{1i} AGE_{ij}$	0.71	0.10	<0.001	0.65	0.10	<0.001	0.65	0.10	<0.001	0.65	0.10	<0.001
δ_0	-25.88	1.29	<0.001	-28.02	1.88	<0.001	-27.91	1.85	<0.001	-28.04	1.85	<0.001
κ_0	14.35	1.40	<0.001	14.22	1.30	<0.001	14.55	1.05	<0.001	11.39	1.56	<0.001
$\kappa_1 SPEI_{ij}$	-1.08	0.32	<0.001									
$\kappa_2 DIST\_C_{ij}$							1.27	0.45	0.005			
$\kappa_3 I\_C_{ij}$										5.27	2.12	0.01
$\delta_2 SPEI_{ij}$	4.16	0.81	<0.001	1.89	0.45	<0.001	1.92	0.45	<0.001	1.93	0.45	<0.001

Chapter 3. Study of the juvenile wood distribution along the bole considering the influence of the silvicultural treatments

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Abstract

Wood use for structural use has increased in the last decade in Spain. However, raw material needs to comply with requirements that are not always present. Knowledge about the wood quality from the trees on the stand is essential for providing feedback to forest managers and for taking the required actions to obtain suitable silviculture treatments.

Two of the main wood species, used in construction in Spain, *Pinus nigra* and *Pinus sylvestris,* have been studied in order to determine the amount of juvenile wood, which has been identified as a very harmful characteristic for wood end uses. How it is distributed at different heights along the bole and the effect several silvicultural treatments have had on juvenile wood formation has been analyzed.

The juvenile-mature wood boundary (transition year) was calculated using segmented linear mixed models annual latewood density, obtained through micro X-ray densitometry, silvicultural practices and a drought index.

The results show how juvenile and mature wood is distributed along the bole as well as how the proportion of juvenile wood varies according to different treatments, but especially when the silvicultural practices used are hard thinning and pruning.

3.1 Introduction

On wood for structural uses, the properties of round wood and the final processed lumber are important in terms of complying with construction standards. With the increasing demand in Europe for construction timber, the importance of wood quality in the sawn timber industry is essential.

Due to changes in forest management and improved genetic material, rotation periods have been reduced as growth rates have increased. However, as a result of this, there has been a significant reduction in their important mechanical properties (Dowse and Wessels 2013; Wessels et al. 2014; Hermoso et al. 2016). As these problems arose, there has been an increase on the number of researches done on wood quality, with wood density and MFA being the two most influential properties for predicting mechanical properties (Tsoumis 2009; Burdon et al. 2001; Auty et al. 2014; Moore et al. 2015; Mäkinen and Hynynen 2012). The impact of silvicultural interventions and planting density not only affects growth and therefore, wood volume; but also, how straight the bole is, the type and amount of branches, as well as its internal characteristics (Ulvcrona and Ahnlund 2011; Mörling 2002; Barbour et al. 1994; Rais et al. 2014; Erasmus et al. 2016).

One characteristic of conifers is that on the first rings growing near the pith, the wood that is formed has different properties than that which is farther from it. This area of wood in the first years is called Juvenile Wood (JW), which is distinguished by, being less dense and having a higher MFA, among other properties, and thus, lower elasto-mechanical properties (Larson 1969; Burdon et al. 2004). When the JW properties stabilizes over the years, it is considered to be Mature Wood (MW).

Although JW it's the name still used by users of this material in Spain, on the wood scientific community the nomenclature for this inner part of the bole has been modified, calling it corewood (CW) and the outer part outerwood (OW) (Burdon et al. 2004). The new nomenclature allows to explain the variation that happens along the bole as the hydraulic and mechanical demands change trough the life of the tree (Lachenbruch et al. 2011). In this paper the terms JW/MW will be used to differentiate two areas of the density radial pattern along the bole. The JW will be defined as the area where its density increases really fast and the MW the area when the density values more or less stabilizes.

As density can be measured easily with high resolution using micro X-ray densitometry, this study was carried out using this methodology considering the annual variation in Latewood density (LW) as the dependent variable (Sauter et al. 1999; Gapare et al. 2006), on a segmented mixed linear model for estimating the transition between JW and MW.

The objective of this paper is to analyze the proportion of juvenile wood along the bole and compare it between plots that have different silviculture regimes on two of the *Pinus* species used for structural purposes in Spain, *Pinus nigra* Arnold subsp. *nigra* (Black pine) (PN) and *Pinus sylvestris* L. (Scots pine) (PS).

3.2 Material and methods

3.2.1 Sampling

Two different thinning and pruning trials established by INIA-CIFOR at the end of the past century, were used for obtaining the wood samples.

The first site is a pure plantation *Pinus nigra* Arnold subsp. *nigra* (Black pine) (PN) located in the municipality of Zarzuela de Jadraque (Guadalajara, Spain) (41°1´N, 3º4´W). It was planted in 1962 and consists of a control, thinning (CFSP) and thinning and 5 m pruning (CFCP) regimes at an altitude of 1005 m.a.s.l., on a generally flat area with a 1–10 % slope in NW direction. In this area, the average annual rainfall is 489 mm, and the average annual temperature is 10.9 ºC (AEMET, 2017).

For the PN 12 trees were felled. Then disks at basal height and at every 3 m were extracted until the diameter was less than 7.5 cm, plus another two disks were extracted at 1.3 m and at 4.3 m as described in Figure 3.1. In this paper, the study was carried on up to a height of 12 m, which all trees reached.

From all the disks, two 2 mm-thick and 40 mm-wide strips, cut from the cross section were sawn, avoiding compression wood if possible. This was done by obtaining the strips perpendicular to the slope and visually checking for compression wood. Once these strips had been obtained, they were immersed in n-Pentane for 48 h to eliminate extractives (Gapare et al. 2006; Rodríguez and Ortega 2006). Once extracted, the samples were stored in a climatic chamber at 20 ºC and at 65 % RH until their moisture content was 12 %. Then they were scanned with an X-ray to assess the microdensity of the strip using the same equipment as described in Rodríguez and Ortega (2006). The images were processed using LIGNOVISION™ and TSAP-Win™ software (http://www.rinntech.de). A fixed boundary between earlywood and latewood was set as being half the variation in density in each ring, and average values for each growth ring such as ring width, mean ring density, earlywood width, earlywood density, latewood width, latewood density and texture were obtained.

The second site is a *Pinus sylvestris* L. (Scots pine) (PS) pure plantation located in the Guadarrama mountain range, in the La Morcuera Forest (Madrid, Spain) (40º50´N, 3º5´W). This forest stand comes from a plantation done in 1954 where control (CONTROL), light thinning (CDSP), light thinning and 3 m pruning (CDP3), heavy thinning (CFSP) and heavy thinning and 5 m pruning (CFP5) trials had been carried out. It is located at an altitude of 1550 m.a.s.l. on the northern face of the mountain with a NE orientation and a 10–50 % slope in the trial area. In this area, the average annual rainfall is 1062 mm, and the average annual temperature is 7 ºC (AEMET, 2017).

Here, 15 trees were felled, and disks were extracted as in the black pine methodology described above, except for the disks at heights of 1.3 m and 4.3 m.

3.2.2 Juvenile-Mature wood proportion

In order to assess the proportion of juvenile-mature wood, the transition year (TY) between them needs to be accurately determined. To do so, latewood density (LW) was the wood characteristic selected (Sauter et al. 1998; Gapare et al. 2006).

A two-step procedure was carried out as in Ruano et al. (n.d.). First, an initial TY was estimated with the "segmented" (Muggeo 2008) package in R (R Core Team 2017) linking yearly density LW at each height to the Standardized Precipitation Evapotranspiration Index (SPEI) (Beguería and Vicente-Serrano 2017) and age, excluding the treatment. This was done to account for the density variation produced by severe droughts (Arzac et al. 2018). Next, the best fitted model was run through the function developed in R for mixed segmented models (Muggeo et al. 2014; Muggeo et al. 2017), taking into account all the variables including treatment.

In this way the TY was obtained and, in turn, the proportion of JW from the average of both diametrical strips of the disk (one on each side of the pith) was calculated.

The percentage that resulted at each height was calculated taking into consideration treatments in order to analyze what influence these had on juvenile wood growth patterns.

The volume was also calculated between each tree height sampled using the Smalian method for cubication.

3.3 Results and discussion

The results will be presented separately for each species.

3.3.1 *Pinus nigra*

The results regarding how silviculture influenced the TY obtained showed no clear differences between treatments (Figure 3.2.) as this occurred before the first silvicultural intervention was carried out. At a height of 12 m, a slight difference between the pruned and thinned ones and the control group was observed, but the crown might have influenced the moment at which the TY occurred.

In Figure 3.3. the percentage of JW to MW is compared at each height per plot type, but some differences relating to the use of different silvicultural treatments could be observed. Due to the increase in radial growth brought about by late thinning, the extent of MW length on each strip increased, then the percentage of JW in respect to the total reduced. There also seemed to be a difference between CFCP and CFSP inside the crown at a height of 12 m, which occurs because in the thinned plots the percentage of JW increases slightly compared with the pruned ones. This effect is in keeping with the findings of Larson (1969).

An analysis from a perspective of volume is presented in Table 3.1. Note the difference in terms of total volume per treatment applied in comparison with that for the control group, as the MW is affected by late thinning, as mentioned previously. Little difference can be seen between pruned and not pruned in terms of total volume and the percentage of JW.

Table 3.1. PN volume per tree in m^3 per plot type and JW volume percentage.

Id tree	Height	Plot type	JW Volume	MW Volume	Tree Volume	%JW Volume
13	0 - 12	CONTROL	0.079	0.142	0.221	36
47	0 - 12		0.070	0.142	0.212	33
51	0 - 12		0.041	0.114	0.155	27
56	0 - 12		0.039	0.130	0.169	23
6	0 - 12	CFSP	0.075	0.280	0.355	21
21	0 - 12		0.074	0.252	0.327	23
29	0 - 12		0.041	0.286	0.327	13
38	0 - 12		0.056	0.257	0.313	18
4	0 - 12	CFCP	0.044	0.249	0.292	15
16	0 - 12		0.084	0.283	0.367	23
31	0 - 12		0.058	0.257	0.315	18
45	0 - 12		0.074	0.355	0.429	17

Figure 3.4. shows a reconstructed tree with its radial section area of JW-MW along the bole based on the medium length strips from the disks extracted at different heights. Different plot type trees are shown.

On PN the CFCP treatment shows better results (Figure 3.4.) than those for CFSP, in terms of its degree of taper, mainly in the 3-9 m section of the bole, where when bucked to a specific merchantable length, sawmills can obtain products for structural use and therefore high quality is required.

There have been reports in the literature concerning the effects thinning and pruning, but depending on the variable measured, the age at which they are applied and their intensity, different effects can be seen (Peltola et al. 2007; Ulvcrona and Ahnlund 2011; Vincent et al. 2011; Moore et al. 2015; Mörling 2002; Barbour et al. 1994; Paul 1958). Even so, most of these reports conclude that these effects are limited to the following few years after treatment. So, if this is considered, clearly thinning and pruning operations applied after the TY is reached, will not only increase total volumes in Mediterranean forests but also the percentage of quality wood obtained from them.

3.3.2 *Pinus sylvestris*

As in the PN results, the TY determined in PS does not show any clear differences between silviculture treatments and control plots (Figure 3.5.). At 9 m a huge variation can be seen in just the thinned plots. At 12 m, there seems to be differences between the pruned plots and the control, but not as regards the thinned ones for this species.

On comparing the percentage of JW to. MW at each height when the plot type is taken into consideration, some differences can also be observed (Figure 3.6.). Due to the increase in radial growth produced by late thinning, the length of MW length on each strip increased, so the percentage of JW reduced, as in PN. As yet, no explanation has been found for the marked variations between these two types of wood at 9 m in the control group.

Regarding the total volume of each type of wood, in Table 3.2. significative differences can be observed in terms of the total volume per treatment, as late thinning affected MW, as well as pruning which caused an increase in the total volume produced. The percentage of JW was higher on the Control plots.

Table 3.2. PS volume per tree in m^3 per plot type and JW volume percentage.

Id tree	Height	Plot type	JW Volume	MW Volume	Tree Volume	%JW Volume
04	0 - 12	CONTROL	0.051	0.137	0.188	27
26	0 - 12		0.056	0.146	0.202	28
61	0 - 9		0.088	0.168	0.256	34
16	0 - 12	CDSP	0.073	0.285	0.359	20
34	0 - 12		0.080	0.288	0.368	22
74	0 - 9		0.055	0.192	0.247	22
14	0 - 12	CDP3	0.065	0.269	0.334	19
40	0 - 12		0.120	0.465	0.585	20
52	0 - 12		0.057	0.453	0.509	11
07	0 - 12	CFSP	0.056	0.253	0.309	18
35	0 - 12		0.047	0.278	0.325	15
55	0 - 12		0.066	0.223	0.288	23

Id tree	Height	Plot type	JW Volume	MW Volume	Tree Volume	%JW Volume
20	0 - 12	CFP5	0.057	0.291	0.348	16
48	0 - 12		0.060	0.344	0.404	15
66	0 - 12		0.071	0.473	0.544	13

In Figure 3.7. there is a reconstructed tree with its area of JW-MW on a radial section based on data yielded from the medium length strips obtained for each silvicultural treatment under study.

In Figure 3.7., note the volume of JW reduces with treatments due to the previously mentioned increase in the volume of MW, with respect to the total volume. Stronger thinning combined with higher pruning produces a greater reduction in the volume of JW (CFP5).

On PS, as mentioned above, stronger thinning combined with higher pruning (CFP5) produces a greater reduction in the volume of JW. There is another advantage to using this latter treatment, it generates clearwood, that is important in terms of quality wood for structural use, as knots are reduced to the part closest to the pith and there is a small reduction in tree taper at heights of between 3 and 6 m. This was observed on plots on both species, which is also in keeping with the findings of Larson et al. (2001).

On PS, while pruning at 5 m seems to influence the degree of taper, pruning at 3 m seems to have no clear effect on it and, as carrying out this treatment is costly, either performing late pruning enhanced up to 5 m or not doing it at all, should be considered.

Regarding the percentage of JW on PS when comparing both pruning, at 3 m on pruned plots (CDP3) the percentage of juvenile wood is highly variable (Table 3.2.), so no clear conclusion can be obtained.

3.4 Conclusions

The growth response after silvicultural treatments show that the amount of JW reduces in percentage and total volume increases with any silvicultural treatment applied to PN and the same is true for PS, as any treatment leads to a reduction in the proportion of JW and to an increase in total volume in Mediterranean forests.

Exclusively using TY does not help ascertain the effect silvicultural treatment has due to the fact that the treatments under study were applied after the TY at most heights along the bole, and at 12 m the crown might be an influencing factor as well.

As stated in many papers in the literature, results may vary with the intensity and time of the thinning as well as the amount of green pruning removed. Also, additional research is required to support these results which could also be supplemented with some destructive sampling of the processed trees to evaluate if there is any difference in MW or in the general quality of the wood between treatments in the end product, as well as an MFA analysis.

Conflict of interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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3.6 Figures

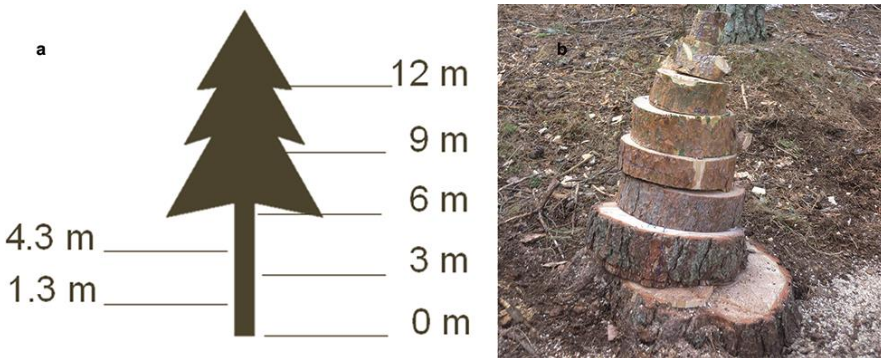

Figure 3.1. Disk sampling from each tree. a) Sketch showing the sampled heights b) Disks obtained from a sampled tree

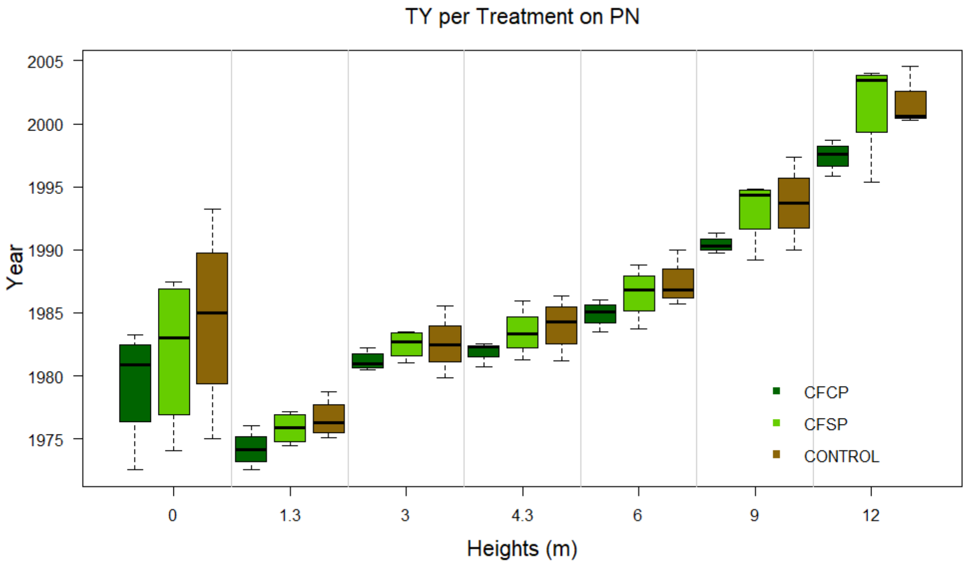

Figure 3.2. TY per treatment on PN plots

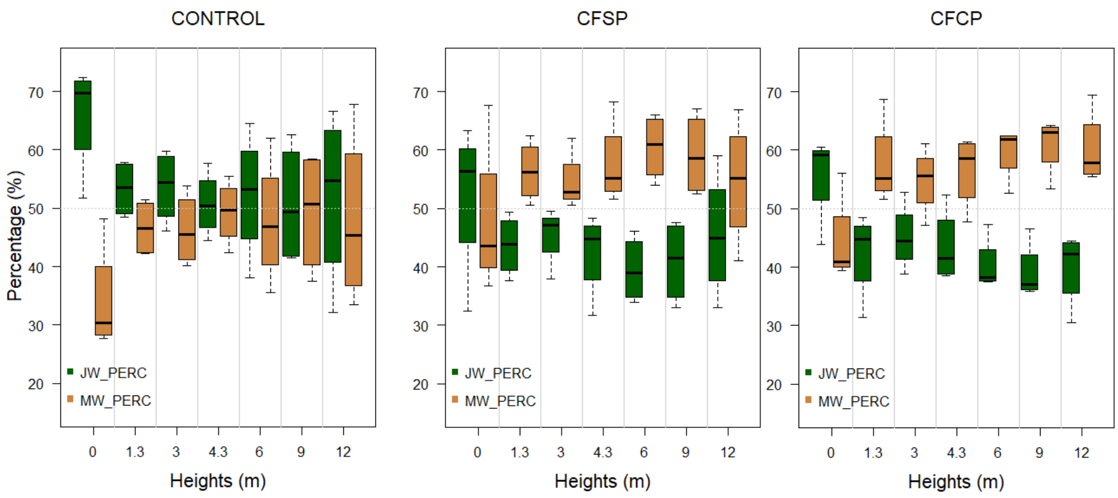

Figure 3.3. PN percentage length of JW and MW at each height for each treatment

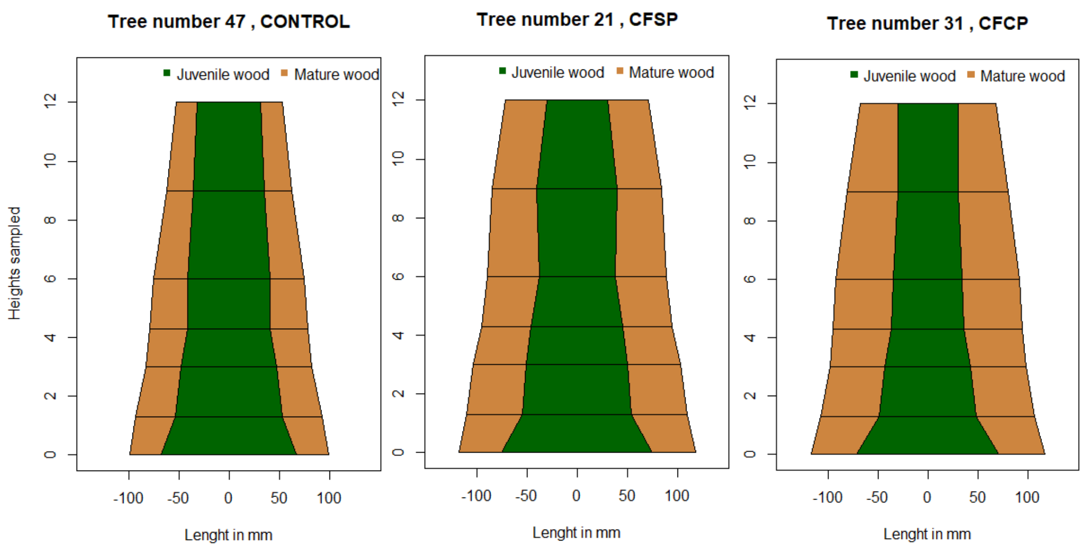

Figure 3.4. PN JW/MW tree reconstruction along the bole

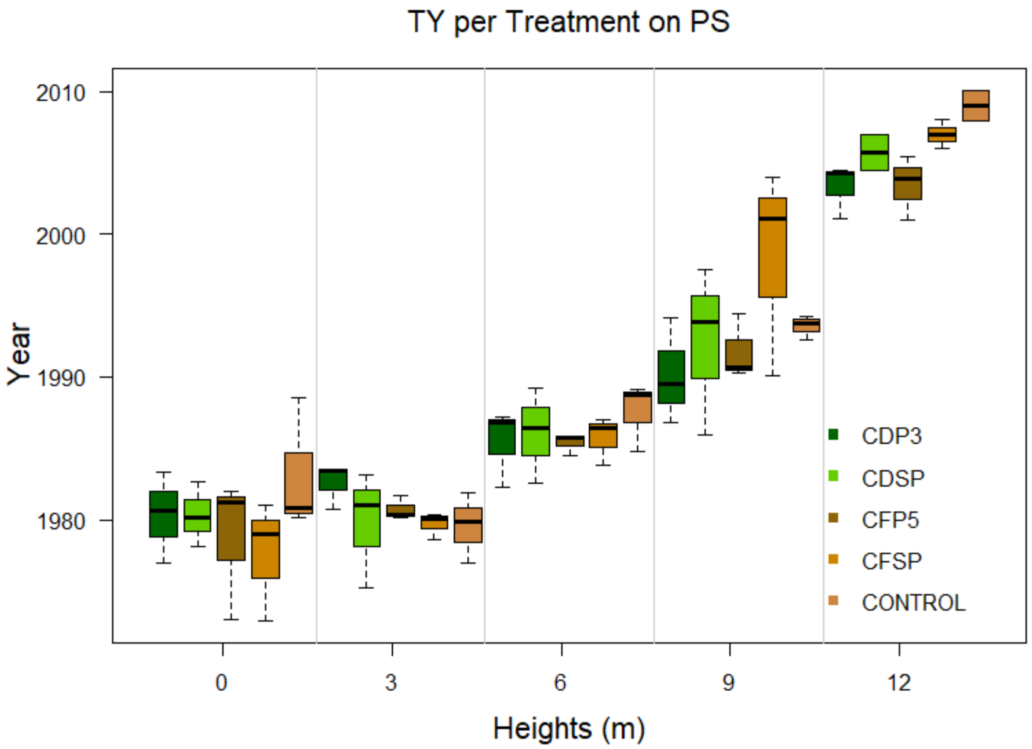

Figure 3.5. TY per treatment on PS plots

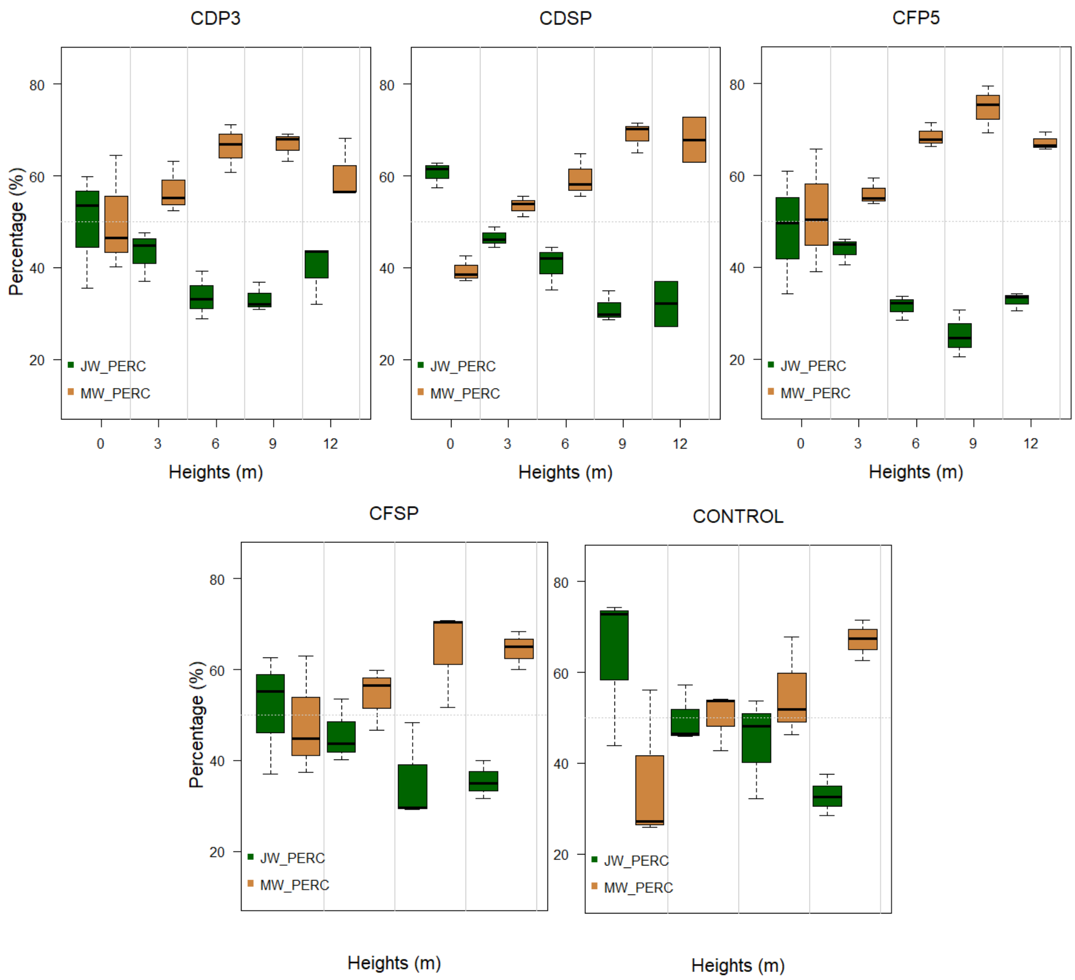

Figure 3.6. PS percentage length of JW and MW at each height for each treatment

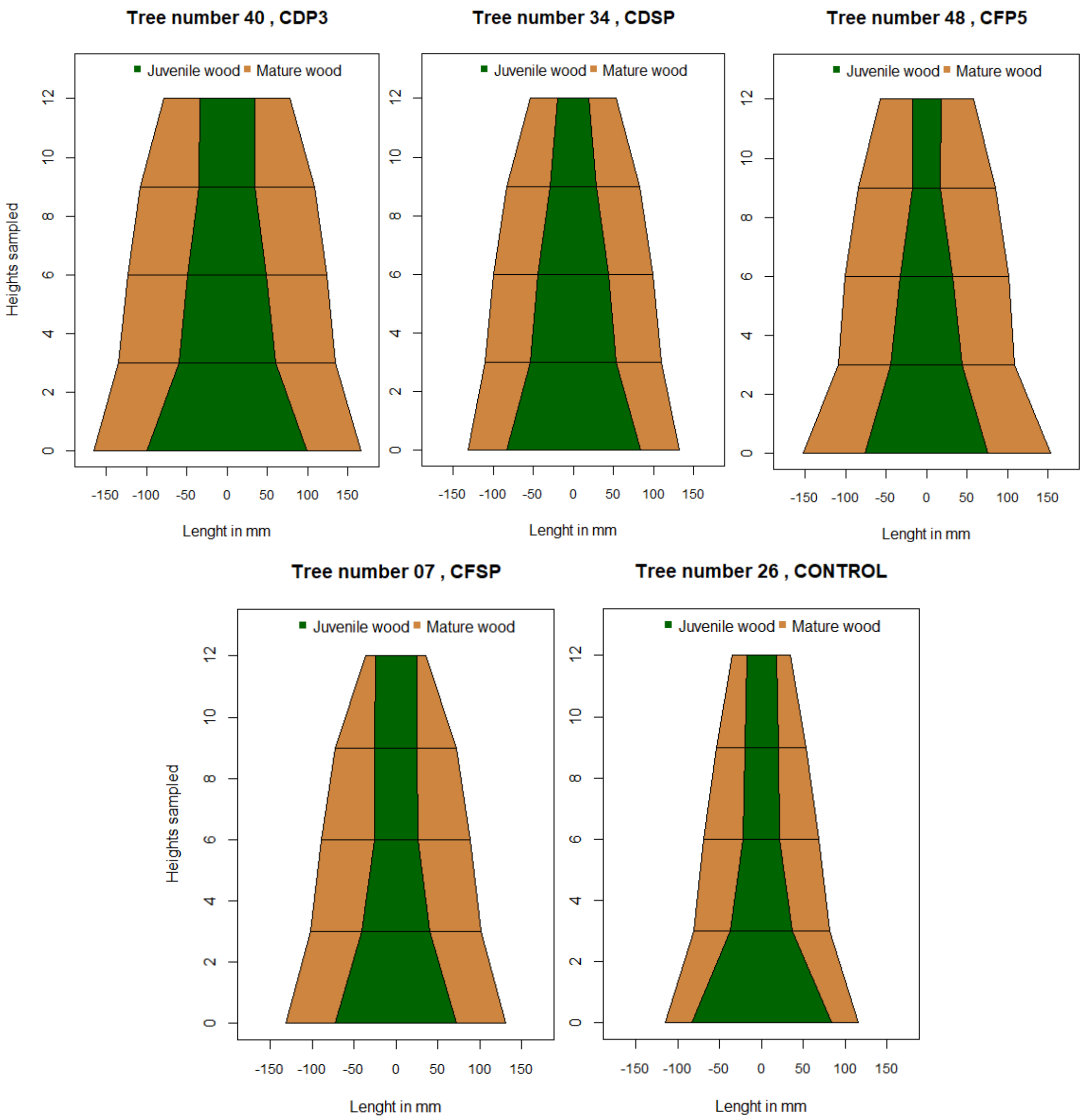

Figure 3.7. PS JW/MW tree reconstruction along the bole

Chapter 4. Height growth measurements as a way to assess the juvenile wood/ mature wood boundary area at basal height

This chapter has been submitted as:

Ruano A, Ruiz-Peinado R, Fernández-Golfín J, Hermoso E (n.d.) Height growth for assessing juvenile-mature wood transition on *Pinus sylvestris* and *Pinus nigra* Spanish stands. Wood Science and Technology (Submitted)

Impact Factor (SJR): 0.97. Q1 Forestry, rank 15 / 129.

Abstract

One of the characteristics of great relevance in the wood quality in Spanish coniferous forests due to growth conditions is the presence of juvenile wood. This wood presents properties and characteristics inferior to those in mature wood, which condition its appropriateness for certain uses. In plantations with short-rotations, the percentage of juvenile timber is higher, and the profitability of the wood can be affected due to its unsuitability for high added value applications, such as structural. This work focuses on determining if the use of models of current annual increase in height, can provide suitable estimations of the year or transition zone between juvenile and mature wood. This knowledge contributes to analyze the expected yield of quality wood. The material studied is from *Pinus sylvestris* L. (Scots pine) and *Pinus nigra* Arnold subsp. *nigra* (black pine) pure stands. Results show that the transition year of the trees differ widely if analyzed by the height functions or by densitometry.

Key words

Juvenile wood, accumulated height growth, X-ray densitometry, Scots pine, black pine.

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4.1 Introduction

As with many other living organisms, a tree goes through different phases of development until it reaches maturity. From an external point of view, this can be observed, for example, as the leaves from saplings are morphologically different to those from mature trees and, as described in Larson (1969) and Burdon et al. (2004), there are certain structures that only appear when a tree grows older. Taking flowering as an example, and just as with other species, a tree is considered having reached maturity when it starts to reproduce (Fernandez and Cornejo 2016). Also, hydraulic and mechanical demands change trough the life of the tree (Lachenbruch et al. 2011)

But inside the tree trunk there are also some anatomical, physical and mechanical variations in radial and axial directions during growth processes. (Burdon et al. 2004). Although these internal variations can occur over a span of years, mostly depending on the physical, mechanical or chemical characteristics, it has become convention to consider two different areas inside the cross section of a stem; the juvenile wood and the mature wood (Larson et al. 2001; Ilic et al. 2003).

The juvenile wood can be defined as a still imperfect wood, present in the inner part of the bole near the pith, in which wood characteristics undergo rapid and progressive changes in successively older growth rings (Larson et al. 2001). Although juvenile wood it's the name still used by users of this material, trends on the wood scientific community have agreed to a better nomenclature for this inner part of the bole, calling it corewood (CW) and the outer part outerwood (OW). This terminology also explains the fact that the juvenile wood from the upper part of the bole differs to the lower part, which is due to the "physiological aging" (Burdon et al. 2004). So, in this paper the juvenile/mature wood terminology will be changed to the CW/OW that also enables the explanation of the changes along the bole.

CW is characterized by having a cellular structure with smaller tracheid length, lumen diameter, wall thickness, transverse shrinkage, stiffness and cellulose/lignin ratio. Other properties are lower, such as density and mechanical properties but others, such as spiral grain and microfibril angle are higher. One phenomenon sometimes related to CW is the presence of wider growth-rings and high levels of compression wood, although these last two relationships are not mutually exclusive. (Larson 1969; Zobel and Sprague 1998; Larson et al. 2001; Ilic et al. 2003; Rodríguez and Ortega 2006; Ivković et al. 2009).

All of these variations have undesirable effects on the physical-mechanical and technological properties of the material (Larson 1969; Burdon et al. 2004; Hermoso et al. 2013). The higher the proportion of CW, the greater incidence of different drying distortions such as spring, bow, crook and twist (Ilic et al. 2003) resulting in diminished prospects for profitable end use and economic return for most products on the wood industry. Although it affects differently depending on the end product, being the most affected one's solid dimension lumber and Kraft pulp. It has been even reported some positive traits on oriented strand board, medium density fiberboard and some types of mechanical pulp (Moore and Cown 2017).

The transition year (TY) between CW and OW can be found by analyzing different properties. The boundary tends to change according to the wood property studied (Bendtsen and Senft 1986) with variable patterns from pith to bark. (Ilic et al. 2003; Bendtsen and Senft 1986; Larson et al. 2001; Burdon et al. 2004).

Basic specific gravity and density have been extensively used as indicators of CW presence. Microfibril angle is also an important characteristic for wood dimensional stability and stiffnes, but the costs of its assessment are higher. This is why this study is based on the density radial variation. Density can easily be measured, with high precision and resolution, using micro X-ray densitometry techniques and is related to the mechanical properties of wood as it is a predictor of the modulus of elasticity and rupture (MOE and MOR) (Rodríguez and Ortega 2006).

Kučera (1994) proposed a hypothesis relating annual height increments to juvenile wood formation in Norway spruce. It is an interesting and practical theory for gathering data on standing trees and obtaining information on the CW-OW boundary regarding wood density more easily, but validation is needed as nothing similar has been carried out on *Pinus* species growing in a Mediterranean climate.

The objective of this work was to assess the suitability of calculating the transition between corewood and outerwood in *Pinus sylvestris* L. and *Pinus nigra* Arnold subsp. *nigra* trees growing in a Mediterranean climate in the center of the Iberian Peninsula, between two different properties. For that purpose, a comparison was made of the results obtained from the best fitted height growth equation and the measurements taken from ring latewood and mean wood density from micro X-ray densitometry. In this study, for the density variation the TY estimated as a reference was the year the variation becomes more stable in successive growth rings using mean and latewood densities. Segmented regressions will be used to estimate this year.

4.2 Material and methods

4.2.1 Sampling

Two sites established by INIA-CIFOR in Spain at the end of the last century where different experimental thinning and pruning regimes were applied, were used to collect the wood samples.

The first site was a pure plantation of *Pinus nigra* Arnold subsp. *nigra* (black pine) located in the municipality of Zarzuela de Jadraque (Guadalajara, Spain) (41°1´N, 3º4´W), planted in 1962, at an altitude of 1,005 m.a.s.l., on a mostly flat area with a 1–10 % slope in NW direction. In this area, the average annual rainfall is 489 mm and the average annual temperature is 10.9º C. (AEMET 2017).

Twelve trees were felled and on each, as seen on Figure 4.1.a, every height increment observed was noted on the field report using a 30 m long measuring tape. Then, discs at basal height and at every 3 meters were extracted plus another two at 1.3 meters and 4.3 meters (Figure 4.1.b). The increment heights were corroborated with the number of years present on each of the disks extracted along the bole as in these species an increment shoot (whorl) usually relates to one year's growth (Larson 1969).

From the basal sample two strips, 2 mm thick, were extracted from the cross section, attempting to avoid compression wood (in Figure 4.1.c, obtention of the strips at different heights from different trees, not only the basal one). This was carried out by extracting the strips perpendicular to the slope and visually checking for compression wood. Once the strips had been gathered, they were immersed in n-Pentane for 48 h to eliminate extractives (Gapare et al. 2006). Then, the samples were stored in a climatic chamber at 20º C and 65 % RH to reach a moisture content of 12%. They were then scanned using X-ray densitometry, using the same equipment as described in Rodríguez and Ortega (2006). The images were processed using LIGNOVISION™ and TSAP-Win™ software (http://www.rinntech.de), with a fixed boundary set as being half the variation in density in each ring to distinguish between earlywood and latewood. For each growth ring, the averaged values were obtained of ring width, mean ring density, earlywood width, earlywood density, latewood width, latewood density and texture (each year's proportion between earlywood and the latewood). Although after some trials the characteristics with a clearer breakpoint where latewood density and mean ring density.

The second site was in a *Pinus sylvestris* L. (Scots pine) pure plantation, located in the Guadarrama mountain range in La Morcuera Forest (Madrid, Spain) (40º50´N, 3º5´W). The plantation was carried out in 1954. It is located at an altitude of 1,550 m.a.s.l. on the Northern face, with a NE orientation and a 10–50 % slope in the trial area. Average annual rainfall is 1,062 mm and the average annual temperature is 7º C. (AEMET 2017).

In this case, fifteen trees were felled and the procedure for collecting data was the same as described above for the black pine.

Figure 4.1. a) Height increment measurement on felled tree b) Extracted Scots pine discs c) Strips obtained

4.2.2 Calculation of transition year by height functions

Increment heights were transformed into accumulated heights so that the S-shaped height-growth age function from Michajlov (1952), cited in Kučera (1994), could be used. This function consists of three parameters and is defined as:

$$y = a * e^{-(\frac{k}{t^c})}$$

Where y is height in meters, t is age in years and a, k and c are parameters calculated for each tree in order to best fit each growth curve.

The juvenile stage ends when the first derivative of the current annual height increment function reaches its maximum (Kučera 1994). When this maximum was reached, Kučera compared it with the basic density, latewood percentage, fiber thickness and fiber length TYs of each tree. All these TYs seemed to coincide with the maximum. Although it was calculated as a reference, it makes no sense to use this growth function as it adjusted for a different species in a different climatic region and is more in accordance with the characteristic growth of that species in that region.

For that reason, other commonly used growth functions were tested (Richards, Hossfeld, Gompertz, vonBertalanffy, monomolecular-Weber and Chapman-Richards) being the one with the lowest AICc (Akaike information criterion (AIC) with a correction for small sample sizes), BIC (Bayesian information criterion) and higher pseudo R^2 the Chapman-Richards function. This function follows the same principles as the function in Kučera (1994). It is commonly used to describe a cumulative growth curve variable, e.g. height, diameter, basal area and volume. Also, it has being used before in Spain for model site index development (height-diameter) on *Pinus sylvestris* (Rojo 1994, Rojo and Montero 1996), *Pinus pinea* (García Güemes 1999; Cañadas 2000) and *Pinus halepensis* (Montero et al. 2001).

In our case it will be fixed as a tree height function:

$$y = a * (1 - e^{-b*t})^c$$

Where y is height in meters, t is age in years and a, b and c are parameters calculated for each tree in order to best fit each growth curve. The TY is calculated in the same manner as in Kučera (1994) by finding the maximum in the first derivative.

After determining the transition age with both functions, it was compared with that obtained via micro X-ray densitometry.

4.2.3 Calculation of transition year by micro X-ray Densitometry

The TYs were established by comparing two different density variables attained via micro X-ray densitometry using segmented regression with R statistical software (R Core Team 2017). The first was carried out using mean ring density (MD) in a similar way to Goudie and Di Lucca (2004) but, when possible, with the modification proposed by Mansfield et al. (2007) with two break points (BP), and if the AICc when compared with only one break point was lower. For the second, latewood density (LW) was used as in Sauter et al. (1998) and Gapare et al. (2006). Subsequently, both models were compared to observe if results were different and, if so, a determination made as to which density variable detected the TY earlier. As wood density is related with MOE and MOR, knowing which one calculates the TY earlier will give an idea of when, by density, the OW vary if calculated by MD or LW, as it is MD the one more related.

When assessing the TY with MD the segmented (Muggeo 2008) package in R (R Core Team 2017) was used. Next, the average TY calculated from both strips from the disk (one from each side of the pith) was calculated to be compared with the growth increment function.

To assess the TY with LW, two different regressions were made. The first using segmented package in R and a second by performing a piecewise regression using the Least Squared Error (LSE) instead of the Maximum Likelihood Error (MLE) as in the segmented package, and not being constrained to be continuous, to allow more flexibility.

The TY was calculated by generating an average of the 4 TY obtained from each disk (side A, side B) was used to be compared with the one obtained by Chapman-Richards.

4.3 Results and discussion

The TYs formulated from the MD profile were calculated with two break points, as in Mansfield et al. (2007) being the second one the TY, when the AICc was better than that obtained with just one break point (Figure 4.3. and 4.2.).

When assessing the TYs of the MD profile in *Pinus nigra* trees, the trend on all samples was similar to the three segmented regression proposed by Mansfield, but this could only be observed on 5 out of the 15 *Pinus sylvestris* trees (for this reason, there are some missing values in Table 4.2.). One explanation for this could be alterations produced by the severe droughts of 1971 and 1973-1974, when the *Pinus sylvestris* stand was relatively young and may have been more affected. These droughts may have caused a smaller growth and an increase in wood density that could have masked those trends.

From the results, it seems that the two break points trend is not clear with most of the LW samples. Consequently, a regression, similar to that proposed by Sauter et al. (1998), was chosen with two segmented regressions and only one break point. On Figure 4.3. and Figure 4.2. the TYs obtained from a black pine and a Scots pine for each density profile type can be observed. The vertical lines indicate the TY obtained by each regression.

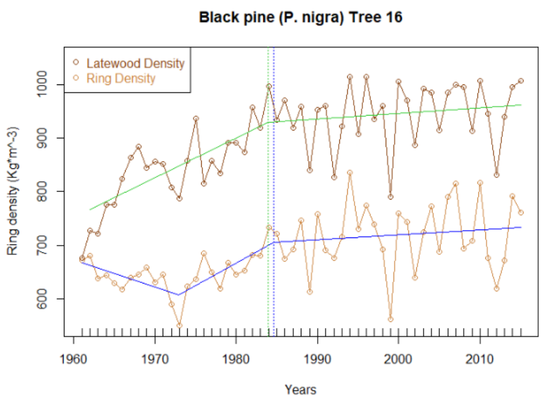

Figure 4.3. LW and MD black pine segmented regressions

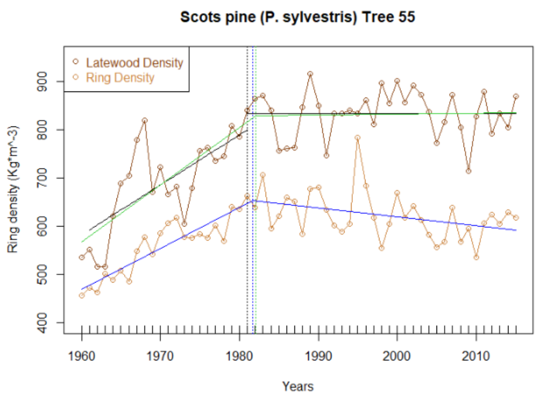

Figure 4.2. LW and MD Scots pine segmented regressions

Table 4.1. shows a summary of the TYs obtained for the black pine by micro X-ray densitometry for MD, LW and also the results obtained Chapman-Richards functions. Table 4.2. shows the same summary but for the Scots pine species.

On Table 4.1. and Table 4.2. it can additionally be observed that the TY is usually determined earlier when calculated on LW rather than on MD, in both species, concurring with the results shown in Rodríguez and Ortega (2006).

Table 4.1 Black pine's mean TY in accordance with the different methodologies

Species	Tree	Height function TY	Densitometry TY		
		Chapman-Richards	TY LW	1st BP MD	2nd BP and TY MD
PN	A04	1979	1985	1968	1985
PN	A06	1979	1987	1990	1994
PN	A13	1979	1975	1969	1978
PN	A16	1982	1984	1975	1985
PN	A21	1977	1989	1976	1991
PN	A29	1984	1977	1973	1982
PN	A31	1977	1985	1975	1987
PN	A38	1977	1988	1972	1990
PN	A45	1977	1986	1982	1994
PN	A47	1978	1984	1965	1985
PN	A51	1983	1990	1978	1992
PN	A56	1982	1987	1975	1984

Table 4.2 Sctots pine's mean TY in accordance with the different methodologies

Species	Tree	Height function TY	Densitometry TY		
		Chapman-Richards	TY LW	1st BP MD	2nd BP and TY MD
PS	S04	1977	1982		1987
PS	S07	1977	1985		
PS	S14	1970	1984		1984
PS	S16	1972	1989	1971	1991
PS	S20	1973	1985		1985
PS	S26	1973	1982	1973	1986
PS	S34	1976	1981	1968	1983
PS	S35	1971	1980		1985
PS	S40	1974	1987	1988	1991
PS	S48	1975	1982		1982
PS	S52	1970	1980	1966	1982
PS	S55	1965	1980		1981
PS	S61	1971	1988		1987
PS	S66	1974	1981		1984
PS	S74	1969	1980		1981

Using the regressions proposed by Mansfield et al. (2007), an attempt was made to relate the initial inflection point, as well as the second one, where it reaches the TY and where the OW starts forming, with the TY obtained by the increment function. However, the adjustments were not possible. The growth function seems to reach the TY at a different time as the ones obtained from the X-ray densitometry.

Chapman-Richards function estimate a TY not coinciding to the ones obtained using micro X-ray densitometry with the samples of this study.

These results lead us to suppose that height increment growth, at least in our samples, is not driving the changes in to the development of CW in pines in Mediterranean forests at the same time as when assessed by density. This is a setback as by the mechanics explanation on the radial pattern variation (Lachenbruch et al. 2011), it could have been expected that the maximum current annual height and density radial variation were somehow related, as it is with the *Picea*. Other variables might be needed to be included if wanted to match the TY obtained by density as in Kučera (1994), such as site, drought, crown development or genetics.

The method proposed by Kučera, used to assess the TY based only on height increment measurements, seems that it should not be used on pines on Mediterranean species, if it´s density the characteristic that is of most interest to assess for an end use.

In both species at basal height, the TY was determined before any silvicultural treatment having been implemented, therefore it could not be assessed if any treatment might influence or shift the TY and thus, this information was discarded for the analysis.

4.4 Conclusions

The measurement of increments and the TY calculated using Chapman-Richards growth functions, does not make possible the estimation of the TY obtained through density for the Spanish provenances studied of Scots and black pines. This is likely due to other variables affecting growth in Mediterranean species and the different height growth patterns of these species compared to the *Picea*.

The LW TY was determined earlier than when using MD and it seemed to be an easier way to assess the TY, as simplify the process not to check prior for the existence of two or one breakpoints.

Mansfield's approach using a three segmented regression on mean ring density, seem to adjust on most of the *Pinus nigra* strips but not for *Pinus sylvestris* ones, probably due to the influence of their climate conditions.

In pursuing assessment of the TY this way, it would be necessary to look for different adjustment growth functions in Mediterranean species, in addition to consider other covariates to be included to approximate the TY obtained through heights, to the one calculated by density.

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Chapter 5. Study of multipoint near infrared spectroscopy (NIRs) methodology for determining the transition between juvenile and mature wood.

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Abstract

Where lumber is used for structural purposes it is important to know the proportion of juvenile wood because it has poorer physical and mechanical properties, which will have an impact on the final use of the material. Hence, several approaches to obtain reliable methods to determine the amount of juvenile wood are analyzed. The aim of this study is to evaluate the use of near infrared spectroscopy (NIRs) as a means to determine the transition point from juvenile wood to mature wood, thus revealing the amount of both types of wood. The study is conducted with *Pinus sylvestris* L. wood sampled from trees in experimental plots belonging to the INIA, located in the Central mountain system of Spain. Cores are extracted from trees and processed, and then samples are analyzed using a Brucker MultiPurpose Analyzer (MPA) equipped with an external fiber optic probe. The results are derived from two calibration models; one quantitative model, using reference data from increment core density measurements obtained through micro X-ray densitometry, and a qualitative model, which is more complicated since the transition from juvenile wood to mature wood does not occur at one given moment in time but rather is a continuous process in which overlap exists between both types.

5.1 Introduction

One of the difficulties of using wood for structures has to do with its heterogeneity in terms of physical and chemical properties, which vary not only at site, species and tree level, but also within the tree itself. There are substantial changes across the bole, from the pith to the bark, and even between the earlywood and latewood of each year. This variation in properties is caused by several factors that interact with the tree, such as climate, site, silviculture and genotype among others (Larson 1969, Larson et al. 2001, Baldwin et al. 2000, Rodríguez and Ortega 2006, Burdon et al. 2004).

At any height, in the transversal direction of the tree, there is a marked variation from the pith towards the bark known as juvenile wood (JW). JW can be described as wood which is still immature, the characteristics of which show rapid and progressive changes in the rings outward from the pith in a transverse direction until a point is reached where the properties are stabilized. The properties of JW vary along the trunk and it is usually more present inside the crown area, which is why it has received various names (Larson et al.

2001, Burdon et al. 2004). Although corewood (CW) is a better term if the longitudinal variation is considered, the term juvenile wood (JW) is used as a synonym in this manuscript as the Spanish industrial sector uses this term. Furthermore, in this study the radial patterns are assessed independently.

Today, due to the tendency in silvicultural practice towards reducing rotation lengths, there has been a significant increase in the amount of JW present in the trunk. The formation, quantification and consequences associated with the proportion of JW are currently being studied under the CIFOR-INIA project RTA2014-0005, focusing on the main Spanish conifers grown to produce timber for structural use. The poorer physical-mechanical and technical properties associated with the presence of JW, as well as problems which arise as the wood dries, caused by the unequal contractions which characterize it, lead to lower probability of end use for structural purposes and therefore reduced economic revenues (Larson 1969, Zobel and Sprague1998 Hermoso et al. 2003, UNE 56.544).

One of the main problems is that of actually identifying JW since it varies depending on the property studied. To determine the approximate proportion, several methodologies are used, such as the analysis of discs extracted from a felled tree or increment cores extracted from standing trees with an increment borer. A densitometry analysis or some other analysis that allows the transition point (TP) between JW and mature wood (MW) to be identified is subsequently performed, thus allowing us to determine the proportion of both types of wood. Furthermore, as mentioned above, depending on the characteristic chosen for analysis (microfibril angle, densitometry, tracheid length, cell wall thickness, cellulose/lignin ratio, shrinkage, MOE), the TP may vary (Bendtsen and Senft 1986, Sauter et al. 1999).

The objective of this work was to develop a qualitative and quantitative approach using the NIR technique to determine the transition point between JW and MW on increment cores extracted at two heights (1.3 and 4.3 meters). These increment cores were analyzed using micro X-ray densitometry and an evaluation was conducted to determine whether it was spectrally feasible to perform a single model fit to detect the amount of juvenile wood at both heights or, given the variation in its properties along the bole, whether two different ones would be required.

5.2 Materials and methods

5.2.1 Study area

The plots where the study was carried out belong to the network of Sustainable Forest Management Testing Sites (SEGeForS) of the Forest Research Centre (CIFOR), INIA, Spain. At these sites different intensities of thinning and pruning in a forest stand have been tested so there is a large amount of information on the development of the stands following different silvicultural operations. This information is recorded in the different five-year inventories carried out by CIFOR since 1991 in the case of *Pinus sylvestris* L. (Scots pine).

The study plots chosen for *Pinus sylvestris* L. study are located at “La Morcuera” in the Central mountain system (Madrid province, Spain). These plots are situated at an altitude of 1,550 m a.s.l. on the north face of the mountain with a NE orientation and a variable slope of 10-50%. The average annual rainfall is 1,062 mm and average annual temperature is 7ºC.

5.2.2 Sampling design

For the purposes of the study, different data were collected for the two species depending on the silvicultural practices applied.

Two increment cores were extracted at heights of 1.30 m and 4.30 m from five trees per plot in each block and treatment. The five trees selected in each case were representative of the average height and DBH. The cores were extracted at the abovementioned heights because the most valuable and merchantable part of the bole are the lower saw logs (Kinney S-A 2013). The increment cores were always extracted on the upslope side of the bole with the same orientation, reaching as far as the pith and as perpendicular as possible to the longitudinal direction of the fibers.

In the studied stands the silvicultural treatments present are: Control plots, heavily thinned plots both with and without pruning at 5 m, and lightly thinned plots with and without pruning at 3 m.

5.2.3 NIRs acquisition

According to Sauter et al. (1999) and to our own analysis (Ruano et al. n.d. b), it is easier to determine the transition point between juvenile and adult wood using only densitometry data from the latewood (LW) part of the ring. The methodology followed for the micro X-ray densitometry acquisition and processing on the transverse section is that described in Ruano et al. (n.d. a). With this in mind, the LW spectrum of each ring of all the increment cores was obtained and correlated with its density to perform the quantitative regression.

Using data from two different heights on the commercially viable part of the bole, a more accurate model can be fitted than would be possible with data from a single height only. Furthermore, it allows the influence of sample height to be tested.

After conditioning, the increment cores obtained were sawn into 2 mm thick planks. They were then immersed in a 95% n-Pentane solution for 48 h to eliminate extractives before performing the densitometry analysis (Gapare et al. 2006). They were subsequently scanned with a Fourier Transform Spectroscope (FT_IR) and analyzed using Bruker's MultiPurpose Analyzer (MPA), equipped with an external optical fiber probe with 3 mm path length, a spectral resolution of 2cm^{-1} and a spectral range varying from 780 to 2777 nm. To scan the LW part of the ring only, a black coating (Metal VelvetTM, www.acktar.com) was used to reduce the optical path length, without increasing the spectrum noise to 1 mm. In Figure 5.1. shows how the measurements were taken in the laboratory.

The section of the wood to be scanned, the preparation of the sample, the moisture content and the number of latent variable PLS have a significant influence on the results (Schimleck 2013, Xu et al. 2011, Fujimoto et al. 2010, Hoffmeyer and Pendersen 1995, Mora and Schimleck 2009, Alves et al. 2012).Thus, it was decided to acclimatize the samples to 20oC and 60% relative humidity to attain a homogenous moisture content at around 12% when measured.

The scanning of the section used to relate it to the density, was carried out in the transversal direction, that is, the direction in which the increment cores where sawn, since this direction registers more variation and stronger signal (Adedipe et al. 2012). Although there are several studies, such as Giroud et al. (2015), which do not take the direction into account, according to research undertaken by Schimleck et al. (2005) scarce differences exist between the two directions.

Using the NIRs, the spectra of the LW part of the rings of each increment core exceeding a thickness of 0.5 mm thick were scanned. Altogether, 470 spectra were obtained of which, on average, 40 belonged to the same increment core. The spectral resolution used was 8 cm^{-1} and for sampling purposes the "simple scan time" was set to 256 scan per shot.

5.3 Results and discussion

The first step performed on the 470 spectra was a Principal Component Analysis (PCA) combined with a Box-Plot to discard spectral outliers.

Subsequently, the samples were divided into two parts, one part for calibration and the other for validation. Different fittings were tested using the OPUS software. Partial Least Squares (PLS) regression followed by autoscaling was performed on the raw data, but other spectra pre-processing was also tested (base-line subtraction, Savinsky-Golay smoothing, vector normalization, minimum-maximum normalization, multiplicative scattering correction, median and mean centering, first and second derivative, as well as combinations of these techniques) to try to fit the results to the density data obtained through microdensitometry.

Initially, the best quantitative fits achieved with microdensitometry were not good as expected, the best one being that with an R^2 coefficient of 52% and a RPD of 1.7 (ratio between standard deviation (SD) and standard cross-validation error (SECV)).

In an attempt to analyze the causes of these results, based on the knowledge that the properties of juvenile wood vary along the trunk, two different fittings were performed according to the heights studied, taking into considering whether the trees had been pruned or not and if so up to what height. The latter consideration was included because several studies have suggested that distance to the living crown has an impact on the generation of wood (Larson 1969, Baldwin et al. 2000). As a result of including this factor, fitting was improved by as much as 66% and a RPD of 2.1 was achieved. However, the fit was still far from a 3 RPD (the threshold at which the predictive ability of the model is considered to be excellent) or even the desirable minimum of 2.5 for adequate prediction accuracy, although at least it points towards possible progress with the procedure.

After reviewing the pertinent bibliography for the causes, we identified two possible factors which could lead to these results. The penetration depth of NIRs in several studies has been found to depend on the wave range, from ~1-2 mm around 2500 nm to 5 mm below 1400 nm. Hence, it is likely that noise was sampled from the surface on which the increment core was laid. Additionally, the signal to noise ratio could be improved if the spectral resolution is decreased.

Three different approaches were proposed to solve the problem. The first one is to use the black coating described above underneath the sample, preventing any other inference on the sampling from beneath the increment core. This allows the study to continue with the samples taken, reducing noise from underneath the core.

The second option is to reduce the spectral resolution to 16 cm^{-1} in order to decrease the noise of the spectra obtained. Nevertheless, the results obtained after the spectral resolution may be similar to those already obtained after the Savinsky-Golay smoothing.

A final possibility is to increase the number of samples and try a different calibration with the different tree heights analyzed (1.3 and 4.3 m).

As regards the qualitative method, this was discarded as a possibility with the data obtained since the transition from juvenile wood to mature wood appeared not to occur in given year according to the spectra but rather involves a continuous process occurring in 3-4 rings, leading to problems of overlapping between the two areas.

5.4 Conclusions

In this study we found difficulty achieving a satisfactory fit between the measurements obtained using multipoint NIRs and the density data derived from micro X-ray densitometry.

Analyzing the possible causes and solutions, three possible approaches where proposed. These were to use a black coating under the sample, to reduce the spectral resolution and to increase the number of samples.

As regards the qualitative method, introducing a transition area between the JW and MW could lead to improved results. The results may also be improved by analyzing the lignin/cellulose ratio and comparing it to the NIRs results.

An approach using Hyperspectral NIRs imagery will be used in order to test whether this technique will allow the JW/MW boundary to be determined more rapidly and accurately.

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5.6 Figures

Figure 5.1. Scanning cores with NIRs probe

Chapter 6. Study of hyperspectral near infrared spectroscopy for determining the juvenile wood

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Abstract:

The ratio of juvenile wood (JW) to mature wood (MW) is relevant for structural wood applications because of their different properties. Near infrared hyperspectral imaging (NIR-HI) indicates after calibration the spatial distribution of JW and MW, and this approach is less time consuming than the established micro X-ray densitometry (µXRD). In the present study, a comparative detection of the JW and MW of *Pinus sylvestris* L. was performed by NIR-HI and µXRD and the NIR-HI results were evaluated in combination with three chemometric approaches, namely, the principal component analysis (PCA), partitional k-means unsupervised classification (p-k-mUC), and partial least squares discriminant analysis (PLS-DA) in the range of 900-1700 nm. The best NIR-HI results can be obtained when the transition point of earlywood (EW) and latewood (LW) are assessed separately by PLS-DA. The presented results are useful for an automating data evaluation and simplified data collection.

6.1 Introduction

Wood is a heterogeneous biomaterial. Inside a tree, the properties are different in radial (pith to bark) and longitudinal (axial) directions. Moreover, within each annual ring the properties of earlywood (EW) and latewood (LW) are also different, and the same is true for juvenile wood (JW) and mature wood (MW) (Burdon et al. 2004; Shi et al. 2005; Hamzeh et al. 2011). Typically, the JW contains shorter tracheids with larger lumen diameter, and smaller wall thicknesses, and JW also exhibits a lower basic and specific density, higher moisture content (MC), and lower transverse shrinkage and stiffness. The cellulose/lignin ratios and the content of hemicelluloses are lower in JW. The microfibril angle (MFA) in the cell walls is higher than in MW, the growth-rings of JW are wider. The moiety of compression wood (cW) in JW is usually higher, but the presence or absence of cW is not a selection criterion for JW, because cW can also be found in MW (Ilic et al. 2003). The JW from the upper part of the stem is not the same as in the lower part because of physiological aging (Larson 1969; Rowell 1983; Zobel and Sprague 1998; Ilic et al. 2003; Burdon et al. 2004; Rodríguez and Ortega 2006; Ivković et al. 2009). All these variations have negative effects on the physical-mechanical and technological properties of the material (Larson 1969; Zobel and Sprague 1998; Burdon et al. 2004; Hermoso et al. 2013) and detract the final usage and production economy.

Density is the key parameter for physical/mechanical properties of wood also in the context of JW detection via µXRD profiles. Both stiffness and strength of wood can be predicted based on density (Rodríguez and Ortega 2006). MFA determination can also be indicative for the presence of JW (Wang and Stewart 2012; Mansfield et al. 2009) accompanied by tracheid length and cell wall thickness measurements.

Calibration based near infrared (NIR) spectroscopy in combination with chemometric methods has a high potential for quick assessment of wood species, provenances, and mechanical properties (Kobori et al. 2014; Sandak et al. 2016). NIR hyperspectral imaging (NIR-HI) provides an image with spatial dimensions of the NIR spectral data, which can related to the MC, and chemical and mechanical properties of anisotropic objects (Duncker and Spieker 2009; Fernandes et al. 2013; Zitek et al. 2014; Haddadi et al. 2015; Defoirdt et al. 2017; Ma et al. 2017; Sandak et al. 2017). NIR-HI is an alternative to the more time consuming µXRD approach for the detection of JW and MW and density variations (Burdon et al. 2004).

The objective of this work is to assess the potential of the NIR-HI method for identification of JW and MW moieties in Scots pine (*Pinus sylvestris* L.) wood from Spain. The transition point (TP) between JW and MW was previously determined based on segmented regressions from µXRD data.

6.2 Material and methods

6.2.1 Area of tree sampling

The samples were taken from a Scots pine plantation located in the Sistema Central of Spain, in La Morcuera Forest (40º50´N, 3º5´W), in an even-aged pure stand site for experimental thinning and pruning trials. The trial was installed in 1991 when the stand was 37 years old and in 1991 and 2001 thinning and pruning operations were carried out. This site consists of 15 permanent plots of 0.1 ha (25 m x 40 m) divided into five treatments with three repetitions.

6.2.2 Material processing

A 10-meter buffer area was established inside the border of each plot to avoid any edge effect, and one tree per plot was selected, i.e. 15 trees were felled, three from each of the five treatments. Thereafter, a 15 cm disc was extracted every three meters from the stem beginning with the basal disc. From each disc, two 2 mm wide strips were cut from the cross section with a north/south orientation to avoid the presence of cW. This was done as a first calibration attempt in order to prevent image noise with homogeneous samples in focus. The strips were then immersed in n-pentane for 48 h and the extracted samples were stored in a climatic chamber until a MC of 12% was reached. Finally, µXRD scanning was performed in accordance with Rodríguez and Ortega (2006). The images were processed by LIGNOVISION™ and TSAP-Win™ software (RINNTECH™, Heidelberg, Germany). A segmented regression analysis was performed in R statistical software (R Core Team 2017).

6.2.3 Hyperspectral measurements

For NIR-HI, two of the three repetitions of each treatment were scanned. The strips from the 10 trees analyzed with µXRD were conditioned to an MC of 12% again before scanning, without any further surface treatment. At 3 m height, the strips from 8 out of 10 trees were scanned. The wood strips were also scanned by an NIR-HI instrument located at the University of Natural Resources and Life Sciences (Vienna, Austria), Department of Material Sciences and Process Engineering Institute of Wood Technology and Renewable Materials. The system components are: (1) Xenics NIR camera (Xeva-USB-FPA-1.7-320-TE1-100 Hz camera with InGaAs focal plane array sensor with 2% pixel noise – XEVA 6179; 0.9 - 1.7 µm; 320 × 256 pixel matrix; 12 bit); (2) Specim N17E spectrograph operating in the range of 900-1700 nm with an objective lens, (3) a 600 mm Y-table gear; (4) Stable diffuse 45/0 illumination created by halogen bulbs. The camera was cooled down to between -8ºC and -13°C by forced convection (TE-1) cooling for image noise reduction. The Y table was driven by a stepping motor controlled by textual commands (www.isel.com).

The camera was calibrated in the range 959-1630 nm with a spectral resolution of 3.329 nm. Before measurement, a two-point calibration was carried out based on a diffuse reflectance standard (Sphereoptics) as a "white reference" and by completely covering the objective lens for a "black reference". The field of view for the samples was selected by setting the appropriate height of the spectrograph in relation to the sample. Image focusing was achieved by adjusting the lens. The set-up of the optics resulted in a resolution of 0.150 mm per pixel. The image processing system and the sensor were controlled by Argus software (Firtha 2010).

6.2.4 Image treatment

The NIR-HIs were treated with a noise reduction algorithm called "salt and pepper", which detects unserviceable bright or dark pixels. These pixels were replaced by a neighboring pixel's algorithm script in MATLAB® (Firtha et al. 2008), which detects x, y pixels in an x, y, z matrix, which are different from their neighbors on the z axis. The difference from its neighbors and standard deviance is calculated by means of a convolution filter. The pixel is considered suspicious, if the difference is greater than the deviance and is disregarded and replaced by the average of its surrounding neighbors. Less than 2% of pixels were replaced in this manner as this kind of replacement smooths the images.

Because of the abnormal spectra present at the borders of the strips and of the background spectra of the image, a mask was generated to exclude them from the analysis. Figure 6.1. shows: (a) the original spectra, (b) the spectra after the application of the noise reduction algorithm, and (c) the final spectra after the removal of the image background and edge effects.

6.2.5 Statistical analysis

The goal was the transition point (TP) determination between JW and MW by comparing the densitometry results and NIR-HIs. The analyses of the hypercubes were carried out by: principal component analysis (PCA), a partitional k-means unsupervised classification (p-k-mUC), and a partial least squares discriminant analysis (PLS-DA), with the aid of PLS Toolbox 8.6.2 and MIA_Toolbox 3.0.6 (2018) software in MATLAB®.

6.3 Results and discussion

6.3.1 PCA approach

The PCA model in combination with different preprocessing treatments was applied in accordance with Williams et al. (2009) to check, whether the differences in the eigenvectors in the PCA's score plot were high enough to assess two different classes corresponding to JW and MW. Firstly, three columns of pixels from the image had to be excluded because of abnormal wavelengths caused by the camera's dead pixels along the image pixel columns, which were not automatically corrected. Figure 6.2. illustrates the process in terms of excluding invalid data points by selecting pixels with high Q-residuals and Hotelling's-T^2, which seemed to be higher and grouped. After each group was eliminated and a new PCA model was created, as the median value was changed.

From the ten trees scanned by NIR-HI at the basal height and from the eight trees scanned at 3 m, cluster density differences were detected in only four trees by means of PCA score plot (PC1 vs. PC2). The other four stems, and the other two that were only scanned at the basal height, did not show any differences, irrespective of the preprocessing method applied. An influence of silvicultural treatments in these results was not detected.

Median centering was the best preprocessing for TP detection. As the loadings in Figure 6.3. show, the small band near 1375 nm is almost lost in most cases after smoothing. The 1st spectral derivation enhanced its intensity, however, the peaks in 1st derivative spectra are displaced. The 2nd derivatization was also tested without the expected improvement. The application of score plots between PC2 vs PC3 was also tried for spectral evaluation (Williams et al. 2009). In the present paper the scores of PC1 vs. PC2 show two different density clusters, but in the score plots PC2 vs. PC3 are not differentiated.

The loadings concerning the wavelength effects are presented in Figure 6.3., for a strip that differs between MW and JW by showing two clusters in the PCA, and in Figure 6.4., for a strip that does not differ concerning the PCA clusters for JW and MW. Two bands at ≈1375 and ≈1215 nm could be identified as relevant for JW and MW differentiation. In summary, the bands suitable to this purpose are between 1190-1222 nm; 1369-1382 nm, and 1415-1432 nm. These wavelength regions are already described by Schwanninger et al. (2011) and are in agreement with findings of Burdon et al. (2004) and Ilic et al. (2003) concerning the chemical property variations between JW and MW. As the quoted authors pointed out, JW has a lower cellulose/lignin ratio and lower hemicelluloses content and the NIR-HI is reflecting these differences.

The PCA score plots were able to differentiate cW, which has higher density and higher lignin and galactan content (Ilic et al. 2003). The µXRD data indicate cW areas with a density of around 100 kg m^{-3} higher. The pink areas selected in the strips in Figure 6.5.

correspond to cW detected in the PCA scores plot and to its location in each strip. Figure 6.5. also shows in a) a strip with two different clusters, the one on the left corresponding to JW and the one on the right to MW, and in c) a strip with one cluster without any differentiation between JW and MW. Duncker and Spiecker (2009) and McLean et al. (2014) also described the differentiation of abnormal wood with higher densities. Accordingly, the present paper demonstrates that NIR-HI in combination with PCA is able to detect tissues with cW if the number of pixels in the image is reasonable. The once detected cW areas were excluded from the classification and a new PCA was carried out.

6.3.2 p-k-mUC

For the preprocessing of p-k-mUC, several options were taken into consideration: Savinsky-Golay smoothing, 1st derivative spectroscopy, extended scatter correction (EMSC), multiplicative signal correction (MSC), baseline Whittaker filtering, median and mean centering, and a combination of several methods. In the end the best pretreatment was a median centering, the same as in the PCA scores plots.

A first approach was conducted made based on five classes to assess the JW/MW areas and the TP between them. In two samples, it was possible to observe the JW/MW in EW and JW/MW in LW reliably. For further improvements, a 2-cluster classification was also carried out. The TP was found, when 75% of the pixels were from type 2 in 20 consecutive pixel rows, and the TP was detected two or three years earlier than in case of segmented density regression. Based on the results of Larson et al. (2001), Ilic et al. (2003), and Ivković et al. (2009), this could be due to different wood characteristics considered for TP assessment. An example in Figure 6.6. shows that the TP was detected by densitometry one year later than with the p-k-mUC approach. The images in Figure 6.6. correspond to (a) A PCA loadings, (b) A 5-cluster classification, (c) A 2-cluster classification, (d) the PC1 vs. PC2 scores plot, and (e) the TP assessed based on LW density obtained from µXRD.

In the case of samples with the silvicultural background of light thinning and pruning followed by a heavy thinning, the detection of the TP was hindered because of the production of wider rings. After ascertaining the pixel assignment of each cluster, a matrix was created for the samples located at 3 m height by means of the R statistical software to assess a binomial logistic regression between the 2-cluster classification and the PCA. The relation found for each strip was significant but high variability did not allow the definition of a general relation.

6.3.3 PLS-DA

This approach was made on the strips from the 8 trees scanned at the basal height and 3 m height. After some exploratory analysis, the best results were found by definition of the regions of interest (ROI's): EW and LW in JW and EW and LW in MW. Superior results could be obtained when EW and LW boundaries were classified separately, hence two different PLS-DA experiments had to be conducted per sample. For the EW boundary, a median centering preprocessing was the most suitable, however, to generate the best results for the LW, 1st derivative spectroscopy followed by autoscaling was the best procedure. The average classification error in cross validation for the pixels in the ROI's was always under 4%. The transition years indicated with arrows in Figure 6.7. and Figure 6.8. match those from µXRD. EW JW/MW areas are seen in Figure 6.7., where dark blue is the JW in EW and the MW in EW is in cyan color with the LW areas in yellow and they are well segregated from EW areas. The EW and the LW areas were not studied simultaneously because of the different preprocessing. In Figure 6.8., the EW area is yellow, the JW in LW is dark blue, and the MW in LW is cyan. In this second case, the 1st derivatization, followed by autoscaling was needed because the bands in the LW spectra were not displaced and little or no bands appeared on the classified image.

6.4 Conclusions

NIR-HI can be calibrated by µXRD results and the JW, MW and the TP between both areas can be determined on the transversal section of the tree. The results are independent from the silvicultural treatment applied in this Scots pine plantations in Spain. The PCA was a useful and easy way to provide additional information on the presence and location of compression wood. Nonetheless, more studies are necessary to obtain a suitable differentiation between JW and MW. The PLS-DA approach was the best in detecting the TP between JW and MW, when the EW and LW were evaluated separately. Every strip was classified within ±1 annual ring difference compared with the LW densitometry. The biggest margin was ±2 annual rings. A previous automatic classification, by combination with a p-k-mUC, between EW and LW, would probably improve the results and could lead to a better automatic process. Further analyses should be performed with non-extracted woods to increase the practical application potential for early JW quantification in standing trees and for wood quality assessment. Tests would also be needed for early JW quantification in standing trees by increment borer experiments with high spatial resolution to be able to distinguish between EW and LW in the annual rings.

Acknowledgments

This study has been carried out with the support of the Ministry of Economy and Competitivity of the Government of Spain through the Project RTA2014-00005-00-00, and the Training Program for Research Staff (FPI-INIA). I would like to thank Ferenc Firtha for developing the filtering algorithms which enabled the automated correction of dead pixels in the hyperspectral images and to Enrique Garriga and Ramon García who helped me on the field work. To Juan Carlos Cabrero who came up with creative ways on how to proceed, to Eduardo Trobajo who did the micro X-ray densitometry and to the carpenter Emilio Camacho who made the processing of the samples possible.

6.5 References

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6.6 Figures

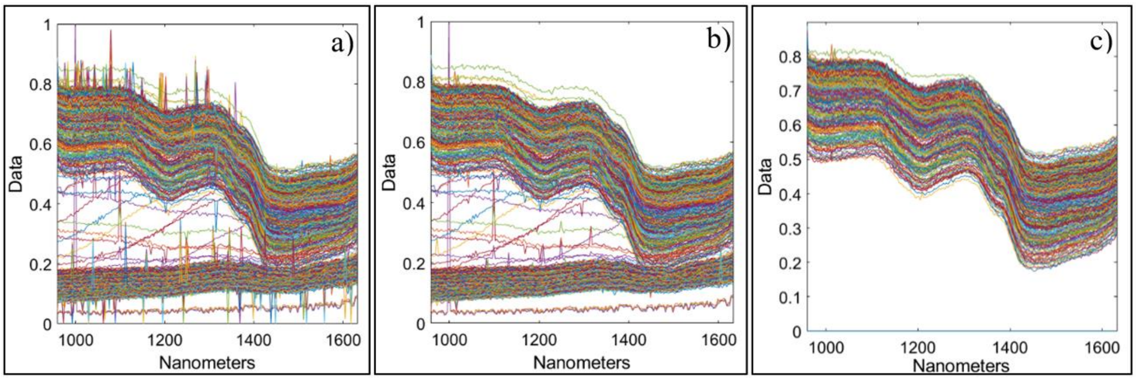

Figure 6.1. Spectrum from the image preprocess followed on every NIR-HI image. (a) Raw spectra, (b) Spectra after noise reduction algorithm, (c) Final spectra after removal of background and edge effects.

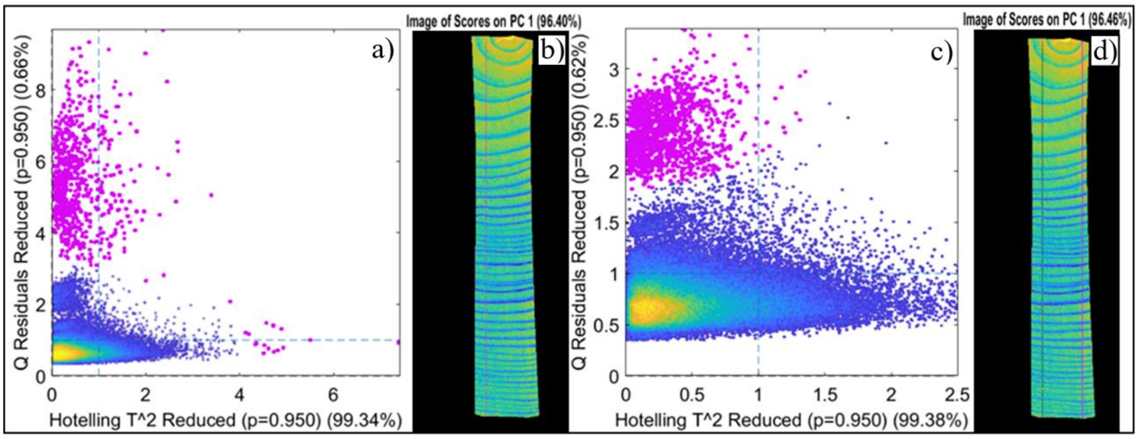

Figure 6.2. Abnormal pixel column detection and elimination process after PCA. (a) Detection of the first column (b) Location in the image (c) Detection of the second and third columns (d) Location in the image

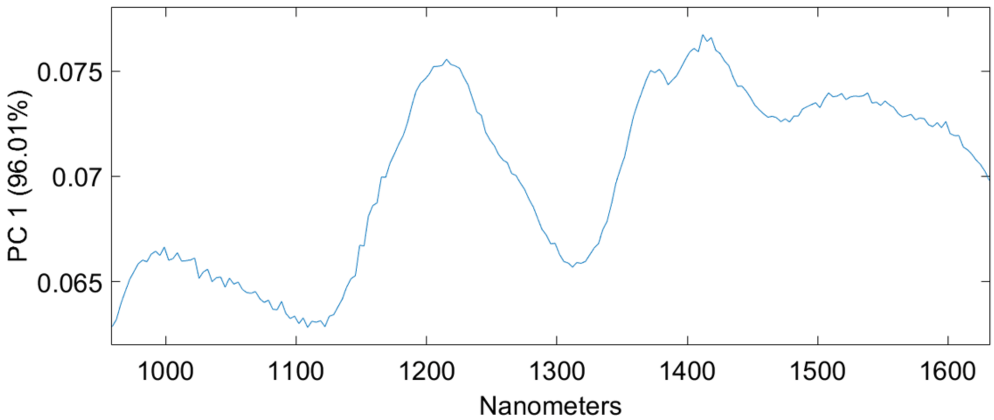

Figure 6.3. PCA loadings with 2 clusters

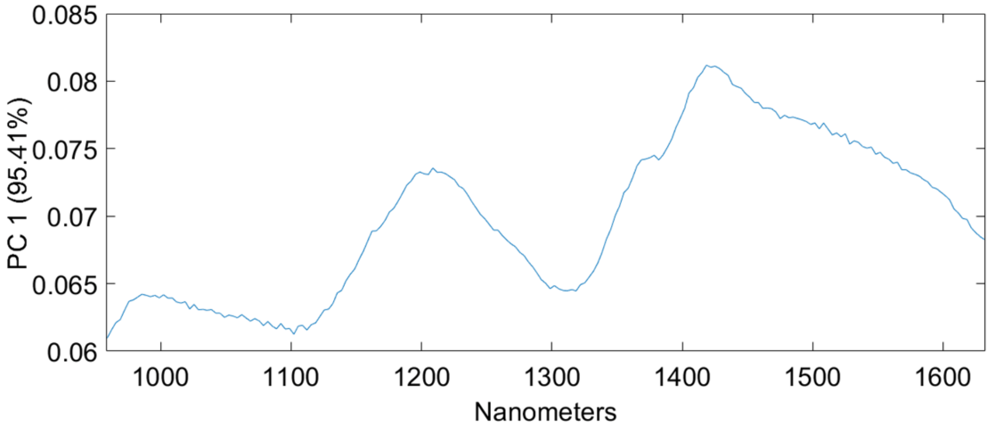

Figure 6.4. PCA loadings with 1 cluster

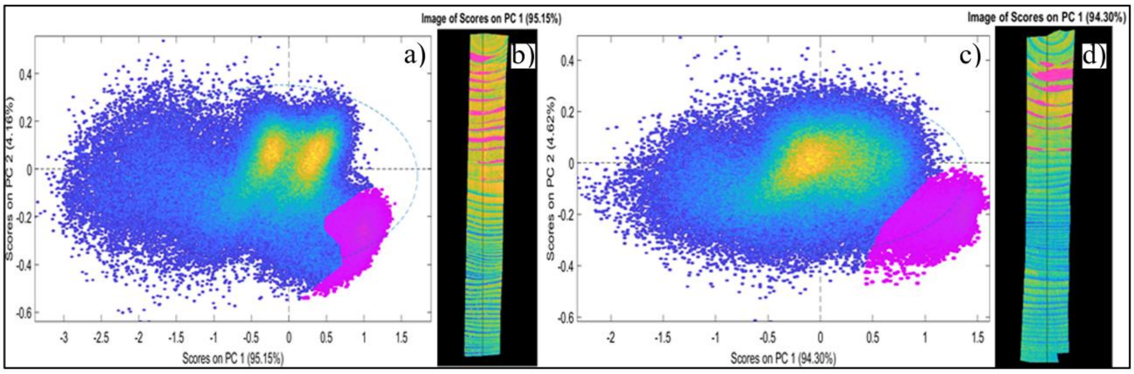

Figure 6.5. PCA scores. Detection, (a) and (c), and location, (b) and (d), of compression wood by a PCA scores plot in two different strips

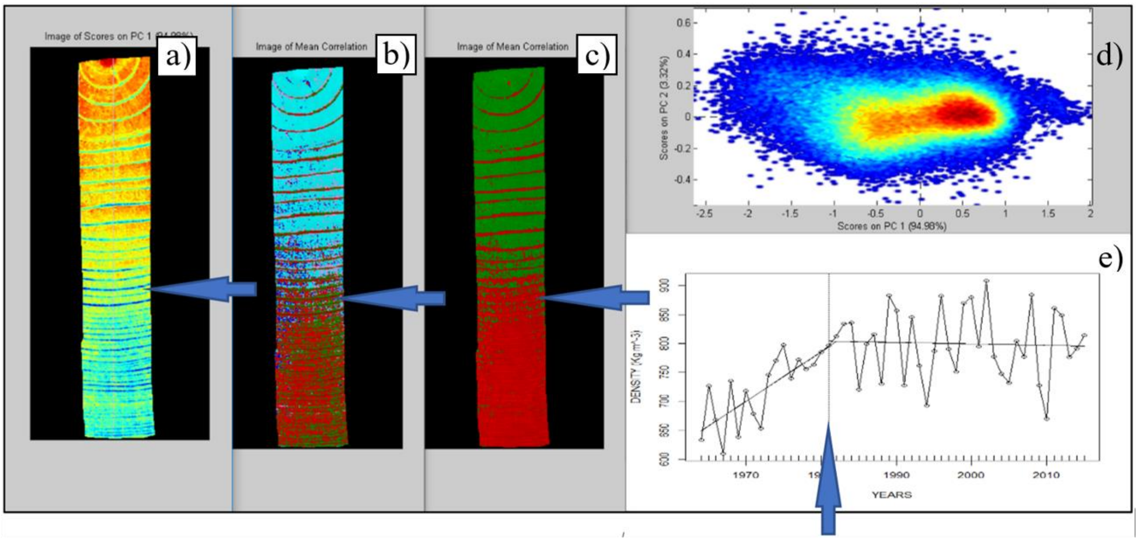

Figure 6.6. Comparison of the different results obtained for the TP determination on a same strip. (a) Transition point PCA, (b) 5-cluster classification, (c) 2-cluster classification, (d) PC1 vs. PC2 scores plot, (e) LW densitometry per year and TP obtained.

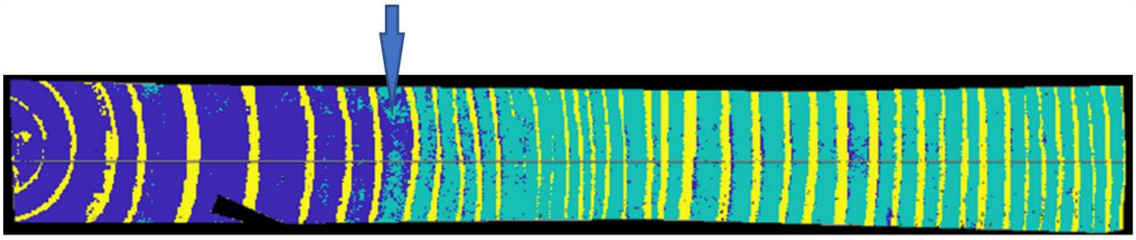

Figure 6.7. PLS-DA Earlywood JW/MW classification

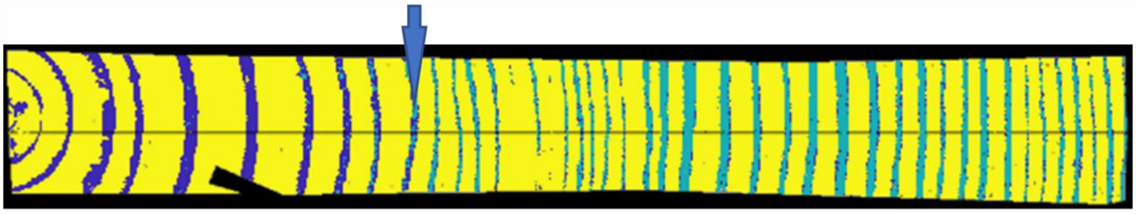

Figure 6.8. PLS-DA Latewood JW/MW classification

Chapter 7. Shrinkage patterns on black pine for estimating juvenile wood

Comparison of shrinkage patterns in juvenile wood versus mature wood in black pine

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7.1 Introduction

It is well known that wood is an anisotropic, hygroscopic material with a tubular structure mainly oriented parallel to the axis of the tree. It is made of cellulose, a highly tensile-resistant material, braced by rays and filled with lignin, which is highly resistant to compression. Cellulose accounts for approximately 40-50 % of the weight of the wood while lignin makes up 15-35%. The rest comprises hemicellulose 25-35 % and other secondary chemical compounds (Pettersen 1984).

As a result of this anatomical structure its properties vary in the longitudinal, radial and tangential directions. Furthermore, due to the hygroscopicity of the material it absorbs and desorbs water to maintain a dynamic balance with the hygrothermal conditions in the surrounding environment.

In solid wood products these two properties are highly important because of the differences in mechanical, chemical and physical properties of the wood inside the trunk, and also because, depending on its humidity, wood shrinks and swells when it varies from an anhydrous state to fiber saturation point (FSP). The FSP is considered to be around 30% moisture content and is determined when no free water remains, only bound water is present in the cell walls. Due to wood being an anisotropic material, the volume variation will not be homogeneous along the sawn material when the hygrothermal conditions in the surrounding environment change. These variations can produce different warps as well as checks and splits in the final wood product, reducing its value and even making it unfit for the original purpose. Several studies have addressed the problem of warping in black pine while drying (Díez et al. 2001, Conde 2003), highlighting the fact that this is an issue for this species.

There are several theories as regards the reasons for these variations in both transversal and longitudinal directions along the tree (Lachenbruch et al. 2011). This study will focus on the radial and angular shrinkage variation that is produced in each ring in the transversal direction along the bole at different heights in order to make a qualitative evaluation of the real effects of juvenile wood on the end products.

In this study angular shrinkage can be related to approximately half of the tangential shrinkage, as only one side of the analyzed sample was cut and measurements were performed along a line. For this reason, tangential shrinkage has not been studied independently.

In the transversal direction, the inner part of the bole, closest to the pith, the structure and properties of the wood undergo rapid changes until they stabilize more or less towards the bark. This inner area has been termed juvenile wood (JW) or corewood to differentiate it from the mature wood (MW) or outerwood (Larson et al. 2001, Burdon et al. 2004).

Although the term corewood also allows us to explain the variation that occurs along the bole, JW is still widely used in the Spanish wood industries. In this paper, the terms JW/MW will be used to differentiate two areas in the radial pattern of the angular and radial shrinkage at different heights. These areas will be compared with the results obtained from previous studies using yearly microdensitometry variations from the pith to the bark.

7.2 Methodology

Within the Experimental Network for Research into Sustainable Forest Management (SEGEFORS), different thinning and pruning trials were established by the INIA-CIFOR in several Spanish locations and with various species at the end of the last century to study the effects of silviculture on those species.

One of these sites, from where the samples were taken, is a pure plantation of *Pinus nigra* Arnold subsp. *nigra* (Black pine) (PN) with thinned plot (CF_SP), plot with thinning and 5 m pruning (CF.CP) and control plot. It is located in the municipality of Zarzuela de Jadraque (Guadalajara, Spain) (41°1´N, 3º4´W) at an altitude of 1,005 m.a.s.l. The site is more or less flat with a 1–10 % North-West facing slope. In this area, the average annual rainfall is 489 mm, and the average annual temperature is 10.9 ºC (AEMET 2017).

In these plots 12 trees were felled, one per plot. Discs at basal height and every 3 meters were then extracted up to the point where the diameter was less than 7.5 cm, although for the purposes of this study we only focus on discs up to a height of 9 m. Two additional discs were extracted at 1.3 meters and at 4.3 meters. The discs were wrapped in plastic laminated film immediately after felling to avoid any humidity loss, and stored while being processed in a climatic chamber set to 4 ºC.

From these discs, a 15 mm thick circular segment, including the center and where the secant is separated 2 cm from the center, was extracted. On this circular segment, passing through the pith, a line was marked on the surface parallel to the border. Auxiliary lines were also marked but are of no interest for the purposes of this study. The circular segment was then scanned in “green condition” using a flatbed Arcus Plus scanner with an optical resolution of 600×1200 dpi, which can be enhanced by interpolation to a 1200×1200 dpi resolution. The circular segments where then stored in a climatic chamber at 20 ºC and 65 % RH until their moisture content was 12 %. After that, the circular segments were scanned again. Figure 7.1. shows an example of the circular segment with the marks.

Subsequently, on each side of the pith along the marked line, the XY location of the intersection between the line and the end of each latewood ring was recorded using CellD software (Olympus). This was done on both the conditioned and the green circular segments. The data obtained was used to calculate the percentage of angular and radial shrinkage of each ring in relation to the center and plotted for all trees at each stem height by creating a script in R (R Core Team 2017). A 3 point mean smoothing was performed to avoid extreme values from abnormal year rings.

Subsequently, a transition year (TY) between juvenile wood and mature wood was estimated with the “segmented” (Muggeo 2008) package in R (R Core Team 2017), for each side from the pith, for the angular and radial shrinkage.

Having determine the TY, the average between side A and B was calculated and the percentage of volume relating the JW area determined. This procedure was chosen as the discs presented only slight eccentricity, with small differences observed between side A and B.

The results were compared to those from a previous study on JW detected according to radial variation in latewood density (Ruano et al. n.d.) to identify whether the volumes of the part of the bole near the pith with highly variable shrinkage (JW) vary significantly.

7.3 Results and Discussion

As can be seen from Figure 7.2., for almost every year ring the angular shrinkage from the pith increases rapidly until it stabilizes after approximately the first 9-11 years, around 2%. When analyzing the radial shrinkage in Figure 7.2., it can also be deduced from the graph that in the first years the shrinkages are especially high, usually between 4 - 9 % but then they more or less stabilize in a short period (8 years) to around 3%. Figure 7.3. shows the mean between the A and the B side of a different tree to that presented in Figure 7.2.

These results are in agreement with other studies carried out into longitudinal shrinkage (Gorman and Kretschmann 2012), where the closer to the pith the higher the shrinkage, highlighting the positive relationship with the Microfibril Angle (MFA). These differences in shrinkage, together with the lower MOE values (Auty and Achim 2008, Moore et al. 2015), are one of the main problems associated with the high presence of JW when the material is used for structural purposes. In this case, as mentioned in the introduction, the differential shrinkage could result in tensions produced while drying leading to warps as well as checks and splits, thereby disturbing the mechanical properties.

The results for the angular shrinkage are in line with those described in the Wood Handbook (2010). As regards the tangential shrinkages, the farther from the pith the greater the shrinkage, until it stabilizes. Although the previously mentioned book states that “as a general rule of thumb, wood shrinks (or swells) approximately twice as much in the tangential direction of the annual rings as compared to the radial direction”, the results in this work are taken from the shrinkages along a line in the radial direction, and reveal that these difference are only slight. However, as explained above, this is due to only measuring along the line and not the two free edges usually measured.

No general trend in height variation was observed when plotted per tree at different heights. Figure 7.4. shows the angular shrinkage and Figure 7.5. shows the radial shrinkage for the same tree along the bole. It can be seen that the radial shrinkage is usually around 1 % more than the angular shrinkage.

If we compare the results of angular and radial shrinkage, in Table 7.1. it can be seen that the age at which the transversal variation becomes more stable is reached earlier in the case of radial shrinkage than for angular shrinkage. As the tree grows more following the applied silviculture regime, the %JW volume is reduced in comparison with the control group. It would be interesting to study and compare the shrinkage effect on trees that have been thinned and pruned prior to reaching the TY.

Table 7.1. Summary of volume radial and angular measurements per tree

idtree	Height	Plot type	RADIAL				ANGULAR			
			JW Volume	MW Volume	Tree Volume	%JW Volume	JW Volume	MW Volume	Tree Volume	%JW Volume
04	0 - 9	CF.CP	0.041	0.208	0.249	16.6	0.038	0.211	0.249	15.2
16	0 - 9	CF.CP	0.034	0.282	0.316	10.7	0.070	0.245	0.316	22.3
31	0 - 9	CF.CP	0.025	0.258	0.283	8.8	0.038	0.245	0.283	13.5
45	0 - 9	CF.CP	0.034	0.332	0.367	9.3	0.064	0.303	0.367	17.4
06	0 - 9	CF_SP	0.043	0.259	0.302	14.3	0.060	0.243	0.302	19.7
21	0 - 9	CF_SP	0.028	0.243	0.272	10.4	0.041	0.231	0.272	15.0
29	0 - 9	CF_SP	0.033	0.248	0.280	11.7	0.036	0.244	0.280	12.8
38	0 - 9	CF_SP	0.028	0.244	0.272	10.3	0.045	0.228	0.272	16.4
13	0 - 9	CONTROL	0.032	0.164	0.196	16.4	0.051	0.145	0.196	26.0
47	0 - 9	CONTROL	0.020	0.162	0.182	11.1	0.044	0.139	0.182	24.0
51	0 - 9	CONTROL	0.024	0.113	0.137	17.5	0.040	0.097	0.137	29.1
56	0 - 9	CONTROL	0.018	0.126	0.143	12.4	0.028	0.115	0.143	19.5

To conclude, the results are compared to those obtained by latewood density radial variation presented in Chapter 3 (Ruano et al. n.d.). If the shrinkage follows more or less the same radial pattern in the longitudinal dimension, the results reveal that the volume of JW, characterized as of lower quality, is smaller in comparison to the density results. In Table 7.2. we can see the same summary table for the JW estimation by latewood density from Chapter 3. In the case of trees receiving some kind of silviculture, the results are quite similar as regards the angular shrinkage estimations, but for the control trees although still higher than the others, the percentage JW estimated is smaller. JW estimation using radial variation is more variable. As a general trend, it can be said that the JW volume calculated based on the radial variation is the smallest of all three methods.

Table 7.2. Summary of volume densitometry measurements y per tree

idtree	Height	Plot type	JW Volume	MW Volume	Tree Volume	%JW Volume
04	0 - 9	CF.CP	0.039	0.207	0.246	15.7
16	0 - 9	CF.CP	0.073	0.238	0.311	23.5
31	0 - 9	CF.CP	0.052	0.226	0.279	18.8
45	0 - 9	CF.CP	0.065	0.298	0.363	17.8

idtree	Height	Plot type	JW Volume	MW Volume	Tree Volume	%JW Volume
06	0 - 9	CF_SP	0.061	0.237	0.298	20.6
21	0 - 9	CF_SP	0.063	0.206	0.270	23.5
29	0 - 9	CF_SP	0.036	0.242	0.277	12.8
38	0 - 9	CF_SP	0.049	0.220	0.268	18.2
13	0 - 9	CONTROL	0.067	0.125	0.192	34.7
47	0 - 9	CONTROL	0.060	0.121	0.181	33.1
51	0 - 9	CONTROL	0.037	0.097	0.134	27.7
56	0 - 9	CONTROL	0.035	0.106	0.141	24.8

These results could be complemented with an MFA analysis, as the longitudinal and radial variation is highly related with the MFA, as well as with the spiral grain (Siau 1995, Clark et al. 2006). The typical MFA transversal pattern reduces its angle along the radial pattern (Moore et al. 2015, Wang et al. 2008). Although grain spirality next to the pith is straighter, and over the first few growth years the tracheids become increasingly inclined, subsequently no consistent significant circumferential variation is described (Walker 1993, Cown et al. 2010, Watt et al. 2013), making it more difficult to identify a relationship with shrinkage patterns.

7.4 Conclusions

Radial shrinkage tends to be higher in the first 8 rings closest to the pith, usually starting between 4 and 9 % and going down until it stabilizes at around 3%.

In contrast, the angular shrinkage is close to 0 or even negative near the pith and increases up to a certain ring (9-11) when it becomes more or less stable at around 2 %. Angular shrinkage stabilizes later than radial shrinkage.

These results are valid along the entire bole, the radial shrinkage being greater and earlier than the angular shrinkage for every height studied. No general patterns can be identified along the same tree at the different heights sampled.

The silvicultural treatments seem not to have an influence on the radial and angular shrinkage following their application. The results seem to suggest that thinning leads to a reduction in the radial and angular percentage JW volume and that if applied together with heavy pruning the reduction tends to be still greater, although this is due to the fact that the tree grows more after the silvicultural treatment has been applied.

It would be of interest in future studies to compare these results with yearly MFA, as well as using samples with two edges in the study (like a plank) as well as to measure shrinkage in the longitudinal direction.

If density is not an issue for strength grading of structural timber on the bole, the volumes of the stable shrinkage area suggest that, if the pattern is similar in the longitudinal dimension, the area that could be segregated for higher quality end use would be larger than that provided by latewood density radial variation.

Further automatization of the process could be implemented to reduce the time required to acquire the data, by using an image processing program. Furthermore, a study analyzing the difference between EW and LW shrinkage could be considered if, instead of marking a line, thin colored pins are used for the EW and LW of each ring.

Fitting the shrinkage curves by using a quadratic linear regression may improve the TY estimation.

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7.6 Figures

Figure 7.1. Dry scanned marked circular segment.

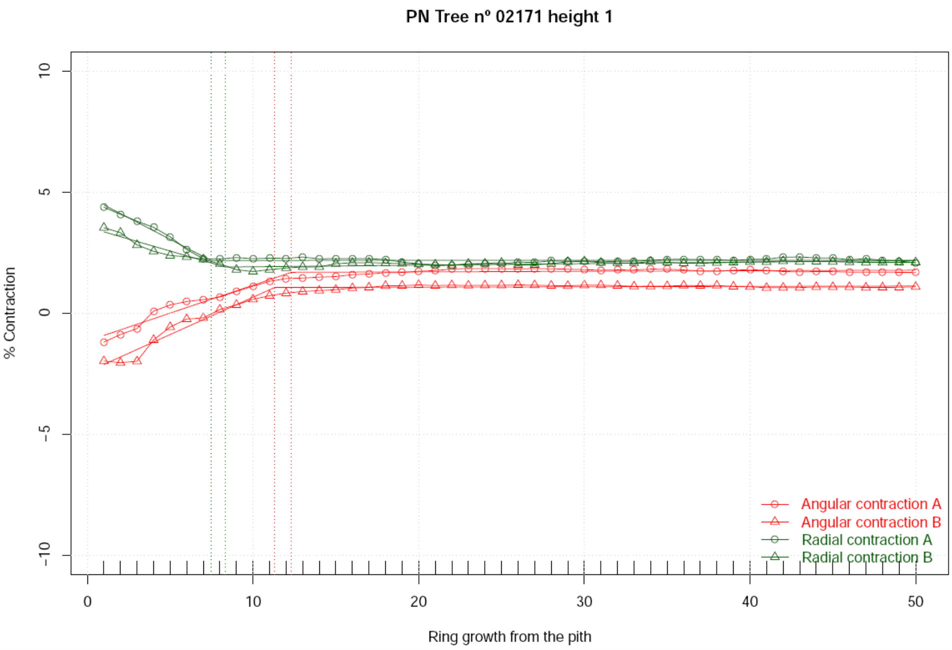

Figure 7.2. Radial and angular shrinkage per year tree ring, side of the pith, and segmented linear model fitted

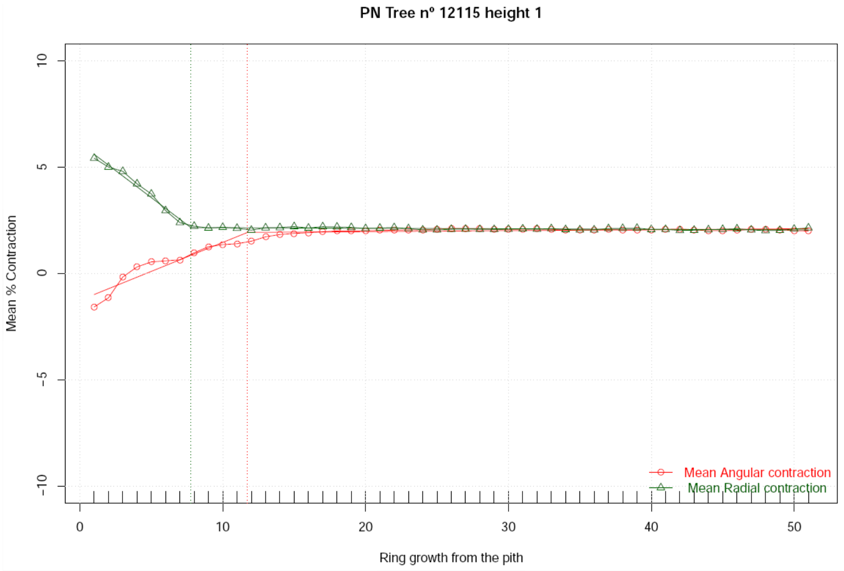

Figure 7.3. Mean radial and angular shrinkage per year tree ring, side of the pith, and segmented linear model fitted

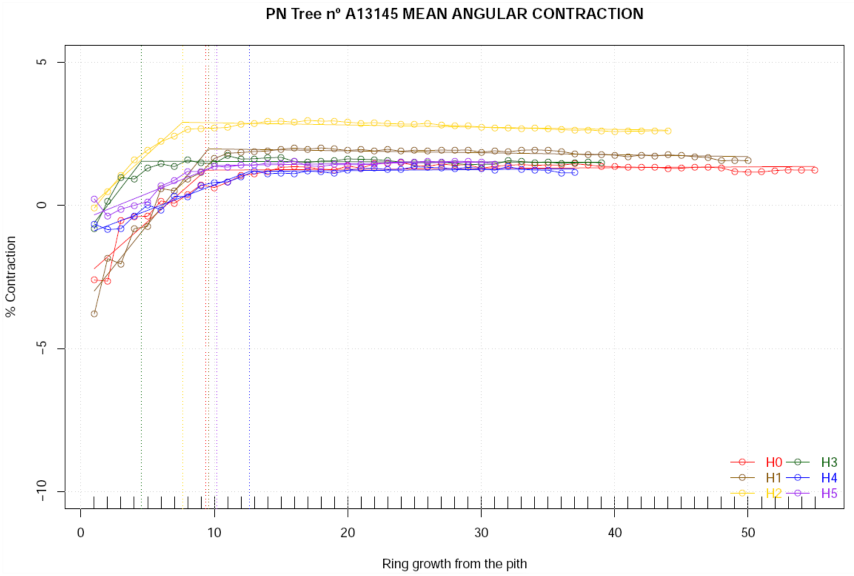

Figure 7.4. Mean angular shrinkage variation along the bole

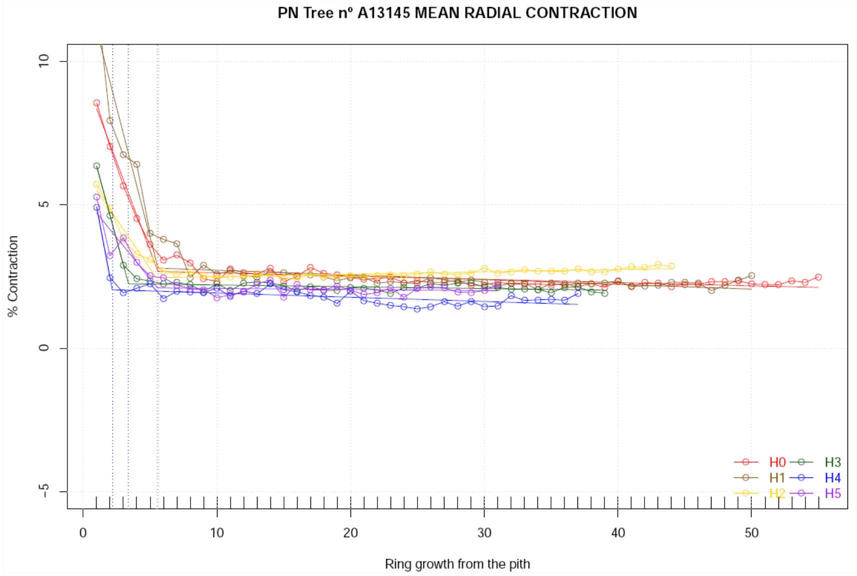

Figure 7.5. Mean radial shrinkage variation along the bole

Chapter 8. General discussion

Although each chapter has its own discussion, a general discussion of the results obtained, highlighting the main objectives attained in each chapter is presented here. Some ideas on how to proceed in future research efforts will be presented at the end.

8.1 Densitometry for suitably estimating JW

When assessing the juvenile wood (JW) and mature wood (MW) areas in a tree, the method most commonly used is usually densitometry, or basic density, because it is relatively easy and cost effective, providing a lot of extra yearly data on different characteristics of the tree. Also, density by itself explains a lot of the MOE variance present in samples (Auty et al. 2014, Díez et al. 2001), as well as being an important characteristic for timber strength according to EU standards (UNE-EN 338:2016). For all these reasons, studying the transversal densitometry pattern of each tree seems to be a reliable predictor of quality and estimator of JW.

After studying the transversal patterns (at different heights) of yearly minimum, mean and maximum density for earlywood (EW) and latewood (LW), as well as their widths and the length ratio between the two (texture), it was found that the simplest method for obtaining the transition year (TY) between JW and MW was by using either yearly maximum density or LW density.

LW density does not provide the more useful yearly mean wood density, that by doing the average per tree ring area gives us the characteristic density, which could be used for grading. However, the use of this method was discarded (Chapter 4, Figure 4.3. and Figure 4.2.), because in some cases there were two breakpoints and in others only one, mainly depending on the species and tree studied. Furthermore, there was a more or less constant difference between yearly mean and LW density, mostly in the MW area. The LW density method usually estimates TY a year or two earlier than through the yearly mean approach, so the results should not vary greatly between the two approaches. In any case, the process would have been more tedious as it is necessary to check every transversal profile individually prior to fitting the segmented model.

Finally, LW density was the trait chosen for estimating the boundary which defines the proportion of JW present, as it was less influenced by abnormal rings produced by droughts or any other variations. Several studies have also used the same variable (Sauter et al. 1999, Gapare et al. 2006).

In order to improve the estimation, to analyze whether silviculture influenced the TY and to improve the analysis by introducing a drought index covariate, an approach using segmented mixed models was implemented in Chapter 2. In this chapter a general trend is identified, namely that the higher up the bole, the earlier the TY occurs. Additionally, after fitting the best models and analyzing the results, the importance of climate on the LW density was clear up to the last height studied, where other effects not included in the model may have a greater influence and mask that of climate. Furthermore, the effect of drought was found to differ depending on whether it took place prior to the LW growing period or during the growth period. The effect of the crown was also significant when modeling parts of the bole that in some cases were within the crown but in others were not. In addition, silviculture seemed to have an effect, albeit of scarce significance, on the LW density.

The different silvicultural practices appeared not to affect the TY in the lower part of the bole, although this was due to the fact that the treatments where applied when the rings were already MW.

However, in Chapter 3, when analyzing the volume of each wood type (JW/MW), it was found that due to the increase in radial growth as a result of thinning carried out after the TY, the extent of MW on each strip increased, and therefore the percentage of JW with respect to the total decreased. Additionally, the reduced taper of the bole when pruned at 5 meters increases its value. An economic analysis should be conducted to assess whether the operational costs could be covered by the higher quality wood produced.

8.2 Height growth curve for estimating JW proportion

Based on Kučera's (1994) study which related the current annual height increment with JW formation in Norway spruce, this approach was tested in Chapter 4 as it could also be performed on standing trees. For the purposes of the study, a more suitable height growth curve function was used which better fitted the data. After testing the most commonly used functions for the Scots pine and black pine, the Chapman-Richards function was selected for both species. When comparing these results with those obtained through LW and mean density, it was found that the growth function seemed to reach the TY at different times and no correlation could be found between them. Other variables might be needed such as site, drought, crown development or genetics, in order to relate the TY obtained through each method. It is also possible that this method is better for estimating other wood characteristics with a different transversal pattern.

8.3 Near infrared spectroscopy (NIRs) for estimating JW proportion

NIRs provides a profile of the organic composition of the analyzed material and has previously been implemented in studies concerning wood species, provenances, and mechanical properties. Since the Lignin/Cellulose ratio of the wood also changes between JW and MW, we tested whether it was possible to relate it to wood density and also whether TY could be detected and correlated with the density results.

The methodology followed in this first trial along with possible ways to address undesired results are explained in Chapter 5. In this study it was not possible to identify a good correlation between the NIRs spectra and density or to segregate each ring spectrum per sample into two different areas. However, it was important as several problems were detected that could affect the calibration, leading to these results. The penetration depth of the NIRs, the spectral resolution and the differences found per tree at different heights were aspects highlighted for future positive outcome. Moreover, these initial results together with our impressions after using this technology, led us to contemplate a different approach for the study; using NIR hyperspectral imaging, thereby maintaining the spatial information.

NIR hyperspectral imaging has been explained in Chapter 6. When analyzing the images, it was found that compression wood and the presence of discontinuities such as the presence of a close due to a whorl or resin pocket were easily detected in each image through a simple PCA. For finer detection between JW and MW, a PLS-DA plus an analysis performed separately for the EW and LW should be done to obtain better results. The results obtained through this technique were compared with the ones obtained by LW densitometry. The results of the comparison showed that the TY was usually determined with ± 1 year of difference and that for the only sample that exceeded that margin, the error was 2 years. These results are especially promising with regard to the automatization of JW detection.

8.4 Shrinkage for estimating JW proportion

The study of yearly angular and radial shrinkage from green to normal conditions described in Chapter 7 showed interesting results as regards the differentiation of two different areas (JW/MW). The angular shrinkage was calculated along a line going through the pith and as explained in that chapter, it relates to half the transversal shrinkage, which is the type typically studied. When comparing the two types of shrinkage studied, the radial shrinkage is greater near the pith but stabilizes earlier (3-7 rings) than the angular shrinkage (9-11 rings), which is low near the pith but increases further from it until it stabilizes. Results regarding the variance of each shrinkage type along the bole in terms of TY or the % variation showed no clear pattern. Likewise, the silvicultural practices show no significant influence on the shrinkage percentage after they are implemented. It would be interesting to study the shrinkage in trees that have been thinned and pruned before the TY is reached. When comparing the % JW volume obtained using this approach with that found through the LW densitometry, angular shrinkage shows similar results, except for the control group where the percentage was lower and presented smaller differences in relation to the other groups. As regards radial shrinkage, differences were also seen in terms of % volume between the trees which had undergone silvicultural interventions of some kind and the control ones. However, the TY was estimated much earlier than by angular shrinkage or LW densitometry. As described in the LW densitometry approach, since the tree grows more in comparison with the control group after the silvicultural intervention, the % volume of JW decreases.

8.5 Limitations of this work and future lines of research

Due to the lack of availability of plots in which long-term studies of this type are carried out, plantation spacing was not included in the current study. However, several studies have reported a positive influence of plantation spacing on certain characteristics of the JW area, stem straightness and genetic heritability of certain wood characteristics. It is important to note that the results of some of these studies relate to fast growing species under 10 years of age (one of the reasons being to shorten the study period) so results for older trees ready to be processed were not considered. Perhaps a long-term study including plant spacing would be of interest.

Another line of research could focus on grafted material from buds taken from the upper part of selected trees, which could result in higher quality trees. Although some studies conducted in the past focused on this aspect, this area of research has been abandoned. Moreover, no reference is made in these studies regarding the material onto which it was grafted. Although a study comparing properties could be conducted at this stage in the plots described in the A.I.2:, that it would be better to wait to see whether differences could be appreciated between grafted and non-grafted trees with regard to the mature part or total tree growth.

The use of non-destructive techniques (NDT), such as time of flight, has been tested for grading on standing trees. It is possible that a relationship between these measurements and the amount of JW in the bole could be identified, even though standing trees are above fiber saturation point and the results may vary according to the season.

Regarding the extraction of increment cores, instead of extracting cores of 5 mm diameter it may be of interest to extract larger ones, with commercial diameters of 10 or 12 mm being available for fiber studies. This will increase the likelihood of boring through the pith and facilitate processing, as well as making it easier to compensate for any inclination of the increment core which may occur on extraction. However, damage to the tree will be considerably greater.

Shrinkage studies carried out on planks would also allow us to analyze tangential shrinkage similar to that produced in end products.

The study of the sampled *Pinus radiata* within the Project RTA2014-00005-00-00 has yet to be completed. Part of this research will include studying whether TY occurred after the implementation of silvicultural interventions and quantifying the effect on the part of the bole closest to the ground.

Finally, with regard to the NIRs studies, it would be interesting to test this approach on the increment cores both with and without prior removal of extractives, focusing on the wavelengths that are of interest for the determination of JW.

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Chapter 9. Conclusions

- In order to assess the juvenile wood (JW) area on a log, micro X-ray densitometry provides a suitable method as it is a relatively cheap, rapid method. It is also related to the stiffness of the material, gives a lot of supplementary information and the dating can be verified. Regarding the study of the boundary between JW and mature wood (MW), in this Thesis the results showed that the best density parameter for automatization of the process is latewood (LW) density. Maximum density can also be used, but in order to detect the boundary correctly some smoothing of the data should be performed to reduce the yearly variation. Mean ring density (MD) can be problematic as the radial pattern, depending on the species and tree, can have one or two breakpoints so a previous analysis per sample is needed to establish each pattern. The LW density transition year (TY) was obtained earlier than when using MD, but the differences as regarding the boundary determination is only one or two years.

- When assessing the TY through increment cores, which can be done on standing trees, the pith needs to be in the sample in order to assess the boundary correctly. By using the wider 10-12 mm increment borer, although it has a greater impact on the tree, there is a higher probability of extracting the pith as well as providing the opportunity to correct any angle that the increment core may present, due to the extraction, at the ‘carpentry’ stage. As regards this potential problem with the extraction angle, a special electric drill with an adapter for the borer may help to mitigate this issue.

- The function developed for segmented mixed models provides a useful tool to predict the TY in a large number of samples using LW density profiles. These models achieve more stable results than by applying segmented regressions to each tree individually where the TY, especially at lower heights, is often not clear. The drought index is relevant to LW density, affecting the slope on the MW or the density in TY determination. Moreover, depending on the moment at which the drought index is calculated during the growth season, the effect changes. Prior to the beginning of the growing season of LW, a negative effect on LW density is observed, whereas if produced during or at the end of the LW growth there is a positive effect.

- Up to a height of 9 meters, TY was reached prior to the implementation of any silvicultural treatment, so further sampling is necessary to assess whether treatment could influence or shift the TY on the lower part of the bole not influenced by the crown. However, within the crown and in the case of the back pine (PN), pruning was found to affect the TY because the LW density required to reach it increased, thus delaying the TY and increasing LW density. In both pine species, thinning seems to have a significant albeit slight negative effect on LW density in the MW, while thinning and pruning combined seemed to have a small positive effect on it compared to the control group. As reported in previous studies, the results presented here may vary depending on the intensity and the timing of thinning, as well as on the amount of green pruning carried out. Further studies are required to confirm these results.

- The growth response after the silvicultural treatments studied reveals that the amount of JW is reduced in percentage as total volume increases with any silvicultural treatment applied after the TY has occurred. This is the case for both, the PN and the Scots pine (PS), in Mediterranean forests. Further research could also be supplemented with some destructive testing of the processed trees to evaluate whether there is any difference between treatments on the MW or in terms of the general quality of the wood in the end product, as well as an MFA analysis.

- The TY calculated using Chapman-Richards growth functions for the accumulated height increments, does not fit the estimation of the TY obtained through density for the Spanish provenances studied of Scots and black pines. This is probably due to other variables affecting growth in Mediterranean species and the different height growth patterns of these species compared to the *Picea*, on which this theory was tested. Mansfield's approach using a three segmented regression for mean ring density, seems to be suitable for most of the *Pinus nigra* strips but not for those of *Pinus sylvestris*.

- The calibration between measurements obtained using multipoint NIRs and density data derived from micro X-ray densitometry was found to be difficult. After analyzing the possible causes three solutions were proposed: using a black coating under the sample, reducing the spectral resolution and increasing the number of samples. As regards the qualitative method, it is possible that the insertion of a transition area between the JW and MW could lead to improved results. Further improvements to the results might also be obtained by analyzing the lignin/cellulose ratio and comparing it to the NIRs results.

- NIR-HI can be calibrated with micro X-ray densitometry results and the JW, MW and transition point (TP) between them can be determined on the transversal section of the tree. The results are independent of the silvicultural treatment applied in the Scots pine plantations studied in Spain. The principal component analysis was found to be a useful and easy way to provide additional information on the presence and location of compression wood. The partial least squares discriminant analysis approach was the best for detecting the TP between JW and MW, when the EW and LW were evaluated separately. Every strip was classified within ±1 annual ring difference compared with the one obtained through LW densitometry. The biggest difference was ±2 annual rings. A previous automatic classification, by combination with a partitional k-means unsupervised classification, between EW and LW, would probably improve the results and could lead to a better automatic process. Further analyses should be performed with non-extracted wood to increase the practical application potential for early JW quantification in standing trees and for wood quality assessment. Tests would also be needed for early JW quantification in standing trees through increment borer experiments using high spatial resolution in order to distinguish between EW and LW in the annual rings closer to the bark.

- Radial shrinkage tends to be high within the first 8 rings nearest to the pith, usually being between 4 and 9% decreasing until it stabilizes at around 3%. Regarding the angular shrinkage, it is close to 0% or even negative near the pith and increases up to a certain ring (9-11) when it becomes more or less stable at around 2 %. These results are valid all along the bole, also the radial shrinkage is greater and has an earlier breaking point than the angular shrinkage for every height studied. No general patterns could be obtained within the same tree at the different heights sampled, either with regard to the variations on the stable part of the shrinkage or the initial shrinkage. The silvicultural treatments applied seem not to influence the radial and angular shrinkage pattern variations. Fitting the shrinkage curves by using a quadratic linear regression may improve the TY estimations.

- If density is not an issue for strength grading of structural timber on the bole, the volume of the area where the shrinkage is more stable suggests that, if the longitudinal shrinkage has a similar pattern , the area that could be segregated for higher quality end use would be larger than that provided by LW density radial variation.

Chapter 9. Conclusiones (español)

- Con el fin de evaluar el área de madera juvenil (JW) en un tronco, la micro densitometría de rayos X proporciona un método adecuado, ya que es un método relativamente barato y rápido. La densidad está también relacionada con la rigidez del material, da una gran cantidad de información complementaria y la datación de los anillos se puede verificar. En cuanto al estudio del límite entre JW y madera madura (MW), en esta tesis los resultados mostraron que el mejor parámetro de densidad para la automatización del proceso es la densidad de madera de verano (LW). También se puede utilizar la densidad máxima, pero para detectar el límite correctamente se debe realizar algún suavizado de los datos para reducir la variación anual. La densidad media de anillo (MD) puede ser problemática ya que el patrón radial, dependiendo de la especie y el árbol, puede tener uno o dos puntos de rotura, por lo que se necesita un análisis previo por muestra para establecer cada patrón. El año de transición (TY) de densidad de LW se obtiene antes que cuando se utiliza MD, pero las diferencias con respecto a la determinación de límites de JW son sólo uno o dos años.

- Para evaluar el TY correctamente a través de cores extraídos, con la ventaja de que se puede hacer en árboles en pie, la medula debe estar en la muestra. Mediante el uso de barrenas con un diámetro más ancho, de 10-12 mm, aunque tiene un mayor impacto en el árbol, hay una mayor probabilidad de extraer la medula, así como proporcionar la oportunidad de corregir cualquier ángulo que el core pueda presentar, debido a la extracción, en la carpintería durante su procesado. En cuanto a este posible problema con el ángulo de extracción, un taladro eléctrico, con un adaptador especial para la barrena, puede ayudar a mitigar este problema.

- La función desarrollada para modelos mixtos segmentados proporciona una herramienta útil para predecir el TY en un gran número de muestras utilizando perfiles de densidad LW. Estos modelos logran resultados más robustos que aplicando regresiones segmentadas a cada árbol individualmente donde el AT, especialmente en las alturas más bajas, a menudo no está tan claro. El índice de sequía es relevante para la densidad de la LW, afectando la pendiente en la MW o la densidad en la determinación del AT. Además, dependiendo del momento en el que se calcule el índice de sequía durante el período vegetativo, el efecto cambia. Antes del comienzo de la formación de LW, se observa un efecto negativo sobre la densidad de LW, mientras que, si ocurre durante el período de crecimiento de LW, hay un efecto positivo.

- Hasta la altura de 9 metros, el TY se alcanzó antes de la realización de cualquier tratamiento selvícola, por lo que sería necesario realizar un muestreo adicional para evaluar si el tratamiento pudiera influir o cambiar el TY en la parte alejada de la influencia de la copa. Sin embargo, dentro de la copa y en el caso del pino laricio (PN), los resultados indican que la poda afecta al TY porque la densidad de LW necesaria para alcanzarlo aumenta, retrasando así el TY y aumentando la densidad de la LW. En ambas especies de pinos, las claras parecen tener un efecto negativo significativo, aunque pequeño, sobre la densidad de la LW en la MW, mientras que la clara y la poda combinadas parecen tener un pequeño efecto positivo en la LW, en comparación con el grupo de control. Como se explica en otros estudios, los resultados presentados aquí pueden variar dependiendo de la intensidad y el momento de la clara, así como de la cantidad de poda verde llevada a cabo. Se requieren más estudios para confirmar estos resultados.

- La respuesta de crecimiento después de los tratamientos selvícolas estudiados revela que la cantidad de JW se reduce en porcentaje ya que aumenta el volumen total con cualquier tratamiento silvícola aplicado después de que se haya producido el TY. Esto se observa en las parcelas de PN y pino silvestre (PS) estudiadas. También podrían complementarse más investigaciones con algunas pruebas destructivas de los árboles procesados para evaluar si existe alguna diferencia entre los tratamientos en términos calidad de la MW o en la calidad general de la madera en el producto final, así como un análisis de microfibrillas.

- El TY calculado utilizando las funciones de crecimiento Chapman-Richards para los incrementos de altura acumulados, no se ajusta a la estimación del TY obtenido a través de la densidad para las procedencias españolas estudiadas de pino laricio y silvestre. Esto se debe probablemente a otras variables que afectan al crecimiento de las especies mediterráneas y a los diferentes patrones de crecimiento de altura de estas especies en comparación con la *Picea*, en la que se probó esta teoría. El enfoque de Mansfield utilizando una regresión de tres segmentos para la densidad media del anillo, parece ser adecuado para la mayoría de las tablillas de PN, pero no para las de PS.

- Respecto a la calibración entre las mediciones obtenidas mediante NIR multipunto y datos de densidad derivados de la micro densitometría de rayos X, resulta no ser muy buena. Después de analizar las posibles causas se proponen tres soluciones: utilizar un recubrimiento negro especial debajo de la muestra, reducir la resolución espectral y aumentar el número de muestras. Por lo que se refiere al método cualitativo, es posible que la inserción de un área de transición entre la JW y la MW pueda dar lugar a mejores resultados. También se podrían obtener mejoras adicionales en los resultados mediante el análisis de la relación lignina/celulosa y compararla con los resultados de los NIR.

- El NIR-HI se puede calibrar con los resultados de la micro densitometría de rayos X y la JW, la MW y el punto de transición (TP) entre ambas pueden ser determinadas en la sección transversal del árbol. Los resultados son independientes del tratamiento selvícola aplicado en las plantaciones de pino silvestre estudiadas en España. Se encontró que el análisis de componentes principales es una manera útil y fácil de proporcionar información adicional sobre la presencia y ubicación de la madera de compresión. El uso de regresiones de mínimos cuadrados parciales obtuvo los mejores resultados para la detección del TP entre JW y MW, cuando la madera de primavera (EW) y la LW se evaluaron por separado. Cada tablilla se clasificó con una diferencia de ±1 anillo en comparación con la obtenida mediante densitometría de LW. Las mayores diferencias fueron de ±2 anillos. Una clasificación automática previa, mediante una combinación con una clasificación no supervisada de k-medias, entre la EW y la LW, probablemente mejoraría los resultados y podría conducir a un mejor proceso de automatización. Deben realizarse nuevos análisis con madera no extraída para aumentar el potencial de aplicación práctica para la cuantificación temprana de JW en árboles en pie y para la evaluación de la calidad de la madera. También serían necesarias pruebas para la cuantificación temprana de JW en árboles en pie a través de cores utilizando alta resolución espacial con el fin de distinguir entre EW y LW en los anillos anuales cercanos a la corteza.

- La contracción radial tiende a ser mayor en los primeros 8 anillos más cercanos a la medula, por lo general empieza estar entre el 4 y el 9% y va disminuyendo hasta que se estabiliza en alrededor del 3%. En cuanto a la contracción angular, empieza alrededor del 0% o incluso negativa cerca de la medula y va aumentando hasta un cierto anillo (9-11) cuando se vuelve más o menos estable alrededor del 2%. Estos resultados son válidos a lo largo del tronco, además la contracción radial es mayor y tiene un punto de rotura anterior que la contracción angular para cada altura estudiada. No se pudieron obtener patrones generales dentro del mismo árbol a las diferentes alturas muestreadas, ya sea con respecto a las variaciones en la parte estable de la contracción o las contracciones iniciales. Los tratamientos selvícolas aplicados parecen no influir en las variaciones anuales de las contracciones radiales y angulares. Ajustar las curvas de contracción mediante una regresión lineal cuadrática puede mejorar las estimaciones de AT.

- Si la densidad no es un problema para la clasificación de resistencia de la madera estructural en el tronco, el volumen del área donde la contracción es más estable sugiere que, si la contracción longitudinal tiene un patrón similar, el área que podría ser segregada para un uso final de mayor calidad sería mayor que la proporcionada por la variación radial de densidad LW.

APPENDIX I: Complementary works

On these Thesis appendixes, several complementary works carried out during the Thesis are in this appendix. The first one is a publication and its abstract, in a journal indexed in the JRC in which the candidate had collaborated. It is related with wood quality when used in outdoors structures and the effect of the particular climate on them. The second one is an informal report on the grafted pines that although interesting for the studying were too young. The third one is the report on the achievements accomplished under the 778322-CARE4C H2020 (Carbon smart forestry under climate change) in South Africa.

A.I.1: Wood decay hazard in Spain using the Scheffer index: Proposal for an improvement

Fernandez-Golfin J, Larrumbide E, Ruano A, Galvan J, Conde M (2016) Wood decay hazard in Spain using the Scheffer index: Proposal for an improvement. Eur J Wood Wood Prod, 74(4), 591–599. Impact Factor (SJR):0.56. Q2 Materials Science, rank 185 / 439.

Abstract

Wood in outdoor conditions is prone to water uptake and release. The influence of wood temperature and moisture on the decay risk is substantial. Different climate indexes and mathematical models have been used to predict the decay risk, being one of the most well-known is the Scheffer index (SI). Scheffer index values (SI1) and modified Scheffer index values considering days with no rain but condensation (SI2) together with the risk of physical and dimensional degradation of wood (RDA) and the severity climate indexes (summer and winter) are calculated for 48 capitals of province in Spain. The relationships between the risk of physical degradation of the wood (RDA) and the climatic severity variables both for summer (SCSI) and winter (WCSI) are analyzed, and a model for predicting the RDA value from the SCSI and WCSI values is proposed. The analysis of the relationship between the Scheffer index (SI1) and SCSI and WCSI variables leads to the conclusion that the decay risk is fundamentally governed by summer climatic severity (SCSI) in coastal areas and by both variables (SCSI and WCSI) in inland areas, the relative insolation value being the variable with the most significant effect, both in summer and winter. The effect of condensations on the decay risk is also assessed, leading to the conclusion that the frequent presence of condensation is an aggravating factor and therefore, this meteorological variable should be considered when calculating the decay risk. A new equation for SI calculation considering the condensation effect, together with a new rating of risk, is also provided.

Keywords

Equilibrium Moisture Content Wood Decay Balearic Island Water Retention Capacity Fungal Activity

A.I.2: Grafted trees for wood quality

The following report is written in Spanish. It was an internal report on the study and an evaluation of the grafted trees for their inclusion on the Thesis.

A.I.3.1. Introducción

La visita se centró en un total de 4 plantaciones: 3 ensayos de altitud realizados sobre pino silvestre (patrón sin identificar), y un banco clonal en el que se plantaron los restos sobrantes del huerto semillero de procedencia “Sierra de Guadarrama” ubicado en el Centro Nacional de Recursos Genéticos Forestales de Valsaín, por si había que sustituir marras en los primeros estadios, así como pinos procedentes de semilla de los árboles plus seleccionados para los injertos. Todos ellos plantados dentro del M.U.P. “PINAR” de Valsaín Nº2 C.U.P (SEGOVIA). Cada plantación está representada por 10 clones representados en 5 ramets, injertados y trasplantados en 1990, con reposición de marras al año siguiente, salvo el banco clonal de Pradorredondillo de la que no han adjuntado datos. El marco de plantación tanto de los ensayos como del banco clonal fue de 3x3 m.

A.I.3.2. Descripción y croquis de los ensayos

En los croquis, las parcelas que aparecen en negrita son las que en el año 1999 estaban vacías. Habría que actualizar y revisar los croquis.

A.I.2.1.1. Ensayo “Cueva del Monje”

Este ensayo se encuentra en el paraje denominado como “Cueva del Monje” situado a una altitud de 1400 metros. Parcela rectangular, siguiendo la curva de nivel, con orientación norte.

Se midió la altura aprox., mediante simetrías midiendo la altura a la primera rama viva y perímetro de tres de los árboles:

Árbol	Altura aprox. (m)	Perímetro (m)	Diámetro (cm)
1CV	7.75	0.58	18.5
2CV	7.55	0.71	22.6
3CV	7.50	0.60	19.1

En la primera imagen se aprecian los árboles medidos y en las otras dos marras en el centro de la parcela y el otro lado de la parcela. No se aprecian árboles bifurcados.

¡¡OJO!! Habría que comprobar de qué clones tenemos muestra, puede que algunos se hayan perdido. Crecimientos desiguales al haber clareado dentro del ensayo para eliminar árboles muertos y afectados por plagas hace 4-5 años, no se han realizado podas, solo poda natural. En las imágenes de la Figura A.2.1. se pueden observar imágenes de dentro de la parcela de ensayo.

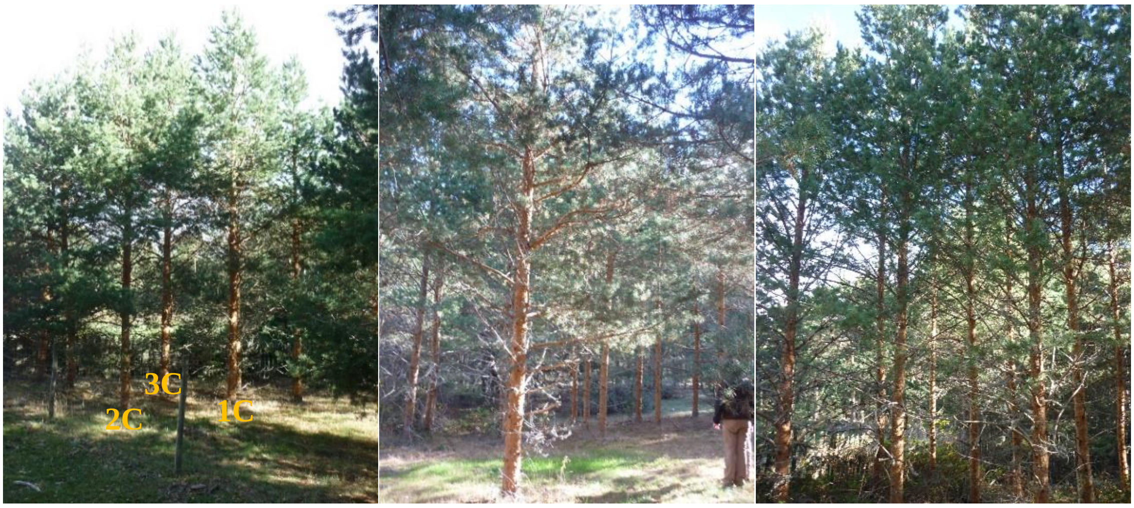

Figura A.2.1. Imágenes del interior de la parcela de ensayo de Cueva del Monje

Este ensayo haría falta muestrearlo de nuevo ya que hay la mitad de los pies que aparecen en el croquis, sobre todo por la parte central, debido a un ataque fuerte de plaga que obligó a su corta, habría que muestrearlo bien previamente para cerciorarse de cuales quedan y cuales no. El vivero de la Cueva del Monje está vacío en la actualidad. En la Figura A.2.2. se puede observar el último croquis actualizado disponible.

69	32	32	56	72	66	64	68
69	32	32	56	72	20	64	68
69	46	32	56	72	20	64	**68**
69	46	40	56	72	20	66	68
69	46	40	40	72	20	66	68
46	46	40	40	56	20	66	64
						66	64

Vivero de la Cueva del Monje

Figura A.2.2. Croquis del ensayo de Cueva del Monje

A.I.2.1.2. Ensayo "Pradorredondillo"

Este ensayo se encuentra en el paraje denominado como "Pradorredondillo" situado a una altitud de 1550 metros. Parcela más o menos cuadrada, siguiendo el borde de la carretera, con orientación norte.

Se midió la altura aprox., mediante simetrías midiendo la altura a la primera rama viva y perímetro de tres de los árboles:

Árbol	Altura aprox. (m)	Perímetro (m)	Diámetro (cm)
1PR	7.60	0.64	20.4
2PR	7.50	0.61	19.4
3PR	7.45	0.63	20.1

En la primera imagen se aprecian los árboles medidos y en las otras lo que se observa desde dentro de la parcela. No se aprecian árboles bifurcados. Presencia de brinzales de procedencia del árbol plus (muy bueno si se quieren hacer ensayos comparativos, aunque no sean genéticamente iguales)

¡¡OJO!! No poseo el croquis del ensayo, habría que comprobar de qué clones tenemos muestra y pedir el croquis. También sería bueno saber de qué árbol plus hay brinzales y cuantos injertos hay de ese árbol plus. Se realizaron podas a 1.8 metros hace 4-5 años (2010-2011, haría falta comprobarlo). En las imágenes de la Figura A.2.3. se pueden observar imágenes de dentro de la parcela de ensayo.

Figura A.2.3. Imágenes del ensayo de Pradorredondillo

No se dispone de croquis, pero me comentaron que existía.

A.I.2.1.3. Ensayo “Vaquerizas”

Este ensayo se encuentra en el paraje denominado como “Vaquerizas” situado a una altitud de 1500 metros. Parcela rectangular, aunque los árboles injertados solo se sitúan en el borde siguiendo el borde sur y este, con orientación norte.

Se midió la altura aprox., mediante simetrías midiendo a 2 metros sobre el tronco y perímetro de dos de los árboles:

Árbol	Altura aprox. (m)	Perímetro (m)	Diámetro (cm)
1V	9.95	0.77	24.5
2V	9.90	0.84	26.7

En la primera imagen se aprecia el borde de árboles injertados, aquí el suelo es más profundo y mejor por lo que los crecimientos son mayores que en los anteriores ensayos. En la otra se observa desde dentro de la parcela la línea de árboles injertados. El interior son brinzales procedentes de árboles plus que se han dejado crecer libremente. No se aprecian árboles bifurcados.

Se han cortado muy pocos, hay seguro de todos los clones. Se realizaron podas a 4 metros, aproximadamente, este mismo año (2015). En las imágenes de la Figura A.2.4. se pueden observar imágenes de dentro de la parcela de ensayo.

Figura A.2.4. Imágenes de la parcela de ensayo Vaquerizas

Falta algún árbol más, pero es más o menos exacto, así a ojo en un reconocimiento rápido. En la Figura A.2.5. se puede observar el último croquis actualizado disponible.

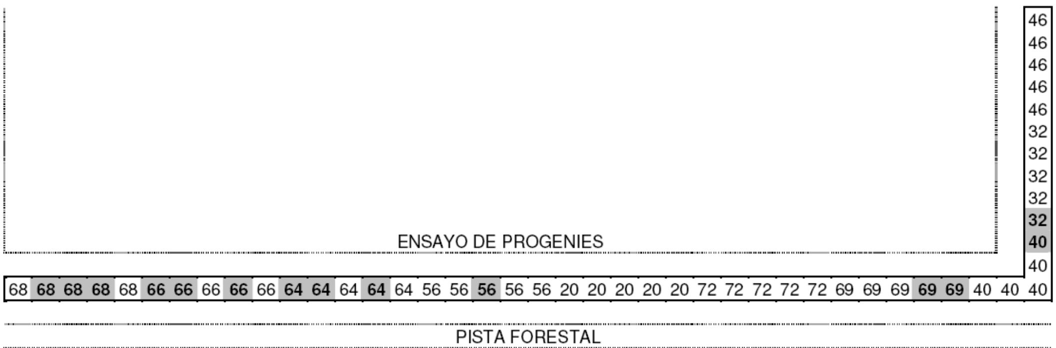

Figura A.2.5. Croquis de la parcela de ensayo Vaquerizas

A.I.2.1.4. Ensayo “Convento de Casarás”

Este ensayo se encuentra en el paraje denominado como “Convento Casarás” situado a una altitud de 1700 metros. Parcela rectangular, con orientación norte.

Se midió la altura aprox., mediante simetrías midiendo a 2 metros sobre el tronco y perímetro de dos de los árboles:

Árbol	Altura aprox. (m)	Perímetro (m)	Diámetro (cm)
1CC	5.45	0.40	12.7
2CC	5.15	0.35	11.1

En la primera imagen se aprecian los árboles injertados, aquí el suelo es muy pedregoso de peor calidad, están a mayor altitud, más expuesto, por lo que los árboles son más pequeños. En otras se observan desde dentro de la parcela los árboles injertados y algunos huecos de marras en los ensayos. Se aprecia un árbol bifurcado.

Se han perdido algunos pies, parece que pueda haber de todos los clones. No se han realizado podas. En las imágenes de la Figura A.2.6. se pueden observar imágenes de dentro de la parcela de ensayo.

Figura A.2.6. Imágenes de la parcela de ensayo de Convento de Casarás

Respecto al croquis, al igual que en anterior, falta algún árbol más, pero es más o menos exacto así en un reconocimiento rápido, a ojo. En la Figura A.2.7. se puede observar el último croquis actualizado disponible.

64		**56**	72	66	66	20	**20**	32
64		56	**72**	66	66	20	69	32
64	68	56	**72**	46	66	20	**69**	**32**
64	68	56	72	46	40	20	69	32
64	68	**56**	46	46	**40**	**40**	69	**32**
68	**68**	**72**	**46**		**40**	**40**	**69**	

Figura A.2.7. Croquis de la parcela de ensayo Convento de Casarás

A.I.3.3. Localización en el monte

Planos obtenidos usando la base del IGN, topográfica y ortofoto. Sistema de coordenadas proyectadas ETRS89 UTM Zona 30N. Hoja del mapa topográfico nacional 50: 483 (18-19) de Segovia y 508 (18-20) de Cercedilla (PNOA cedido por el Instituto Geográfico Nacional de España).

Las Figuras A.2.9. y A.2.10. muestran sobre mapa topográfico y ortofoto la localización general de las parcelas. Las Figuras A.2.11., A.2.12., A.2.13. y A.2.14. muestran con detalle la localización forma y tamaño de las parcelas. Las Figuras A.2.12. y A.2.13. están tomadas a la misma escala.

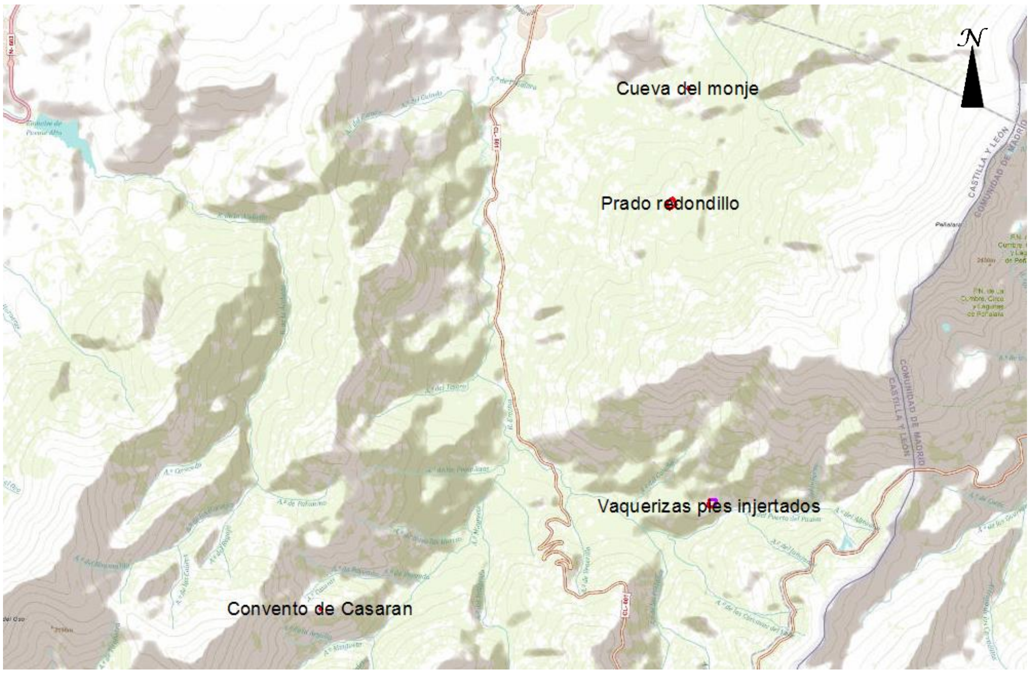

Figura A.2.8. Plano topográfico general con la localización de las parcelas.

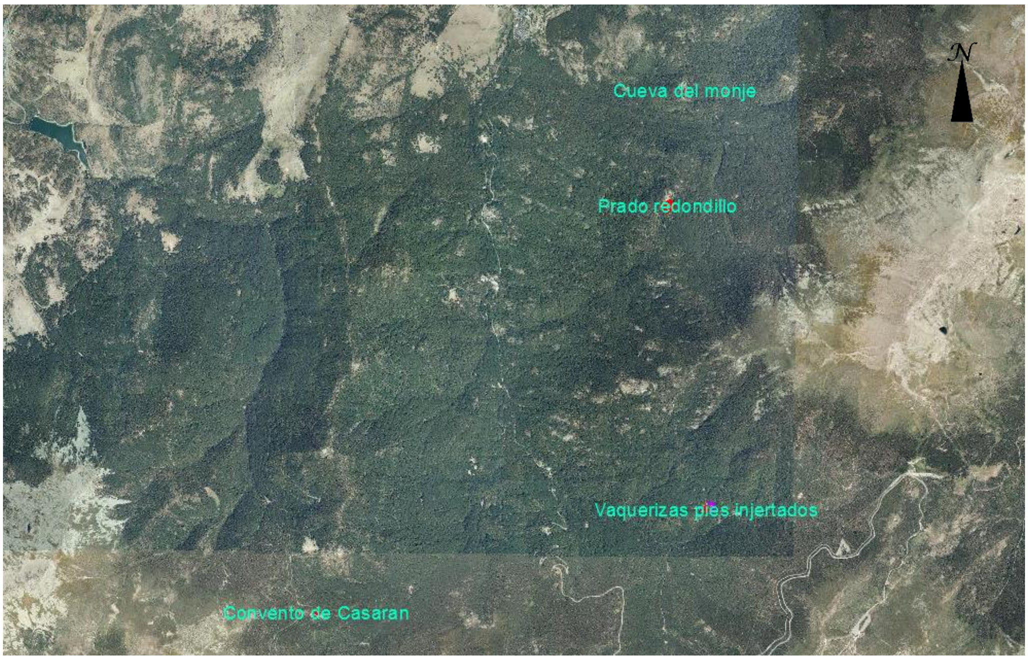

Figura A.2.9. Ortoimagen con la localización de las parcelas.

Figura A.2.10. Imagen de detalle, Ensayo de altitud Cueva del monje.

Figura A.2.11. Imagen de detalle, Pradorredondillo.

Figura A.2.12. Imagen de detalle, Ensayo de altitud Vaquerizas

Figura A.2.13 Imagen de detalle, Ensayo de altitud Convento de Casarás

A.I.3: South Africa secondment (778322-CARE4C H2020)

Main achievements:

Following the work plan defined previously for this secondment, three main activities were developed during it. Two of the activities took place on the CARE4C pine plots in Jonkershoek, the third one in Diepwalle Forest, a rain forest next to Knysna.

- Collecting data for investigating growth and wood quality of 60 trees in total, 30 suppressed and 30 dominant pine trees (*Pinus radiata* D. Don.) on the plots in Jonkershoek (**Topic 1**)
- Preparing the thinning experiment in Jonkershoek (measuring all diameters and installing more than 100 dendrometers) (**Topic 2**)
- Collecting data for an experiment, which analyses the occupation of gaps of different tree species depending on the gap size in one of the remaining natural rain forests in South Africa (**Topic 3**)

A.I.3.1. Topic 1

The selection of 60 trees was already done by Deon Malherbe (Figure A.3.1.) and Hugo Lambrechts, i.e. 30 dominant ones (social class 1 or 2) and 30 subdominant ones (social class 3 or 4). The trees were distributed over the whole area of the experimental plots and parcels in order to get average conditions and independent samples. The trees represent normal trees, normal density conditions, e.g. are not forked or stand at borders, edges etc. The sample tree and its nearest 5-6 neighbours represent the bio-group, which were measured before the sample tree was felled.

Figure A.3.1. Deon Malherbe on the experimental plot in Jonkershoek

The sample trees were measured regarding stem diameter at breast height, tree height, height to the crown base and crown radii in 8 directions. The next 5-6 closest neighbors were measured regarding distance from sample tree foot to foot of neighbor, and tree diameter of the neighbor.

The sample trees were felled carefully to get them unbroken onto the ground (Figure A.3.8.). This is important for taking of stem slices and stem segments for wood quality analyses.

Then, stem discs (thickness 3-5 cm) were obtained from the stem at the foot of the stem, at 1.30 m, 2 m and above this height every 2 m till the tip of the stem (see trees reconstruction in Figure A.3.6.), plus a 40 cm billet free of knots (Figure A.3.2.). The underside of the disc was marked with the tree number, the height of extraction (e.g. 0 m, 1.30 m, etc.) and the north direction.

Figure A.3.2. Discs and billet obtained from a tree

The material was transported to the university in Stellenbosch for further analysis (Figure A.3.3.).

Figure A.3.3. Transport of billets and stem discs from Jonkershoek to the university in Stellenbosch by car

There, the surface of each disc was planned in order to identify the year rings. The year ring width (annual radial increment) was measured in four directions on every disc (Figure A.3.5.). Also, a longitudinal section of "stem-bullets" of each tree, produced from the measurement of all discs can be seen in Figure A.3.6. In Figure A.3.4. it can be observed the tree discs obtained in the laboratory once measured for checking abnormal and data validation.

Figure A.3.4. More than 400 stem discs of 60 trees were analyzed

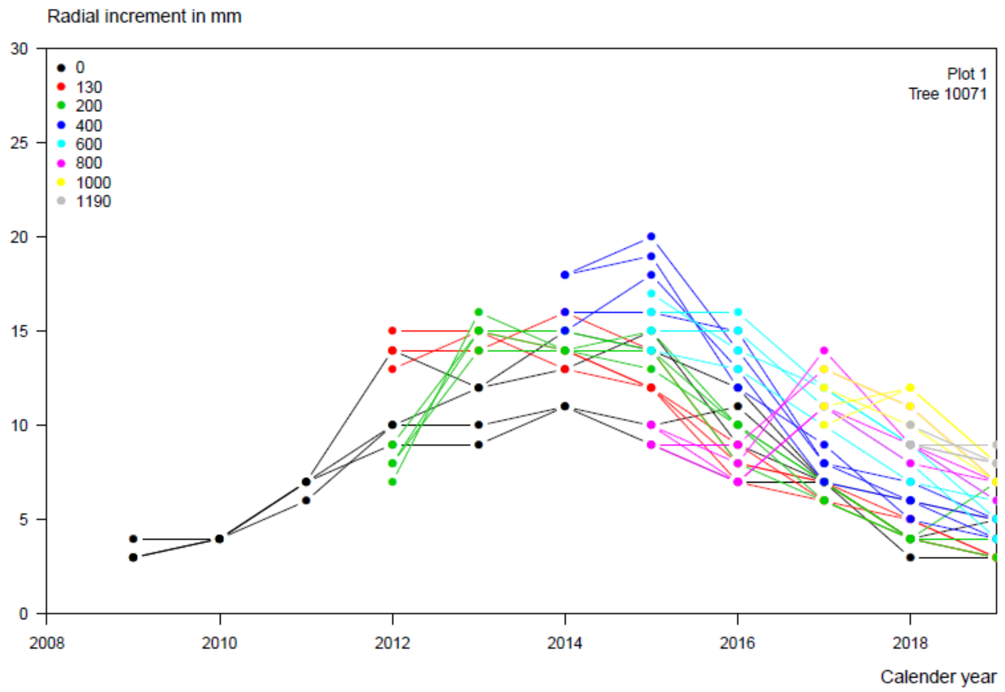

Figure A.3.5 Four annual radial increments measured on each stem disc, per tree measured at different heights

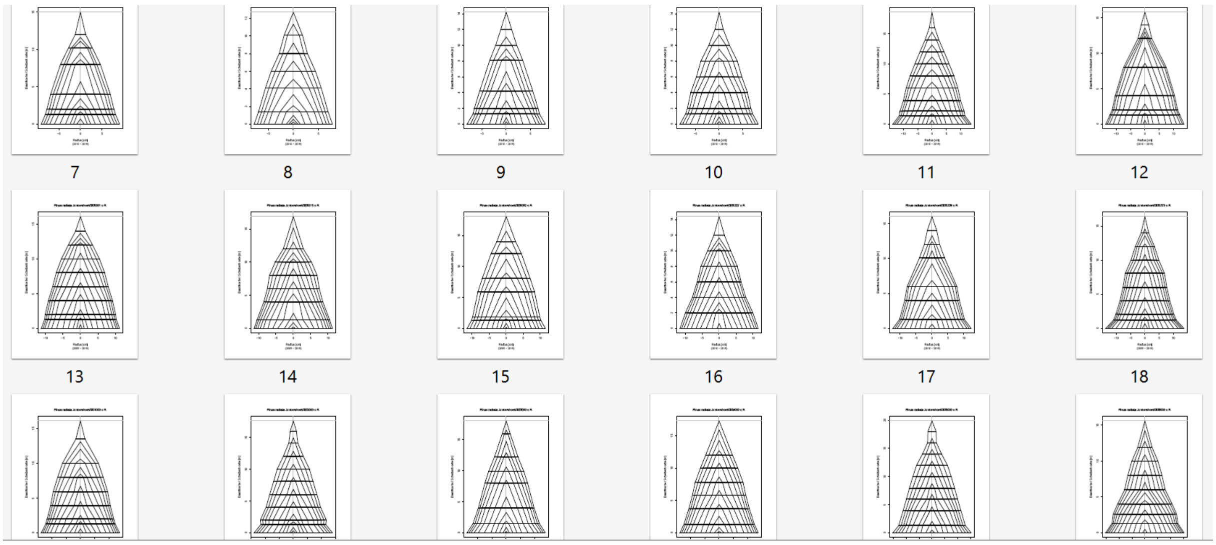

Figure A.3.6. Some longitudinal section of "stem-bullets" produced from the measurement of all discs per tree

Finally, a first attempt was made in order to measure dynamic MOE on the billets by means of the handheld Brookhuis MTG. In Figure A.3.7. it can be seen some of the samples analyzed.

Figure A.3.7. Small sample of all the billets extracted for analyzing wood quality

A.I.3.2. Topic 2

The thinning intervention took place end of February 2019 (Figure A.3.8.). Three different treatments were done: no thinning (untreated), thinning from below and thinning from above.

Figure A.3.8. Thinning took place in February 2019

This new established experiment includes 9 different plots, 3 plots for each treatment and three repetitions. The stand age was 13 years and no other thinning was done in past. Initial stand density accounts for 943 trees per ha and a basal area (BA) of 25.8 m^2 per ha. On the plots where a thinning from above was applied stand density was reduced to approx. 627 trees per ha, and a BA of 18.2 m^2 per ha and with the thinning from below

452 trees per ha and a BA of 18.4. This was done so the BA of both thinning types remained the same. Immediately after thinning, diameters at breast height of all remaining trees were measured. In addition, over 100 dendrometers were installed (Figure A.3.9.).

Figure A.3.9. A new installed dendrometer on one of more than 100 trees

The trees in which the dendrometers where placed, where selected to represent the entire diameter distribution of the plots (when possible) in 5 classes (Figure A.3.10.). Two dendrometers per class were installed plus, if available, another class above and below those 5 classes to see how diameter growth is induced after the thinning on the different classes.

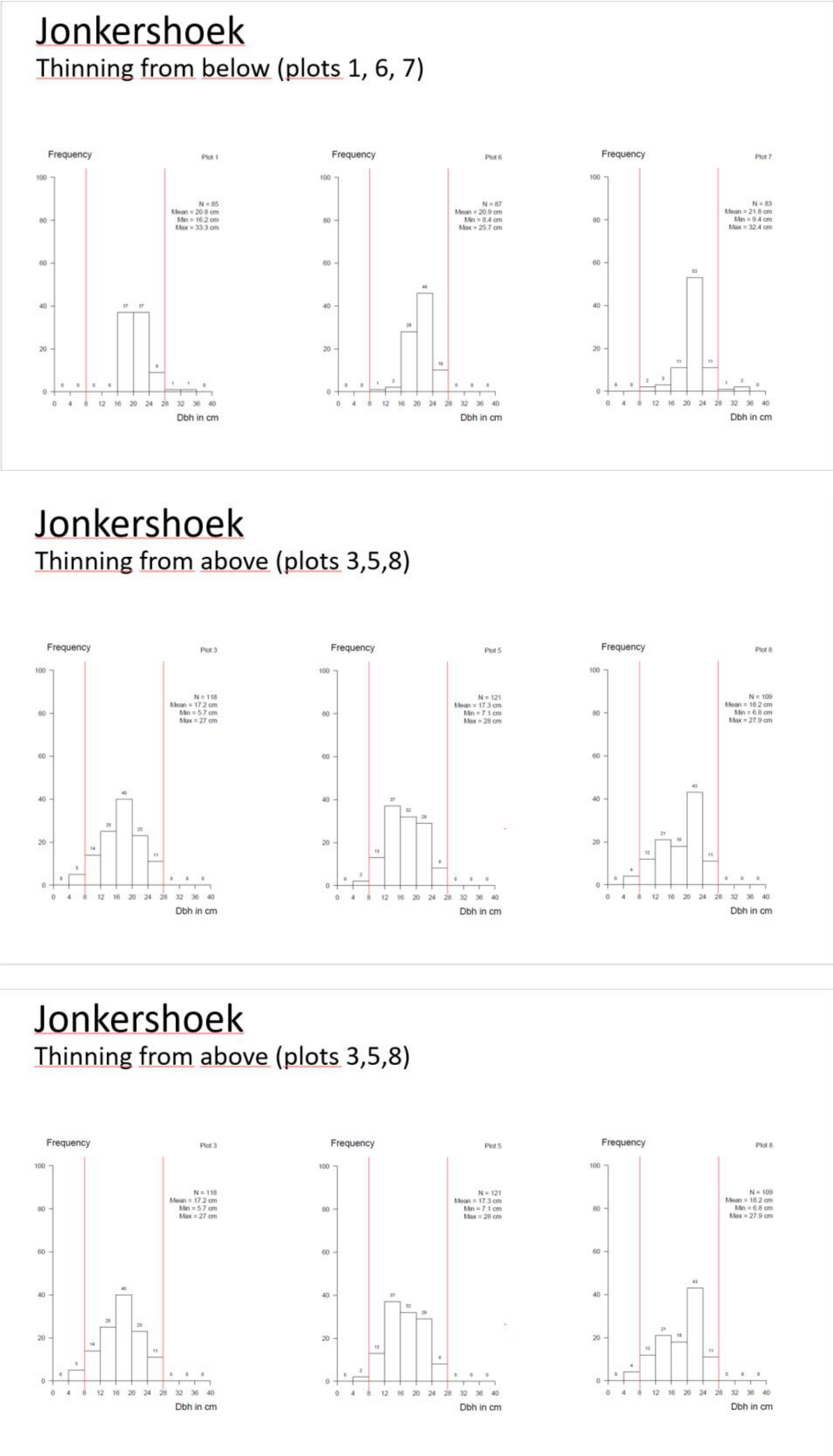

Figure A.3.10. Dbh-distribution of all trees of the 9 plots after thinning in February

It was decided, that at least before the rain period arrived, the dendrometers were going to be read once per month to account for the diametric growth per month. A first measurement of all dendrometers was taken the 9th of April.

A.I.3.3. Topic 3

The last topic is related to afromontane forests growth at a specific site and climatic conditions in South Africa (Figure A.3.11.). They represent a substantial portion of South African natural forest biomes, which in total are few in terms of area. In former times, they have been intensively exploited but are mainly protected now and used only extensively. The forest are quite diverse concerning tree species and species functional traits resulting in a high structural diversity. In the absence of fire, gap dynamic is the main driver of forest development and regeneration. Analyzing tree species-specific growth reaction on temporal higher resource supply, in particular light, helps to understand the natural dynamics of growth and regeneration. The knowledge contributes to keep the forest type sustainable from a conservational point of view, but also allows developing management approaches that aim a continuous cover forestry.

The research on gap dynamics will contribute to the sustainable management of the temperate and subtropical rain forests in South Africa. The focus is on the forest structure and growth in and around gaps, which serve both, the utilization and natural regeneration of close-to-nature forests.

Figure A.3.11. Rain forest in Diepwalle, Knysna

The work is a cooperation project between TUM, the Department of Forest and Wood Science of the Stellenbosch University/SA and SANParks at Knysna and Tsitsikamma National Park and is embedded in the EU-project CARE4C (GA778322).

Together with Andreas Rais, we helped Graham Durrheim (National Park) and Anna Schätzl (master student from TUM) for three days to gather data from an experiment based on gaps dynamics. The border trees of these gaps were used to study the growth reaction to competition release on canopy trees. Diameter and distance from the center were measured for all the border trees by means of a Vertex and a diameter measuring tape. Using a relascope, the stand basal area of six boarder trees was measured as well to be able to describe the competition. Of those six trees, on three of them the diameter distribution of the selected trees by the relascope where measured.