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PROGRAMA DE DOCTORADO EN CONSERVACION Y USO SOSTENIBLE DE SISTEMAS FORESTALES

TESIS DOCTORAL:

USE OF TERRESTRIAL LASER SCANNING (TLS) ON CROWN AND STEM MEASUREMNTENS IN THE SURVEY AND MONITORING OF MIXED FORESTS

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Doctora por la Universidad de Valladolid

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LIST OF ACRONYMS

AIC	Akaike Information Criterion
Asym	Asymmetry of the crown
BA	Basal Area (m^2/ha)
BAL	Basal Area of Largest trees (m^2/ha)
C.I.	Hegyi Index
CBH	Crown at Breast Height (m)
CPA	Crown Projection Area (m^2)
CV	Crown Volume (m^3)
CCC	Lin’s Concordance Correlation Coefficient
DBH	Diameter Breast Height (cm)
M.A.S.L.	meters above sea level
MCWH	Maximum Crown Width Height (m)
TH	Total Height (m)
TLS	Terrestrial Laser Scanning

ABSTRACT

Within the context of the climate crisis, good knowledge of our forests is needed so that we can manage them sustainably in order to keep forests more productive and, more importantly, to keep them resilient and strong. Within this concern, mixed forests seem to be our great allies. However, due to the complex structure of this kind of forest, measuring and evaluating the interaction of species with conventional measurement techniques through tools such as calipers and hypsometers is difficult to do – leading too much of the interactions in these forests being still largely unknown. However, thanks to advancements in science and technology, we can now count on devices such as Terrestrial Laser Scanners (TLS), which can make a faithful reproduction of reality in Three-Dimensions (3D), allowing us to study the forest from our computers. In the last decades, many studies have emerged focusing on the understanding of mixed forest structures, proving more studies are needed to be able to conclude a sound theory as each species seem to interact differently from each other.

How tree species interact with each other can be quantified by the crown of the tree. For this reason in this study, we have analyzed the crown morphology of *Pinus sylvestris* together with two oak species (*Quercus petraea* and *Quercus pyrenaica*) in two locations in northern Spain. Different methodologies were applied to process TLS data, ending in a semiautomatic method thanks to the development in R software of an algorithm that identifies trees as clusters. We have obtained 10 variables for each tree from TLS data, classified as response and explanatory variables. For the mixture *Pinus sylvestris-Quercus petraea* a total of 193 pines and 257 oaks were analyzed and for the mixture *Pinus sylvestris-Quercus pyrenaica* 49 pines and 38 oaks. For the first mixture, we have fitted four crown variables: Maximum Crown Width (MCWH), Crown at Base Height (CBH), Crown Projection Area (CPA), and Crown Volume (CV). The explanatory variables for the models were classified in size, density, competition, and mixture, and each tree was analyzed within three radii of influence (5, 7.5, and 10m) as opposed to the traditional method of differentiation between pure and mixed stands. Thus, we can quantify inter and intra-specific competition of species. For the second mixture (*Pinus sylvestris-Quercus pyrenaica)*, firstly we analyzed how robust our fitted models for *Pinus sylvestris-Quercus petraea* mixture was, and then compared the models. We conducted three analyses, the first one where we utilized the models already developed and tested in the second mixture, the second analysis where we adjusted the coefficients of the models for this second mixture, and the third analysis, where we developed completely new models specifically for this second mixture. Finally, we analyzed wood quality using the Lean and the Sweep of the trunk in the mixture of *Pinus sylvestris - Quercus petraea* as response variables. The model selection was done through the AIC index and the residual analysis of the top 5 models with the lower AIC Index.

Our results have shown us when growing in mixed conditions, pines tend to have larger trunks with narrower and shorter crowns, and oaks tend to remain under a pine canopy with wider and larger crowns and no preference for a radius of influence has been demonstrated. Nevertheless, it was proven that it is necessary to fit models for each specific mixture, as the comparison between models (AIC index) clearly showed, that data was better explained through the mixture-specific models. Regarding the analysis of wood quality, our fitted models showed Lean is a characteristic of the trees affected by the density and competition within the forests , but Sweep was only affected by the size of the tree and asymmetry of the crown, suggesting it is an intrinsic feature of each tree regardless the forest composition.

This study has analyzed the inter and intra-specific competition of three species widely distributed within the Iberian peninsula. The results represent comprehensive insights to provide management guidelines for the use and adaptation of mixed forests in the frame of climate change.

RESUMEN

En el marco de la crisis climática es necesario tener un buen conocimiento de nuestros bosques, para así, poder realizar una gestión sostenible de los mismos al tiempo que conseguimos que sean más productivos, pero sobre todo, más resilientes y resistentes. En este respecto los bosques mixtos parecen ser nuestros grandes aliados. Sin embargo, la forma en que las especies interactúan entre sí es muy desconocida debido a la compleja estructura que presenta este tipo de bosques, que los hace difíciles de medir y evaluar con las técnicas de medición convencionales como la forcípula y el hipsómetro. Gracias al avance de la ciencia y la tecnología, ahora contamos con dispositivos como el escáner Láser, conocido por sus siglas en inglés TLS, que es capaz de hacer una reproducción fidedigna de la realidad en tres dimensiones (3D), por lo que podemos estudiar el bosque desde nuestros ordenadores. En las últimas décadas han surgido muchos estudios centrados en la comprensión de las estructuras de los bosques mixtos demostrando que se necesitan más estudios para poder tener una teoría sólida del manejo de los mismos ya que cada especie parece tener un comportamiento diferente en compañía de otras especies.

La interacción de las especies arbóreas entre sí se puede cuantificar gracias a la copa. Por esta razón en este estudio hemos analizado la morfología de la copa de *Pinus sylvestris* junto con dos especies de roble (*Quercus petraea* y *Quercus pyrenaica*) en dos localidades del norte de España. Se han aplicado diferentes metodologías para procesar los datos TLS. Finalmente hemos trabajado con un método semiautomático gracias al desarrollo de un algoritmo en el software R que identifica los árboles como clusters. Hemos obtenido 10 variables para cada árbol a partir de los datos del TLS, clasificadas como variables de respuesta y explicativas. Para la mezcla *Pinus sylvestris-Quercus petraea* se han analizado un total de 193 pinos y 257 robles y para la mezcla *Pinus sylvestris-Quercus pyrenaica* 49 pinos y 38 robles. Para la primera mezcla, hemos ajustado cuatro variables de copa: Anchura máxima de la copa (MCWH), altura de la copa en la base (CBH), área de proyección de la copa (CPA) y volumen de la copa (CV). Las variables explicativas de los modelos se clasificaron en tamaño, densidad, competencia y mezcla y cada árbol se analizó dentro de tres radios de influencia (5, 7,5 y 10 m), a diferencia del tradicional método de diferenciar entre rodales puros y mixtos. De este modo, hemos podido cuantificar la competencia inter e intraespecífica de las especies. Para la segunda mezcla (*Pinus sylvestris-Quercus pyrenaica*), primero hemos analizado la robustez de nuestros modelos ajustados para la mezcla *Pinus sylvestris-Quercus petraea* y luego hemos comparado los modelos. Llevamos a cabo tres análisis, el primero donde utilizamos los modelos ya desarrollados, probándolos en la segunda mezcla; el segundo análisis donde ajustamos los coeficientes de los modelos para esta segunda mezcla; y el tercer análisis, donde desarrollamos modelos completamente nuevos

específicamente para esta segunda mezcla. Finalmente analizamos la calidad de la madera utilizando como variables de respuesta la inclinación (lean) y el retorcimiento (Sweep) del tronco en la mezcla de *Pinus sylvestris - Quercus petraea*. El modelo de selección se realizó a través del índice AIC y el análisis residual de los 5 mejores modelos con el menor índice AIC.

Nuestros resultados nos han mostrado que cuando crecen en condiciones mixtas, los pinos tienden a tener troncos más grandes con copas más estrechas y cortas y los robles tienden a permanecer bajo el dosel arbóreo de los pinos con copas más anchas y grandes. Respecto al radio de influencia, no quedó demostrada ninguna preferencia clara. Sin embargo, se demostró que es necesario ajustar modelos para cada mezcla específica, ya que la comparación entre modelos (índice AIC) reveló claramente que los datos se explicaban mejor a través de los modelos específicos de la mezcla. En cuanto al análisis de la calidad de la madera, nuestros modelos ajustados mostraron que es una característica que afecta a los árboles según crecen en más o menos densidad y con más o menos competencia, pero el retorcimiento del tronco sólo se vio afectado por el tamaño del árbol y la asimetría de la copa, lo que sugiere que es una característica intrínseca de cada árbol independientemente de la composición de la masa forestal.

Este estudio ha analizado la competencia intra e interespecífica de tres especies ampliamente distribuidas en la península ibérica. Los resultados representan una información exhaustiva que proporciona directrices de gestión para el uso y la adaptación de los bosques mixtos en el marco del cambio climático.

INTRODUCTION

The present state of forests

Within the last decade, the concern about the effects on Earth due to Climate Crisis has been increasing as it is already stressing food and forestry systems, directly impacting, among others, human health, ecosystem functioning, and forest structure (Pörtner et al., 2022). For this reason, forests have received substantial political attention within the last COP26, since it is well known that forests can adapt to climate change, and thus, they are critically important to mitigate and conserve biodiversity (Vähänen, 2021) as they are well recognized to be one of our principal resources to obtain climate neutrality by 2050 (Lier et al., 2022). Nevertheless, maladaptation has been observed across many regions and systems and occurs for many reasons including inadequate knowledge and short-term policies (Pörtner et al., 2022).

Forests also provide goods and ecosystem services (provisioning, regulating, and cultural) from plantations or cultivated forests (Pretzsch & Forrester, 2017; Uhl et al., 2015). Trends suggest social conscience of consuming products from sustainably managed forests is increasing (Europe, 2011). Based on this, management that is solely focused on wood production homogeneously throughout a plantation may miss opportunities to provide other ecosystem services (Himes & Puettmann, 2019) causing economic losses, as has already been experienced in Europe within the last 50 years, where the forests were impacted by extreme heat and drought impacting timber sales for example in Europe (Pörtner et al., 2022). For that reason, understanding forest composition, structure, and functioning within a frame of climate change, is crucial to ensure ecosystem services to our society (Muñoz-Gálvez et al., 2021).

Shifts in the temperature-precipitation domain that many species experienced during the last decade are likely to increase under a warmer and drier climate, and this may lead to directional, large-scale changes in forest composition (Hartmann et al., 2022) as forests are dependent on different abiotic factors (Bohn et al., 2014). Climate change scenarios project a worrisome increase of 2–5 ◦C in the 21st century coupled with a decrease in precipitation of up to 30%, and a higher frequency and intensity of extreme drought events (Muñoz-Gálvez et al., 2021). As an example, it is expected that, in the temperate zones, even in compliance with the Paris agreements (UNFCCC, 2015), forest productivity is estimated to drop by 23%, assuming forest management and composition are the same as we have nowadays (Bohn, 2021).

Therefore, there is an urgent need for adequate management strategies to enhance long-term forest resilience (Muñoz-Gálvez et al., 2021) as temperature changes could turn forests into carbon sinks or carbon sources (Bohn et al., 2014) without the proper management. For that reason, the objectives marked by the new European Union (EU) forest strategy for 2030 are focused on improving the quantity and quality of EU forests and strengthening their protection, restoration and resilience.

The Importance of Mixed forests

Forests cover almost one-third of the Earth's land surface (Vähänen, 2021). Around 4% of these forests are undisturbed by human activity, while 29% of the managed forests are monocultures and 51% contain two or three species. In Europe, these mixed forests cover 23% of the pan-European region (UNECE & FAO, 2011).

Under potential global warming effects, forest research has experimented with a shift from mono-specific to more complex forest stands e.g. Aldea, 2018; Bravo-Oviedo et al., 2014; Bravo et al., 2021; Cattaneo et al., 2020; del Río et al., 2018, 2019; Merlin et al., 2015; Pretzsch & Schütze, 2021; Riofrio, 2018), not only because several studies have proved high biodiversity level is linked to mixed forests with high forests productivity (Bayer, Seifert, & Pretzsch, 2013; Forrester & Bauhus, 2016; Liang et al., 2016; Pretzsch & Forrester, 2017) compared to monocultures (Pretzsch & Schütze, 2014; Riofrío et al., 2017), but also because these stands present some advantages over monospecific ones concerning ecological functions and services (Forrester, 2017; Pretzsch & Forrester, 2017), showing to be more resilient, resistant, and recover faster from storms (Bravo et al., 2021; Pretzsch et al., 2017). Most recently, Rodríguez De Prado et al.(2022), proved, as well, that growth rates for mixed stands were higher than in pure stands. However, there is a need for more data and understanding to identify whether these observations represent a global trend (Hartmann et al., 2022; Heym et al., 2017), since different tree species compositions with different growth rates and final heights will likely develop more structurally diverse forests than those composed of only one or few species (Pretzsch & Forrester, 2017). As an example of this complexity, it is even difficult to reconcile all points of view and to describe mixed forests in a single definition (Bravo-Oviedo et al., 2014), because the understanding of tree species interaction in their structure and functioning is still poor (Pretzsch, 2014). Considering that mixed forest dynamics vary on a small scale (Metz et al., 2013) more studies are still needed across a variety of forest types to establish a sound theoretical approach across scales (Uzquiano et al., 2021).

Models and TLS

To fully understand forest dynamics, especially in mixed forests, we need models that incorporate essential aspects such as emergent properties, multiple and multi-scale interactions or spatial, functional, and structural variability (Bravo et al., 2019), because it is well known in natural science that structures determine processes and that processes in return modify structures (Pommerening & Grabarnik, 2019). Diameter at Breast Height (DBH) and Total Tree Height (TH) are the two most common and easy variables for measuring, analyzing, and modeling forest stands (Pretzsch, 2009, Chapter 7). They are used separately or together in addition to tree species for estimating other important single-tree attributes such as the cross-sectional area, stem volume, or biomass (Luoma et al., 2019).

Data of forest ecosystems are not only temporal but also spatial (Pommerening & Grabarnik, 2019). For this reason, Spatial systems analysis of forest ecosystems is therefore an important branch of ecological statistics integrating research on forest structure, sampling, monitoring, and modeling (Bravo et al., 2019; Pommerening & Grabarnik, 2019). However, the main limitation forestry models have traditionally dealt with is the reconstruction of spatial forest structure as they are usually based on approximations of the forest structure leading to large errors (Dassot et al., 2011), very hard to validate, and difficult to compare across other forest structures (Disney et al., 2018). In addition, forestry models ignore the three-dimensional nature of stand structure, its most important characteristic (Pretzsch, 2009, Chapter 7). Historically, in structure research, often, the necessary methods have been developed within the framework of mathematical statistics (Pommerening & Grabarnik, 2019). Nowadays, thanks to technological advances, this has enormously improved (Bravo et al., 2019)

Terrestrial Laser Scanning (TLS) provides us with an accurate tree structure representation, enabling us to obtain detailed information at the tree or plot scales (Dassot et al., 2011). For this reason, TLS has become the main forest strategy to understand forest dynamics through its structure, which becomes even more complex in mixed forests (McElhinny et al., 2005). Since its implementation in forestry science, many authors have developed different studies based on mixed forest structures (e.g. (Martin-Ducup et al., 2016; Pretzsch & Zenner, 2017; Seidel et al., 2011; Wei et al., 2016) as species identity modifies the mixture outcomes (Bravo et al., 2021). This is why it is so necessary to study all possible species mixtures to define an appropriate management strategy for each species composition (Bravo et al., 2021) based on accurate and numerical analyses.

The Crown information

The crowns of trees have been subjected to much less mensurational study (Hemery et al., 2005). However, as pointed out previously, due to the emerging society requirements, crowns are being further studied (e.g., Barbeito et al., 2017; Bicl-Sorlin & Bell, 2000; Fichtner et al., 2013; Hasenauer & Monserud, 1996; Zarnoch et al., 2004). The crown is a fundamental element of a tree, accomplishing multiple functions (W. Lin et al., 2017). For instance, crown size is closely related to the photosynthetic capacity of a tree (Hardiman et al., 2011; Hemery et al., 2005) and it may reflect the outcome of interspecific interactions (Seidel et al., 2011), looking to fully utilize limiting resources in different space and time (Bravo et al., 2021).

In a mixed stand the inter and intra-specific competition effect between trees is shown through the crown (Barbeito et al., 2017; Cattaneo et al., 2020; Lin et al., 2017). The tree structure is highly dependent on the species composition of the competitors, and it can vary considerably from one species to another (del Río et al., 2019; Pretzsch & Schütze, 2014), but have been barely studied due to the difficulty in measuring and defining them accurately, as they were defined through geometric forms. Thus, more efficient algorithms need to be developed to calculate tree crown variables to facilitate the forest resource survey. (Lin et al., 2017).

The wood quality: Lean and Sweep

the straightening capacity of the stem and its mechanical stability (Lean and sweep) are other key variables in forest trees related to light capture (Sierra-de-Grado et al., 2022). despite their importance to the timber industry, they have not been considered (Thies et al., 2004). By studying these measurements we will understand the trade-off with other functions that may imply differential resource allocation patterns (Sierra-de-Grado et al., 2022) so that future wood resources can be better utilized (Höwler et al., 2017).

Despite the necessity of study, the role of bark in the straightening process should be investigated in the longer term (Sierra-de-Grado et al., 2022). The information on inner wood quality is usually based on manipulative experiments at an early stage where data are not available before the trees are felled (Höwler et al., 2017) or they are based on subjective classification criteria, to avoid felling the tree (Thies et al., 2004). TLS allows to get around this problem and to obtain numerical measurements of wood quality such as the lean and the sweep of the stems objectively without felling the tree, thus, allowing longer-term experiments to understand how inter and intra-specific interaction acts on trees.

The development of wood quality models can be used to characterize the Lean and Sweep of tree species, which will help in understanding the cost-benefit balance of the adaptive growth of the tree (Thies et al., 2004) as well as understanding the different influences between neighboring trees.

Pinus sylvestris, Quercus petraea and *Quercus pyrenaica*

Determining how the variability is influenced by tree inter or intra-specific interaction status in different species is particularly important for tree allometry applications in forest practice and modeling (del Río et al., 2019). For this reason, several studies have focused on pine-pine mixtures in different regions of the Iberian Peninsula (Riofrio, 2018), and some others on Scots pine-oak mixtures (Aldea Mallo, 2018; del Río & Sterba, 2009). In both cases, it was established that mixed stands support a greater increase in volume per occupied area compared to monoculture suggesting a species interaction with reduced levels of competition in the former (Aldea Mallo, 2018; del Río & Sterba, 2009). In either case, results from studies focused on Scots pine are quite distinct, probably due to the large distribution area of the species with high variability in its response to climatic conditions (Del Río et al., 2017).

This research is focused on Scots pine (*Pinus sylvestris* L.*)*, Sessile oak (*Quercus petraea* (Matt.) Liebl.), and Pyrenean oak (*Quercus pyrenaica* Willd.) to get a bit more insight into the ecology of these species. In the Iberian Peninsula, low altitudes sites are mainly dominated by Quercus spp., while higher and colder areas are dominated by conifers (mainly Pinus spp.). (Muñoz-Gálvez et al., 2021). However, it is very common to find them mixed (Figures 1 and 2).

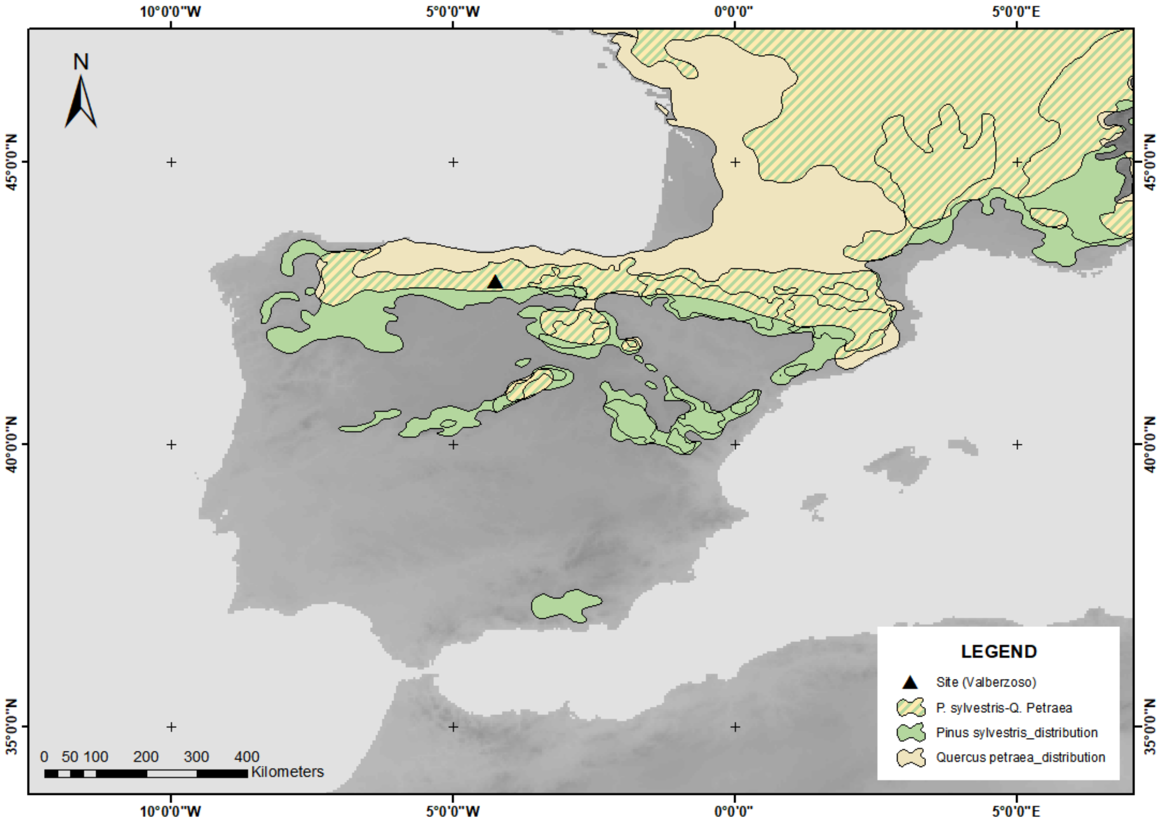


Figure 1. Area of distribution for *Pinus sylvestris*, *Quercus petraea,* and mixed forest stands of both species in Spain. The study site is marked by a black triangle.

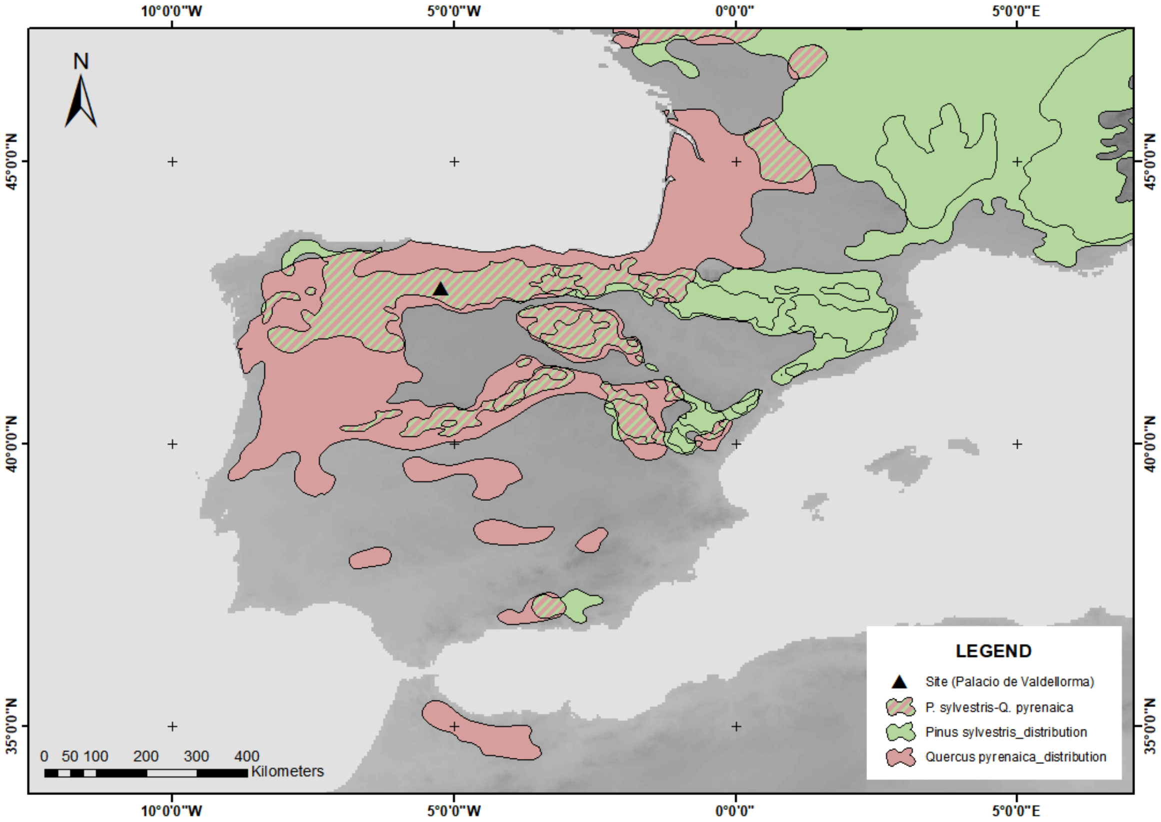


Figure 2. Area of distribution for Pinus sylvestris, Quercus pyrenaica, and mixed forest stands of both species in Spain. The study site is marked by a black triangle.

Pinus sylvestris is the most widely distributed pine species in the world (Riofrio, 2018; Vallet & Perot, 2018), the species with the biggest area extension in Europe (Aldea Mallo, 2018; Montero et al., 2008), and the species with a wide silviculture tradition due to its multiple functions as productive and protective species (Montero et al., 2008). In the Iberian Peninsula, Scots pine is mainly found in montane climates: 800-2000 m.a.s.l., 600-1200 mm mean annual precipitation, and summer precipitation above 100 mm (Montero et al., 2008) representing the southernmost distribution of this typical boreal species (Castro et al., 2004). It is a light-demanding pioneer species that can grow in half-light conditions (Riofrio, 2018). It has a deep root system with dominant oblique and long secondary roots that allow access to deeper soil horizons during drought (Hartmann et al., 2022).

Quercus petraea is widespread in the temperate zone at an altitude between 0 and 1500 or even at 1800 m.a.s.l (Reque, 2008) and is one of the most ecologically and economically important hardwood tree species in Central Europe (Arsić et al., 2021). It is characterized by having deep secondary branches and taproot (Reque, 2008). It has an important protector value as montane species, being the habitat of important animal species as *Ursus arctos arctos* (Clevenger et al., 1992; Reque, 2008; Ruiz-Villar et al., 2019) and is considered well adapted for future climate scenarios (Arsić et al., 2021) thanks to its broad ecological amplitude (Stimm et al., 2021).

Quercus pyrenaica is distributed throughout the western Atlantic Mediterranean regions: West France, Portugal, Spain, and North Morocco. In Spain, the largest area distribution of this species is located in Castilla y Leon, which occupies 67% of its natural distribution area. It is found in sub-humid and continental Mediterranean climates between 400-1600 m.a.s.l. with a mean annual precipitation of 600 mm. It has a powerful root system, a well-developed central axis, and numerous horizontal and superficial roots (J. A. Bravo et al., 2008). It has a short growing season, which may determine its distribution. Summer drought is one of its limiting factors, and it avoids the driest areas (Aldea Mallo, 2018). The Pyrenean oak forests have been widely managed as coppice with silvopastoral uses, such as firewood, livestock grazing, and charcoal. Finally, the changes in land use are making it important to establish a forest-based management production (Bravo et al., 2008) for this species.

Scots Pine and both oaks (Sessile oak and Pyrenean oak) usually establish spontaneous mixed stands where their natural distribution area is the same (Figure 1 and 2). Our study areas, like so many other areas of this type, are the result of forest management strategies during the second half of the twentieth century that included re-introducing pine into oak coppice stands as a method of forest restoration and to increase stand productivity (Aldea Mallo, 2018). However, the abandonment of traditional forest uses and the lack of subsequent management have resulted in structurally and functionally homogeneous dense stands, which are particularly vulnerable to climate change-associated disturbances (Fernández-de-Uña et al., 2015). In this kind of mixed stand, the successional processes are slower and wildlife biodiversity is reduced (Maestre & Cortina, 2004; Ruano et al., 2013). For this reason, the study and comprehension of mixed forests are crucial for their sustainable management.

Motivation of the study

TLS allows us to quantify the admixture effect that varies so much across sites and species (Muñoz-Gálvez et al., 2021). Recent studies related to the application of terrestrial 3D laser scanning systems in forestry focused on the measurement of the crown projection area and crown volume based on the point-cloud data; however, most studies used the laser scanning software only to process the data (W. Lin et al., 2017). Motivated by the still lack of scientific insights into specific advantages of mixed-species forest (Pretzsch & Forrester, 2017) and all the potential TLS can provide us, in this research, we have evaluated two widespread mixtures in Spain, *Pinus sylvestris – Quercus petraea* and *Pinus sylvestris – Quercus pyrenaica* where the complementarity or competition between species may cause overgrow one over the other (Pretzsch & Forrester, 2017) making proper management of these forests difficult. With TLS we can collect accurate data in a way that does not destroy the forest and that allows us to fit new models that take into account the interaction between species, which is a fundamental part of forest management planning to support decision-making (Janowiak et al., 2017; Luoma et al., 2019). The resulting models aim to quantify these two species' composition mixtures and thus, managers can anticipate potential future conditions (Janowiak et al., 2017). This will serve as a tool to support the most appropriate decision-making to be able to do sustainably use of these stands. At the same time, the quantification of these species compositions will also help the work of policymakers and other stakeholders involved in land management.

OBJECTIVES

General Objective

The main objective of this thesis is to determine how inter and intra-specific competition affects crown shape on the individual crown structure and wood quality in a mixed stand composed of *Pinus sylvestris – Quercus petraea* and *Pinus Sylvestris – Quercus pyrenaica* to gain insight on management of these forests.

Specific Objectives

1. **To obtain accurate crown and wood quality data through TLS**

   To characterize the crown and wood quality of every tree within the studied plots we used TLS. We firstly hypothesize that TLS techniques allow foresters to obtain high-quality information as traditional approaches do (e.g. through tools such as calipers and hypsometers). Thereafter, we developed several methods to obtain accurate and objective variables of the crown and the stem from TLS point clouds.

2. **Determine a good approach to study the inter and intra-specific competition**

   To determine the extent of influence of the surrounding trees around the target tree, we determined the three radii of influence (5, 7.5, and 10 m), thus we were able to analyze the density, competition, and mixture effect of the trees as a continuous variable.

3. **Expanding and fitting crown and wood quality models**

   To determine and quantify how species composition affects the crown shape of the trees, we selected crown models and expanded using explanatory variables of size, density, competition, and mixture and tested whether they had positive or negative relationships in their four crown variables (response variables): Maximum Crown Width Height (MCWH), Crown Base Height (CBH), Crown Projection Area (CPA), and Crown Volume (CV).

   We followed the same methodology for wood quality analysis, selecting the Lean and the Sweep of the stem as the response variables.

4. **To test the robustness of crown fitted models**

   To verify the robustness of the first models fitted for *Pinus sylvestris-Quercus petraea,* we conducted three analyses: (1) we applied the models to the data of the mixture *Pinus sylvestris-Quercus pyrenaica,* (2) we fitted the coefficient of the models for this second mixture, and (3) we fitted models specifically for our second mixture *Pinus sylvestris-Quercus pyrenaica.* We then compared all of them using residual analyses and the AIC index.

Graphical approach

The research activity of the thesis is shown in Figures 3 and 4 as a linear evolution. Figure 3 shows the first part of this thesis, which is the collection of data with both TLS and conventional methods, thus our TLS data can be validated. The second part of this figure shows the steps followed for the acquisition of data, which were classified into two groups: (1) Response variables: Maximum Crown Width Height (MCWH), Crown Base Height (CBH), Crown Projection area (CPA), and Crown Volume (CV), and (2) Explanatory Variables, which at the same time were classified in four groups: (1) Size – Diameter at Breast Height (DBH), Total Height (TH) and the square DBH by the TH (d^2h); (2) Density – Total Basal area (BA_{total}); (3) Competition – Total Basal Area of Largest trees (BAL_{total}), Hegyi Index (C.I.) and crown asymmetry (Asym), and (4) the mixture that was calculated based on the ratios of BA, BAL, and the number of pines surrounding the target trees.

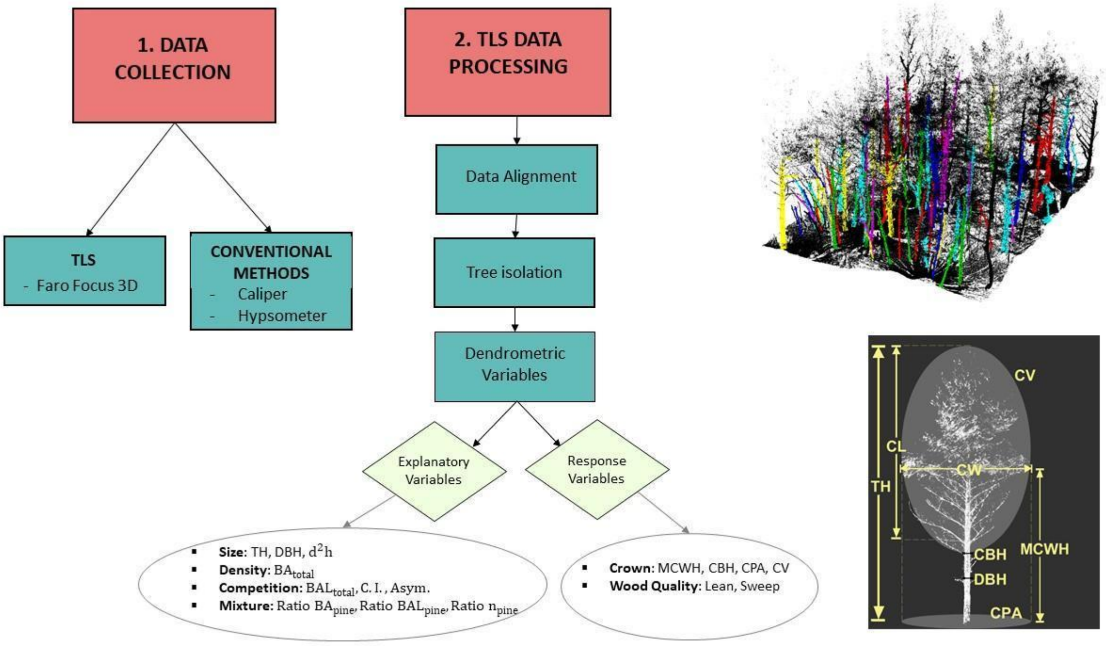


Figure 3. Thesis workflow process of collecting and preparing TLS data for further analysis.

Figure 4 shows the second part of this thesis, which is the analysis of the TLS data. The figure shows the three main steps we implemented. We first created three radii of influence to fit crown models, taking into account the inter and intra-specific competition within those radii of influence. Then, models for crown variables were fitted for the *Pinus sylvestris-Quercus petraea* mixture and then for *Pinus sylvestris-Quercus pyrenaica*. For this second mixture, we did three analyses to check the robustness of our fitted models for the first mixture analysis so its outcomes performed adequately on a wide range of situations been unaffected by departures from the initial conditions. Finally, we fitted wood quality models for the mixture *Pinus sylvestris-Quercus petraea.*

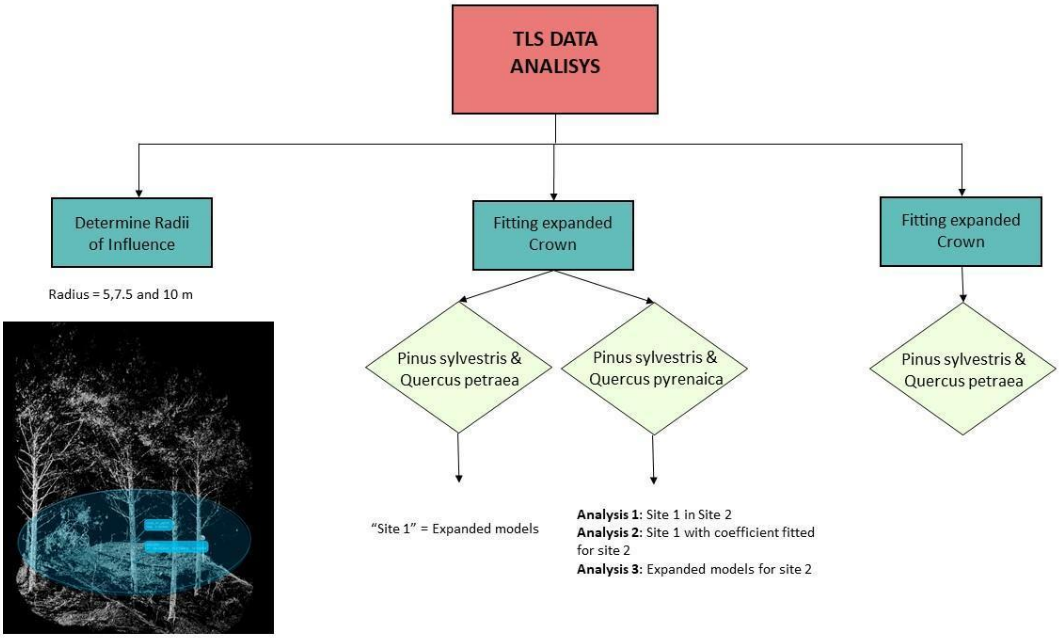


Figure 4. Thesis workflow process of TLS data analysis to obtain crown and wood, quality models.

STUDY AREA

This study has been executed in two experimental sites that belong to the Sustainable Forest Management Research Institute (iuFOR). These sites consist of pine-oak mixtures. The first experimental site, located in Valberzoso (Palencia-Spain), is formed by *Pinus sylvestris* and *Quercus petraea*. The second site is located in Palacio de Valdellorma (León-Spain) and is formed by a mixture of *Pinus sylvestris* and *Quercus pyrenaica*. Both stands have a similar history, coming from an abandoned monospecific pine plantation planted during the 1970 decade that over time has allowed the natural resprout of oak species, which was the previous native forest type in these locations. Nowadays, thanks to this evolution, we have mixed forests at different development stages confirming a semi-uniform forest stand.

Pinus sylvestris – Quercus petraea (Site 1)

Study area

Our first study area consisted of a mix of *Pinus sylvestris* and *Quercus petraea*, located in the municipality of Valberzoso, Northern Spain (Palencia, 42°54’48” N, 4°14’31” W) in the region of Castilla y León at an altitude of 1318 m.a.s.l. This area is located within the Cantabrian Mountain Range, at the border of the Atlantic climate, therefore it is characterized by both continental and Atlantic influences in the climate. The mean annual temperature is 9.9°C but it has a large thermal oscillation (Max. 25.3°C during Summer and min. -1.9°C during Winter). The mean annual precipitation is 1044 mm (Max. 82 mm during October-November and min. 29 mm during July) (AEMET).

The soil parent material of this area originated in the Triassic period and the soil is composed of sandstone and conglomerate, with small zones of oil in the occidental sector which originated during the Carboniferous. The soil of this area has limitations in its development due to the extreme shaping factors in this mountain area, i.e., cold weather, steep slope, and intense deforestation. Nevertheless, in those areas where the slope is less steep and vegetation-covered, high humidity allows well-developed, deep, and acid forest soils. Classified as humic cambisol (CMu) and lithic Leptosol (Lpq) by WRB FAO.

The existing vegetation of the study area corresponds to the evolution of the landscape. It is characterized mainly by the presence of deciduous species, especially large oak and beech forests. Small natural populations of *Pinus sylvestris* can be found in a very singular way, however, there are large plantations of this species, which has enriched the ecosystem of transition to the plateau (Lopez Leiva et al., 2009).

Experimental Design

In September 2017, two triplets were established. Each triplet consists of three plots, one next to each other with similar site conditions (Figure 5). The permanent plots set within each triplet are rectangular, and limits are marked with wooden poles 50 cm in height in each corner. Plot sizes varied to include at least 40 trees of each species of which at least 20 in total are dominant (Table 1). In the pure pine stands the proportion of pine stem varied from 73.1 to 90%, and in pure oak stands from 85.3 to 95.3%. Finally, in the mixed stands, stem pines and oaks' proportion varies from 41.1 to 45.7%, and from 52.4 to 58.9% respectively.

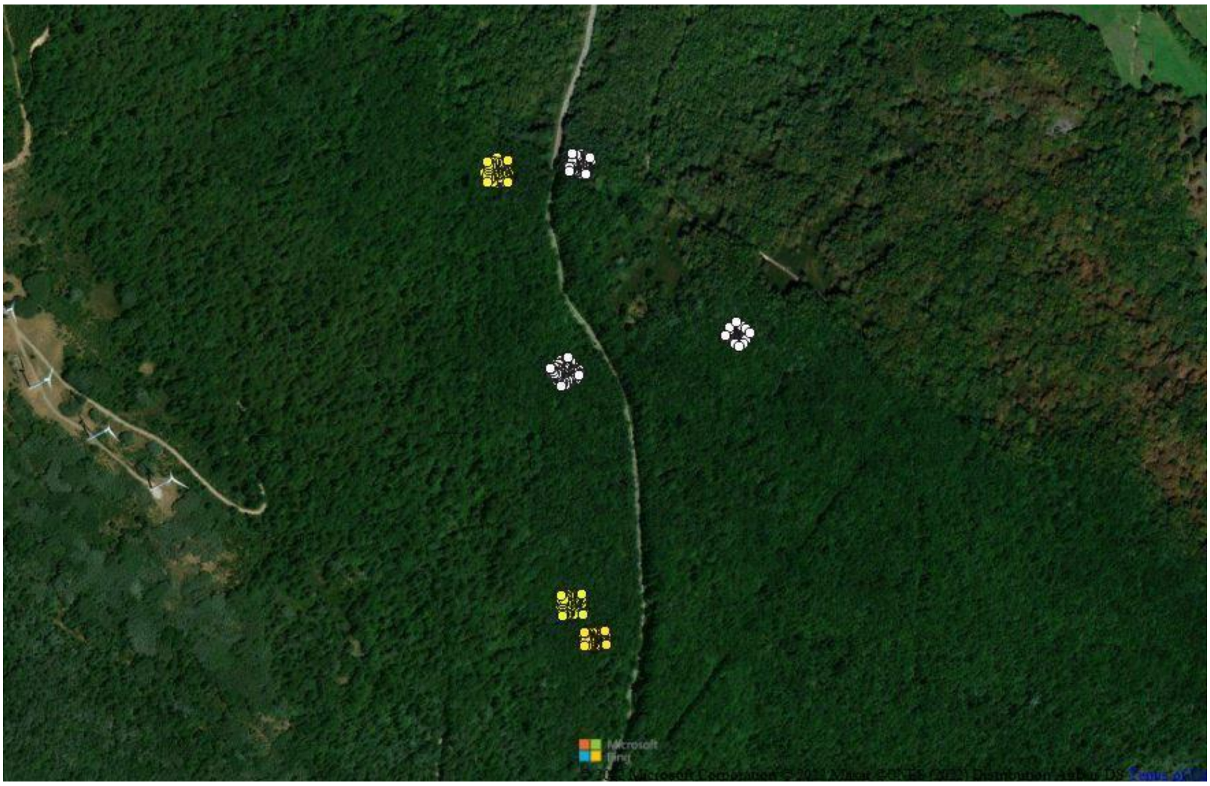


Figure 5. Triplets location. Distinguish by colors. White are triplets belonging to Triplet 1, and yellow are triplets belonging to Triplet 2.

Table 1. Inventory data of oak-pine triplets where stand indicates plot condition (pure or mixed) and the letters Ps and Qp stand for *Pinus sylvestris* and *Quercus petraea* respectively. **n/plot** represents the total number of trees within each plot; **n pines** the number of *Pinus sylvestris*, **n oaks** the number of *Quercus petraea,* and **n other** the number of other species within the plots different from pines and oaks.

Triplet	Plot ID	Plot size (m)	Stand	n/plot	n pines	n oaks	n other
1	2134101	25x25	pure-Ps	70	63	7	--
	4234107	30x30	pure-Qp	102	0	87	15
	92434104	25x25	mix-PsQp	105	48	55	2
2	2134202	30x30	pure_Ps	78	57	21	--
	4234205	20x30	pure-Qp	85	4	81	--
	92434206	30x30	mix-PsQp	107	44	63	--

Pinus sylvestris – Quercus pyrenaica (Site 2)

Study area

The second experimental site was located in Palacio de Valdellorma (León, 42º 45’ 42.4’’ N, 05º 12’ 39.6’’ W) in north-western Spain at an altitude of 990 m.a.s.l. The soil parent material of this area originated in the Era Cenozoic subera tertiary. This area has a moderate slope of 16% and the soil is composed of acid conglomerates based on Miocene clay sediments (IGN, 1991). Soil is classified as lithic Leptosol (LPq) and calcaric Regosol (RGc) by WRB FAO.

This area has a continental Mediterranean climate. The mean annual precipitation is 515 mm with a dry season between July and August. The mean annual temperature is 11.1 ºC (Max. 27.4 ºC during Summer), and the probability of the frost period from December to February.

The existing vegetation of the area is Mediterranean species such as Erika sp., and *Quercus pyrenaica* combined with *Pinus sylvestris* plantation.

Experimental Design

This second experimental site was established in 2013 following a split-plot design: one single block divided into nine plots 50x40m (Figure 6). Within these plots, three forest thinning effects were carried out regarding their Basal Area (BA) during the summer of 2015. The scannings were made in three of the nine plots (Figure 6), and they were made very close in time to the thinning (January 2016), thus, no thinning effect was taken into account in this study (Table 2).

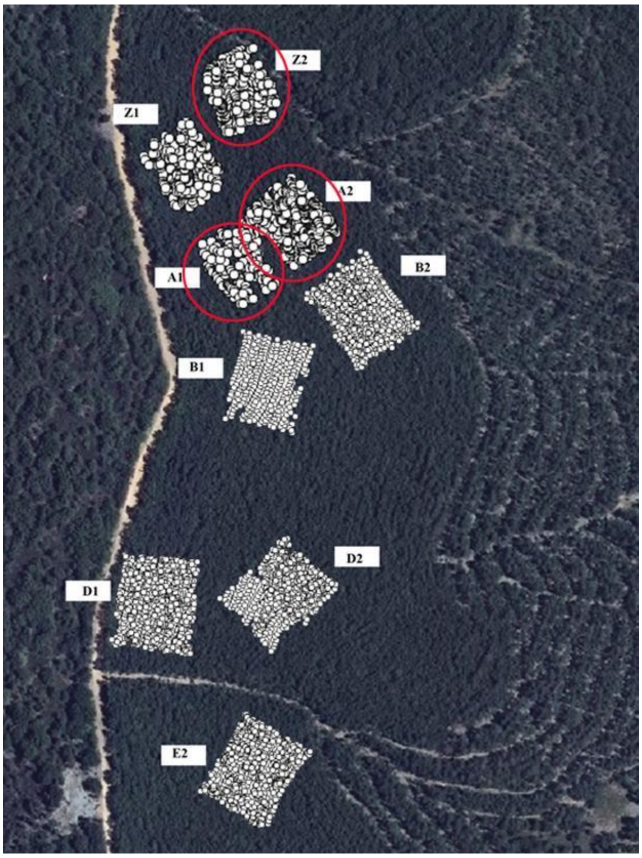


Figure 6. Experimental site of Palacio de Valdellorma, following a split-plot design. Circled in red are the three plots taken for this study.

Table 2. Inventory data of oak-pine of the experimental site of Palacio de Valdellorma. Where "treatment" indicates the intensity of thinning of that plot. **n/plot** represents the total number of trees within each plot; **n pines** the number of *Pinus sylvestris*, **n oaks** the number of *Quercus pyrenaica,* and **n other** the number of other species within the plots different from pines and oaks.

Plot ID	Treatment	n/plot	n pines	n oaks	n other
A1	50%	725	316	398	11
A2	25%	875	283	592	0
Z2	control	774	295	472	7

DATA COLLECTION

Field data

For both sites, all trees belonging to the plots were labeled (tree ID), and each tree position (Cartesian x and y coordinates) was recorded with a Total Station (Topcon 220). Diameter at breast height (DBH) above 7.5 cm was measured with a caliper, and total height (TH) of the tree was measured with a hypsometer Vertex III (Haglöf Sweden) for all of the trees. In addition, for the experimental site of Valberzoso, Crown at Breast Height (CBH) was measured with Vertex III, and the projection radii (in four directions: N, E, S, W) were measured with tape to the closest cm. Tables 3 and 4 summarize the stand characteristics for each species and each experimental site 1 and 2, respectively.

Table 3. Stand characteristics of the study species. n stands for the number of total tree species. DBH is the Diameter at Breast Height in cm. TH is the total height of the tree in m. CBH is the Crown Base Height in m. CPA is the Crown Projection Area in cm^2, and BA is the basal area in m^2/ha.

		Main tree species					
		Pine			Oak		
		n= 254			n= 480		
DBH (cm)	min	13.60			7.20		
	mean (± SD)	29.69	±	6.61	19.91	±	6.51
	Median	29.73			19.65		
	Max	53.35			60.50		
TH (m)	min	10.50			4.00		
	mean (± SD)	18.23	±	1.90	17.32	±	2.93
	Median	18.60			18.00		
	Max	23.90			23.70		
CBH (m)	min	1.10			2.00		
	mean (± SD)	12.56	±	2.08	11.67	±	2.21
	Median	12.70			12.00		
	Max	17.50			16.70		
CPA (cm^2)	min	0.59			0.14		
	mean (± SD)	12.50	±	8.80	9.88	±	9.37
	Median	10.71			7.49		
	Max	56.61			114.20		
BA (m^2/ha)	min	0.17			0.06		
	mean (± SD)	0.92	±	0.41	0.50	±	0.40
	Median	0.90			0.43		
	Max	2.49			4.96		

TLS data collection

For both experimental sites, data collection was the same. The diagram of the following methodology is shown in Diagram 1.

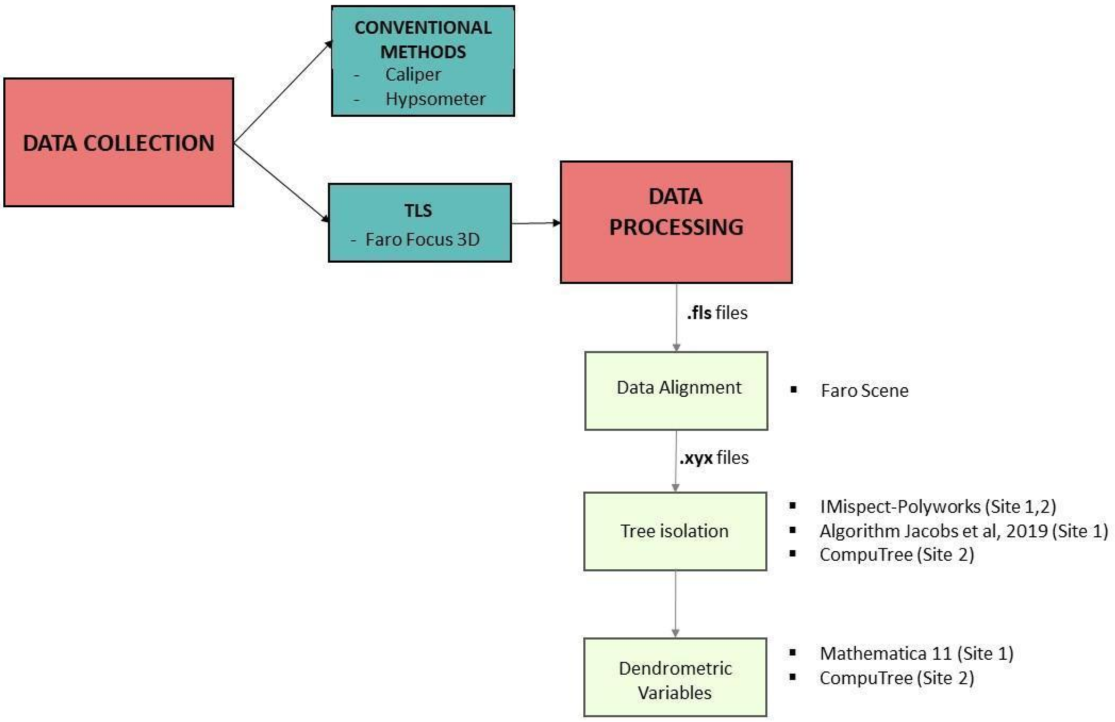


Diagram 1. Flowchart of Fieldwork data collection and the processing flowchart for TLS data.

Georeferencing

During scanning and as supporting material georeferenced plots corners were recorded with a sub-metric GPS Leica model SR20 frequency equipment with external antenna reception AT501. This equipment has an error margin of centimeters. This step was taken to speed up the tree identification process since data scans are metric, i.e. we can make use of TLS data to obtain the data of the densitometric variables but these data are not oriented, either referenced or locally or globally (UTM coordinates) so the correspondence between trees turns difficult. Thanks to this georeferencing we were able to minimize the error of the actual location of the plots, and therefore, make the correspondence of tree identification between field and point clouds easier.

For this purpose, for the first experimental site, we recorded three corners of each plot. Due to canopy cover, we have always chosen the corners closer to the road to ensure the GPS would find enough satellites (Figure 7). For the second experimental site, only five points were needed because plots were closer to each other, and connections between plots were possible to make (Figure 7). For each station, the GPS was located for 30 minutes, so that, the error was minimized.

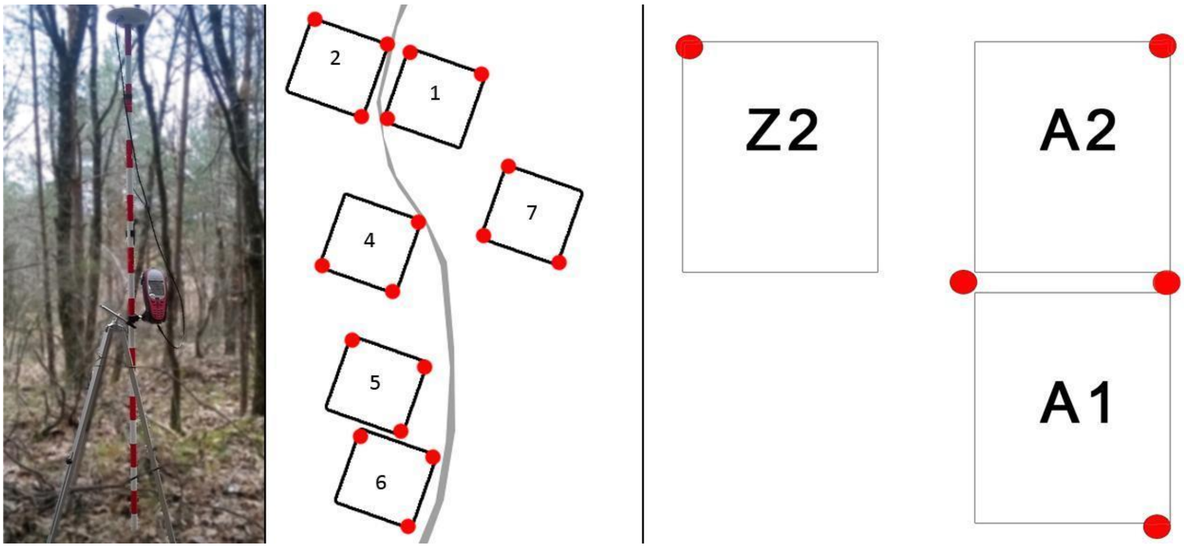


Figure 7. From left to right. Sub-metric GPS Leica Model SR20. Sketch of the experimental plots of Valberzoso and Palacio de Valdellorma. Red circles represent the corners where the GPS sub-metric was placed.

As mentioned before, the perfect identification of these points is very important afterward in deskwork, thus, after each GPS station, the exact place was marked with one white sphere over a wooden pole (needed for the scanning process) and perfectly distinguished from the rest of white spheres (Figure 8).

Figure 8. Characterization of GPS points in the field (left) and identification of these points through the point clouds (right).

TLS data collection

Experimental site 1 (Valberzoso, Palencia) was scanned twice. The first time in September 2018, but after processing data, we observed that the quality of the data was not good enough to study tree architecture due to the leaves of the oak trees were obstructing the stem and crown information, therefore a second scan was performed between February and March 2020. Experimental site 2 (Palacio de Valdellorma, Leon) was scanned in March 2016.

Previous to scanning and to assure the recording of all the trees belonging to the plots and to optimize battery scan life, a pre-design of a multiple-scan approach on each tree-plot map was done. However, the final amount of scanner positions varied depending on the plot density. For experimental site 1, where stand density was the same across all the plots, 12 scanner positions were needed in each plot. For experimental site 2, where different stand density existed the final amount of scan positions were 24 for plot A1 where the thinning intensity was 50% but for plots Z2 and A2, where the thinning intensity was 25% and 0%, respectively, 48 scan positions were needed.

Terrestrial LiDAR data were captured by a Faro Focus 3D device. Panoramic spherical scans were captured, containing a horizontal angle from 0° to 360° and a vertical angle from -60° to 90°. The scan was mounted on a tripod at approximately 1.3 m above the ground. Each scan size was 8192x3414 points, that is to say, 28.0 million points per capture and spatial resolution of 7.670 mm at 10 m. The rest of the characteristics are defined in Table 4.

Table 4. Faro Focus 3D settings characteristics were used to collect the data.

Angular Resolution	0.6135 milirad	**Horizontal field of view**	0° – 360°
Quality	2x	**Vertical field of view**	-60° – 90°
Scan Duration (mm:ss)	approx. 02:08	**Point Distance**	7.670 mm @ 10 m
Scan Size (Pt)	8192x3414		
Points captured per scan	28 M		

Faro Focus 3D had it owns 10 spheres of alignment which were 15 cm in diameter but based on previous experience (Uzquiano, 2014) to facilitate their recognition during processing data, we used 15 bigger spheres: 18 cm diameter cistern buoys, as reference points as they could be recognizable from farther away (Marcos, 2021). They were winded on a one-meter high wooden pole as is shown in Figure 8. During this process, to ensure the correct alignment of scans, we had to take care of two things: (1) The scanner should be able to recognize at least three of them in each scan position. (2) As the number of spheres was not enough to cover the entire plot at once assuring the visibility of three of them in each scan position, they had to be moved as we went scanning along with the plot, therefore we should take care the spheres were recorded in the same position from at least two scan positions. The total time needed for scanning each plot was about two hours, except for plots A2 and Z2 of Experimental site 2, where the final scanning time per plot was 5 hours each.

TLS data processing

To convert scan captions in point clouds we used a Workstation Intel CORE i7-5280K. hard disk SSD 256 GB Samsung 950 PPRO M S2. Hard disk SATA 4TB. WD Blank CPU INTEL 1022 CORE i7-5820K 3.3G. 6 CORE 6 CACHE. 4 memories DIMM 8 GB DDR4.

The first step needed was to convert the panoramic (2D) scans into 3D point clouds. Faro Focus 3D creates .fls files. This extension is only readable by Faro Focus 3D's own software, Faro Scene (Faro Technologies Inc., Lake Marry, USA). We used Version 5.2 and 7.0 for experimental sites 2 and 1 respectively. Thanks to this software, we first made the alignment of scans, i.e. the scan placements, where every scan position is located in its actual position in the field by the recognition of, at least three white spheres with enough points (Figure 9), i.e. spheres were close enough to the scan position to be recognized as spheres if the sphere was 10 m far from the scanner, then we would have one point every 7.67 mm (table 4), but if it was 20 m then we would have one point each 15.34 mm, the closer to the scan, the better. This processing of the scans can be done automatically using the option of Pre-processing (Marcos, 2021). Once the characteristics of the spheres were set into the software, the program searched for them automatically. This processing time varied depending on project size. Our projects varied between 5 and 10 Gb and therefore this processing time varied between 2 hours and 6 hours, respectively. After this pre-processing step is completed, it was executed a manual supervision scan to check the recognition of spheres was done correctly as sometimes it recognized other objects such as leaves or branches as if they were spheres or, on the contrary, did not recognize all the spheres in the scan. Once this process was done, scans were all aligned (Figure 10), and the project was saved as one single point cloud file with a .xyz extension. Therefore, we could edit the plot point clouds in other programs.

Figure 9. Recognition of at least three spheres in every scanned image to be able to do the alignment and therefore convert 2D panoramic images of scans into 3D point clouds.

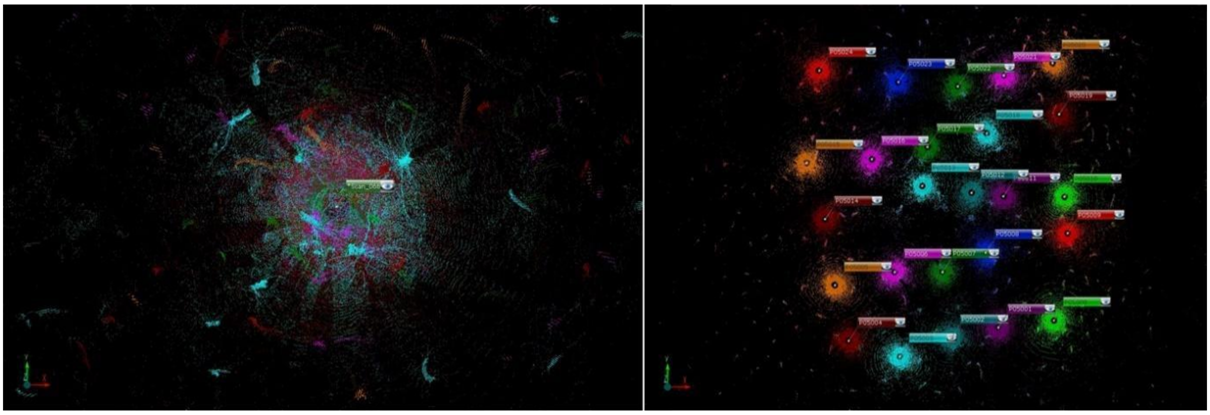


Figure 10. Scan positions performed in Faro Scene. Each scan position is characterized by one color. The image on the left shows one plot without being aligned, and on the right, the scan positions are well located after white spheres were recognized.

To be able to identify each 3D tree with its corresponding ID the .xyz files were imported together with the georeferenced corner of the plots, which had a .txt format to the module IMispect from the software Polyworks Version 12.1.3 (InnovMetric Software Inc., Quebec, Canada) (Barbeito et al., 2017; Ferrarese et al., 2015; Hackenberg et al., 2015) and overlapped the point clouds layer (.xyz files) on the UTM points (the georeferenced corners). This process was done thanks to the characterization made during fieldwork, which let us know, which ones were the georeferenced points to be overlapped on the coordinates (Figure 8). Finally, we imported as text file (.txt format) UTM coordinates of all the trees belonging to the plots. This process was done manually. Since the project was already georeferenced, these points overlapped in their right position (Figure 11).

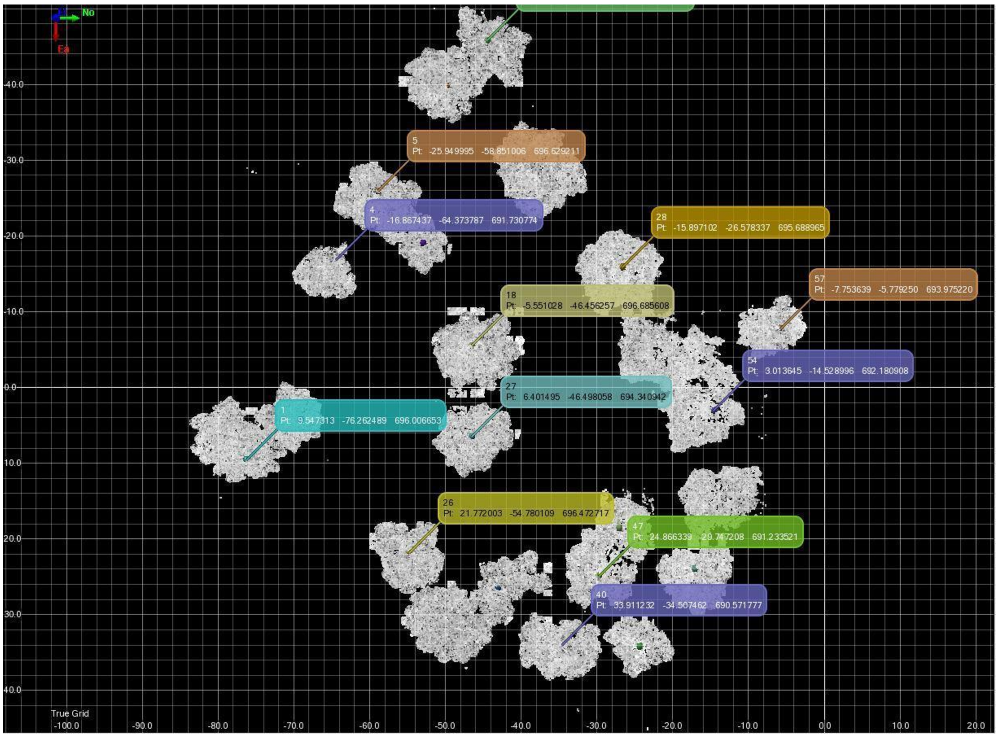


Figure 11. TLS trees correlated with their correspondent ID in the field after the .txt file of UTM tree coordinates was overlapped on point clouds.

Tree segmentation and variable extraction

Tree segmentation consists of obtaining one point cloud for each tree belonging to the plot, i.e. we should have as many point clouds as trees in the plot. This segmentation was done differently in the two experimental sites and is described below.

Pinus sylvestris – Quercus petraea

For our first experimental site, tree segmentation was done in two different ways. For Triplet 1, this isolation was conducted manually: we edited the original point cloud in IMispect selected each tree, and made a copy of the point cloud for each tree. Triplet 2 trees were based on density spatial clustering to detect individual-tree positions. This was performed within the programming environment of R (R Core Team, 2016) using the R packages rlas (Roussel & De Boissieu, 2020), dbscan (Hahsler et al., 2019), TreeLS (De Conto, 2020), and conicfit (Gama & Chernov, 2015), which automatized the method. For this method, only the x- and y-axes are used as input data. Firstly, the rlas package was used to convert our point cloud data into an interchange of 3-dimensional point cloud data process, next, dbscan was automatically able to detect each tree as a cluster, i.e., each recognized cluster (stem), and received a unique number and therefore, could be processed individually. Then each cluster was individually queried as to, which stem base cluster is closest in distance and whether this distance is close enough (≤0.05m) to be classified as associated points. Stems were detected through the Hough Transformation, adapted by Olofsson et al. (2014), implemented in the R Package TreeLS. Followed by De Conto (2016) directions to remove the ground points, leaving only the stem. Finally, dead branches were removed by fitting an ellipse by R Package conicfit. After this step, each tree is visually checked for completeness. If necessary, unrecognized tree parts are added manually, and artifacts not belonging to the tree are removed using the software RiSCAN PRO. More detailed information is provided in (Jacobs et al., 2019). In both cases, final refined data for each tree were needed and it was performed manually in IMispect and the free software Cloud Compare Version 2.11 alpha (Anoia) by deleting points that were not part of the trees or by separating trees, that were identified as only one due to their crown proximity. For this experimental site, all the trees belonging to the study plots were identified, but due to canopy occlusion, especially in oak stands, which made tree separation impossible, the study was finally conducted with 91.2% of the total (Table 5). The total time for the Identification, isolation, and data refining of this experimental site took approximately 5 months.

Table 5. Total trees per plot (n/plot) compared to total point cloud trees isolated (TLS trees)

Triplet	Plot	type	surface	species	n/plot	TLS trees
1	1	pure	25x25	Pine	63	61
	7	pure	25x25	Oak	87	75
	4	mixed	30x30	Pine - Oak	48 - 55	47 - 53
2	2	pure	30x30	Pine	57	47
	5	pure	20x30	Oak	81	74
	6	mixed	30x30	Pine - Oak	44 - 63	38 - 54
				Total	**498**	**449**

EXTRACTION OF VARIABLES

For this experimental site, TLS dendrometric variables were extracted using the software “Mathematica 11” (Wolfram Research Inc., Champaign, IL, USA). In total, for each tree, we obtained eleven variables: Diameter at Breast Height (DBH), Total Height (TH), lean, sweep, and the crown metrics of Crown Base Height (CBH), Maximum Crown Width Height (MCWH), Maximum Area, Crown Volume (CV), Crown Surface Area (CSA), Crown Length (CL) (Figure 12), asymmetry of the crown concerning the stem (asymmetry) and as wood quality variables: Lean and Sweep (Figure 13). An extensive description of the computing process can be found in (Seidel et al., 2011)

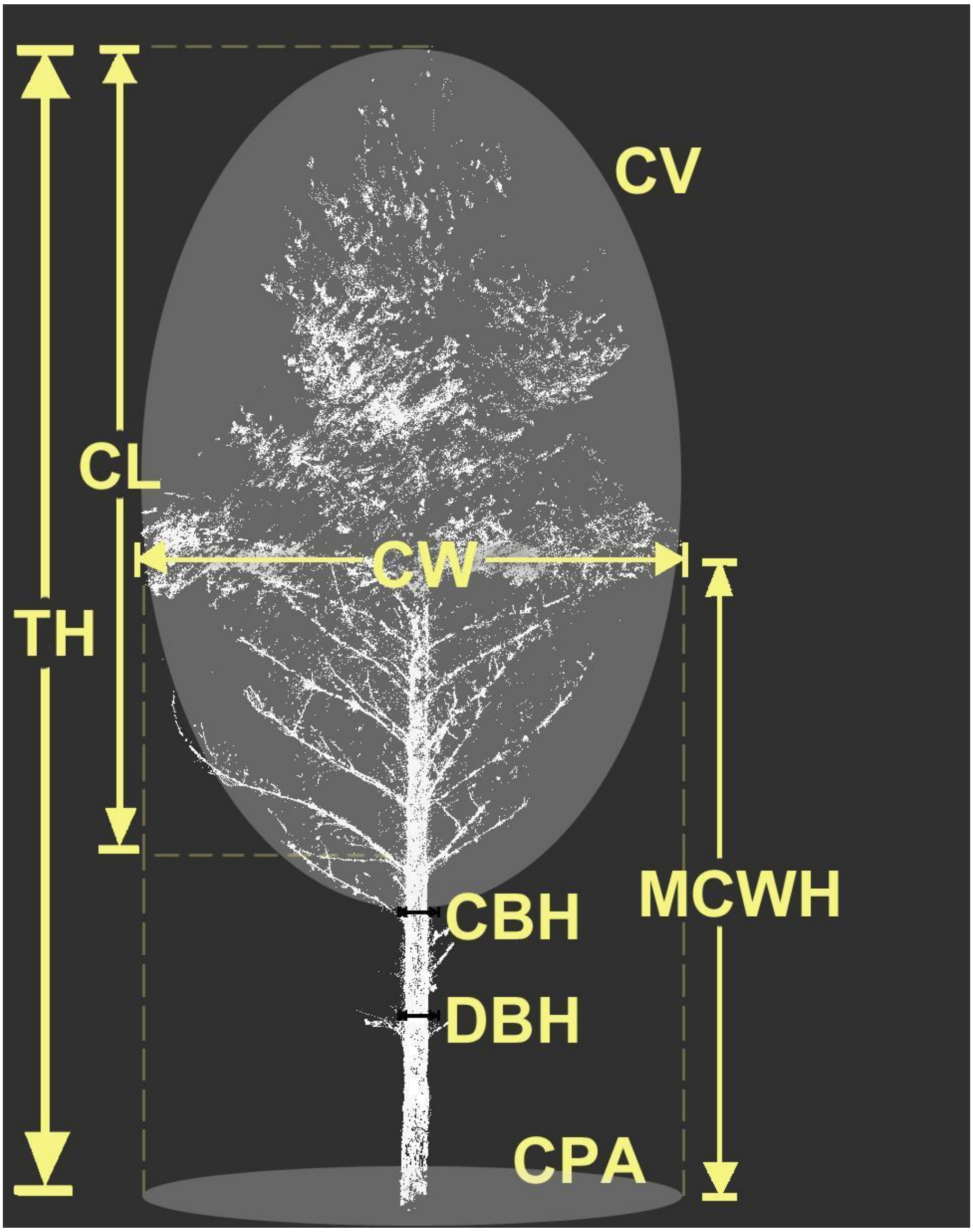


Figure 12. Variables computed for each tree by “Mathematica11” software. TH= Total Height; CL= Crown Length; CW= Crown Width; CBH= Crown Base Height; DBH= Diameter at Breast Height; CPA= Crown Projection Area; MCWH= Maximum Crown Width Height; CV= Crown Volume.

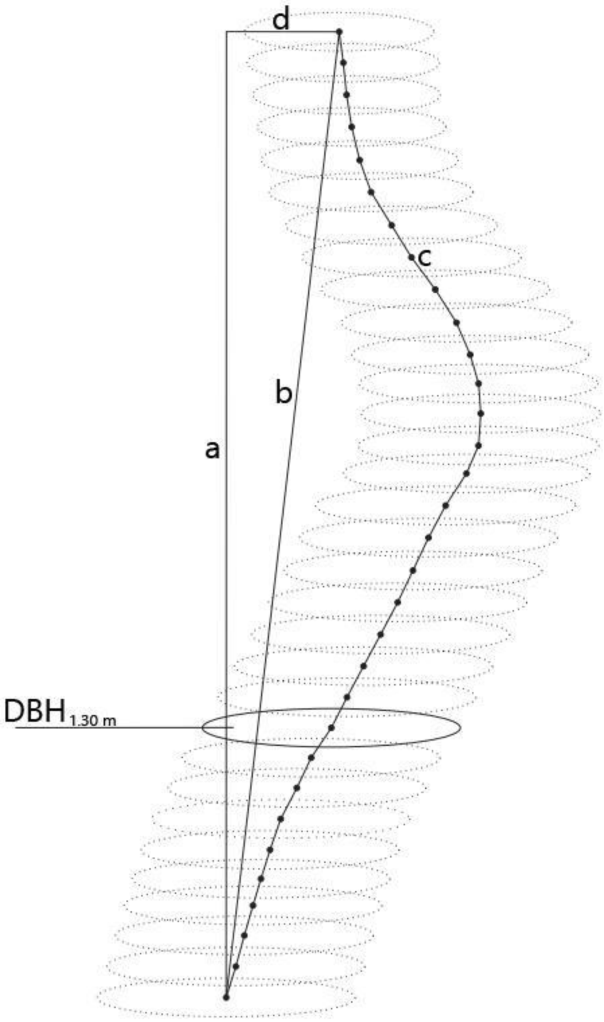


Figure 13. Schematic draft of a stem section. Where **a** represents the height of the tree on the y axis, **b** the longitude of the stem, **d** the lean of the stem, and **c** the sweep of the stem. Image source: Höwler et al. (2017)

Pinus sylvestris – Quercus pyrenaica

For this second case, the isolation of the trees was by a combination of the software Polyworks and CompuTree. In this case, the great canopy occlusion of the stands, the small diameter size of many of the oak trees (Figure 14), and the steep and rugged ground (Figure 15) made the isolation and identification of the trees especially difficult.

Figure 14. The great occlusion of the stands and the small diameter size of many oak trees made the isolation and identification of trees very difficult.

Figure 15. The plot density together with the steep and rugged ground made the identification and isolation of trees especially difficult.

On the other hand, due to the number of scan positions (24, 42, and 43) the size of the project was between 9 and 11 Gb, which slowed down the processing of the data. For these reasons, we decided to isolate the trees with a band diameter (part of other experimental plots) which were easier to identify from the rest of the trees (Figure 16), and from the identification of these, the identification of the left trees was done. This first step was done by module IMispect from Polyworks version 12.1.3 (64 bits).

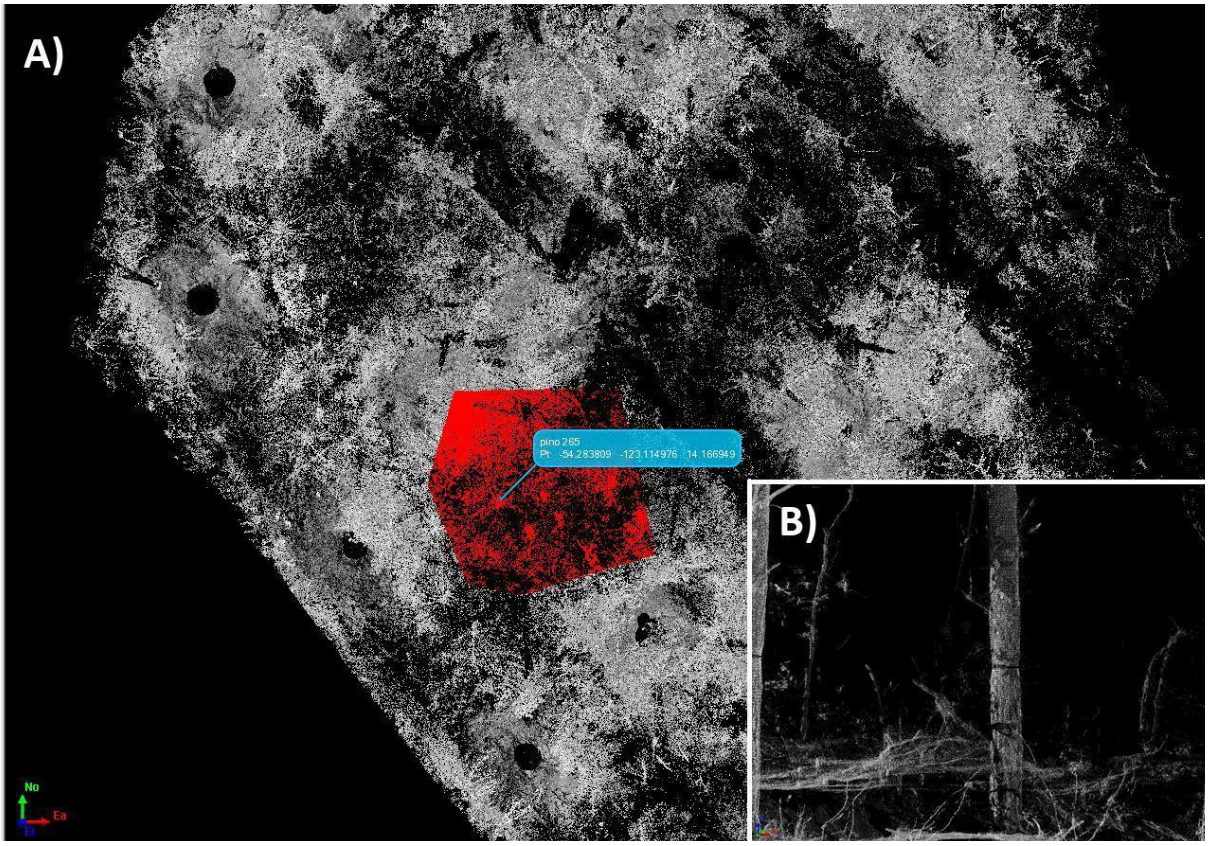


Figure 16. A) Creation of a subplot around trees with dendrometric bands, easy to identify from the point clouds (B).

Once the subplots were created, they were exported as .xyz files and imported to the free software CompuTree version 3.418. We used a script developed by LerFob-INRAE (Nancy-France). This program first identifies each stem, which is validated manually, and once the recognition is done, the program colors each of the trees with different colors. Finally, only one tree could be selected and the rest deleted (Figure 17) (Uzquiano, 2016), this way we isolated a total of 54 pines and 61 oaks (Table 6). These data were exported as ASCII files and imported again to the IMispect module and Cloud Compare Version 2.11. alpha (Anoia) for the final data cleaning.

Table 6. TLS trees that were isolated per plot and species and the total.

Plot ID	Treatment	n pine	n oak
A1	50%	19	22
A2	25%	19	22
Z2	control	16	17
	Total	54	61

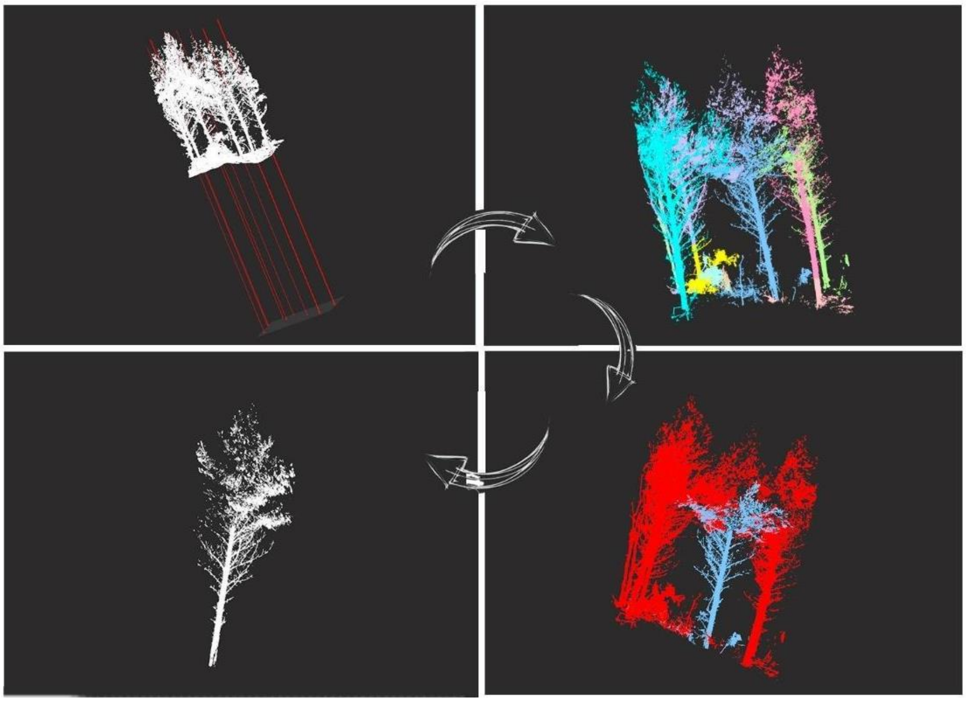


Figure 17. Step by Step Isolation method performed by CompuTree.

EXTRACTION OF VARIABLES

The extraction of the variables of the tree was done with Computree. This program allowed us to create envelopes around each tree every 10 cm (Figure 18). The longitude and area of every envelope every 10 cm surrounding each of the trees were exported as a spreadsheet. This way we defined the DBH, TH MCWH, CPA, and CBH. The CBH was defined as the height at which the diameter of the envelopes was at least twice the BA of the tree (Barbeito et al., 2017).

Figure 18. Envelopes that were created in CompuTree every 10 cm around every tree.

DATA ANALYSIS

Data analysis was conducted using Rstudio Inc. Version 1.1.453. Packages used were: dplyr (Hadley et al., 2020), data.table (Dowle & Srinivasan, 2020), lme4 (Bates et al., 2015), broom (Robinson et al., 2021), ggplot2 (Wickham, 2016), psych (Revelle, 2020), pastecs (Grosjean & Ibanez, 2018), car (Fox & Weisberg, 2019), gridExtra (Auguie, 2017), nls2 (Grothendieck, 2013), and tibble (Müller & Wickham, 2020).

before proceeding with the analysis of the variables through TLS data, we analyzed their degree of affinity with the field data. Firstly, we compared TLS data distribution with Field data distribution with the Kolmogorov-Smirnov test. Following this, we applied Lin's concordance correlation coefficient (CCC) (Lin, 1989) to compare TLS and Field measurements of the same variables.

Crown analysis

To determine the variables we needed for the analysis of the crown variables we based on usual forest modeling literature, and expanded the models following the methodology applied (Lizarralde, 2008) adding the mixture of explanatory variables (Table 7 and Table 8). Once we had the models, we were able to determine and adapt our data to our four categories of explanatory variables (size, density, competition, and, mixture) as shown in Table 8. For the Crown Volume, the explanatory variable d^2h (squared diameter at breast height times height) was included as a size variable since this variable represents a proxy for tree volume. Furthermore, for the CPA response variable, the logarithmic transformation of the Basal Area was included as a density explanatory variable, (Ritter & Nothdurft, 2018). As for mixing variables, we used the Ratio variables of species, and due to the high correlation ($\rho \geq 0.9$) to avoid multicollinearity problems, we decided to study only the ratio variables of pines, based on the more extensive bibliography on the subjects of pines mixture effect than oak mixture effects.

Table 7. Crown models were defined for this study. Response Variables are Maximum Crown Width height (MCWH), Crown Base Height (CBH), Crown Projection Area (CPA), and Crown Volume (CV), and explanatory models were classified into four categories. s= size, d= density, c= competition and m= mixture.

Response Variables	Equation	Author
MCWH	$MCWH = \frac{TH}{1 + e^{\alpha_1 * s + \alpha_2 * d + \alpha_3 * c + \alpha_4 * m}}$	(Pain & Hann, 1982)
CBH	$CBH = \frac{MCWH}{1 + e^{\alpha_1 * (\frac{d}{s}) + \alpha_2 * d + \alpha_3 * c + \alpha_4 * m}}$	(Hann et al., 2003)
CPA	$CPA = e^{\alpha_0 + \alpha_1 s + \alpha_2 * d + \alpha_3 * c + \alpha_4 * m}$	(Ritter & Nothdurft, 2018)
CV	$CV = \alpha_0 + \alpha_1 * s + \alpha_2 * d + \alpha_3 * c + \alpha_4 * m$	(Sanquetta et al., 2015)

Table 8. Categories and variables within each category we have used to define explanatory models

Category	Variable				
Response	MCWH	CBH	CPA	CV	
Explanatory					
- Size	TH	DBH	d^2h		
- Density	BA_{total}				
- Competition	BAL_{total}	BAL_{pine}	BAL_{oak}	Asymmetry	C. I.
- Mixture	Ratio BA_{pine}	Ratio BAL_{pine}	Ratio n_{pine}		

We calculated the Basal area (BA) of each tree from their TLS point clouds and we analyzed the outliers for the variables: DBH, BA, TH, CBH, MCWH, CPA, and CV. Next, following Höwler et al. (2017) methodology, circular sample plots with a variable radius around each target tree were established. Radius size constraints were the size plots of the experimental site 1 (Table 1), the smallest plots we had. Thus, we determined three radii sizes at 5, 7.5, and 10m. Once radii sizes were defined, we used

R software to create point patterns (ppp) using the R package Spatstat (Baddeley & Turner, 2005) to first, delimit the plot size, followed by Siplab package (Garcia, 2014) to determine the Hegyi index (Hegyi, 1974), hereafter referred to as the Competition Index (C.I.), which was calculated according to Hegyi (1974) (Eq. 1)

Eq. 1. $$Hegyi_i = \sum_{j=1}^{n} \frac{DBH}{DBH_i \cdot (dist_{ij}+1)}$$

Where i stands for target tree i, j for competitor tree, DBH for diameter at breast height, and distance between target tree and competitor tree are represented by "dist" within radii encompassing 5, 7.5, and 10.

Within these circular plots, we also determined the BA, the Largest Basal Area (BAL), and the number of tree species around each target tree within each of the three circular subplots (Figure 19). Finally, response variables (CBH, MCWH, Crown Volume) and DBH and TH were compared between sites to see if there were significant differences between species that could explain possible differences in the results.

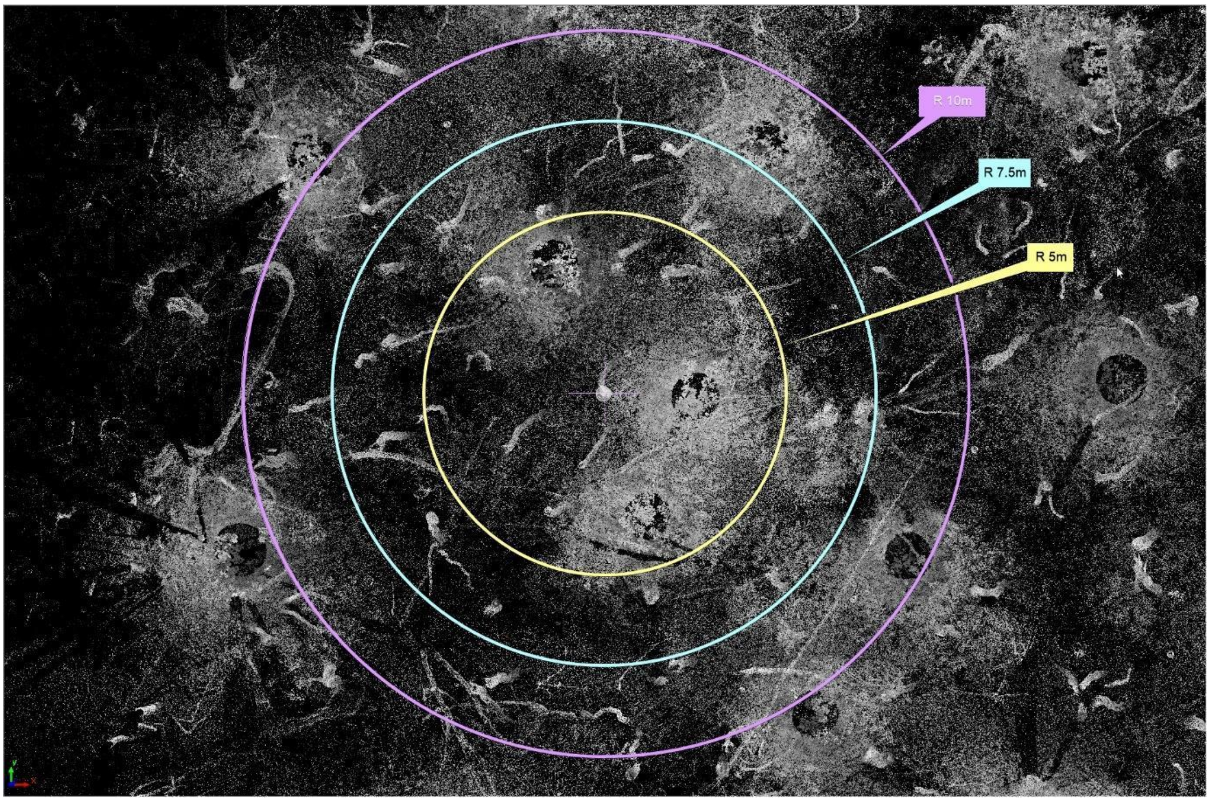


Figure 19. Creation of circular subplots around each target tree with radii = 5, 7.5, and 10 m.

Wood Quality

Wood quality was analyzed only for Experimental site 1. Through the trunk variables Lean and Sweep (Figure 13). No similar models were found in the literature, thus we decided to start applying linear models (Table 9) to see how our data fit.

Table 9. Starting model equations for Lean and Sweep

Response Variables	Equation
Lean	$Lean = \alpha_0 + \alpha_1 * s + \alpha_2 * d + \alpha_3 * c + \alpha_4 * m$
Sweep	$Sweep = \alpha_0 + \alpha_1 * s + \alpha_2 * d + \alpha_3 * c + \alpha_4 * m$

Model Building and Selection

Pinus sylvestris – Quercus petraea

We worked with 193 pines and 256 oaks. For the response variables: MCWH, CBH, and CPA, non-linear regression models were performed using a brute force algorithm from the R package nls2 (Grothendieck, 2013). For the CV, lean, and sweep variables, simple linear regression was used.

For each radius of influence considered (5, 7.5, and 10 m) all possible combinations of explanatory models (size, density, competition, and mixture) were tested. The total amount of models created for each variable varied depending on the number of explanatory variables within the script model. For MCWH and CBH we had 144 models, for CPA and CV where a third size variable (d^2h), plus the Logarithm of BA as density variable, was included we obtained 216 models, and for Lean and Sweep we kept the logarithm of BA as a density variable, but we did not keep d^2h as a size variable. We obtained a total of 180 models.

To select the best model we followed the Akaike Information Criterion (AIC) (Eq. 2), which is a mathematical method for evaluating how well a model fits the data it was generated from. The best-fit model according to AIC is the one that explains the greatest amount of variation using the fewest possible independent variables (Bevans, 2021).

$$\text{Eq. 2.} \quad AIC = 2K - 2ln\,(L)$$

Where K is the number of independent variables used and L is the log-likelihood estimate. To compare AIC, we calculated the Akaike weight, which is interpreted as probabilities. If the Akaike weight approached 1 then, model was unambiguously supported by the data (Johnson & Omland, 2004). The top five models with the lowest AIC index were selected.

Finally, we analyzed the residuals of the top5 models for each response variable, and we calculated the sum of squares error (SSE) of every model to estimate the power of the regression, as well as their R^2 to check the general explanatory power of the models. For non-linear models, we calculated the R^2 (Nagelkerke, 1991). Finally, we created the histogram, density plot, and Q-Q plot for every model to analyze their residuals.

Pinus sylvestris – Quercus pyrenaica

For the analysis of Experimental site 2 we performed three models on 49 pines and 38 oaks. (1) we applied the models fitted in site 1 to this new site; (2) we used the models fitted for site 1 but modified their coefficients for this site 2; and (3) we fitted new models for this site following the same methodology as in Site 1.

For (1) and (2), where we wanted to see the goodness-of-fit of the models fitted for site 1, we firstly created a graph of predicted vs. actual values adjusting a regression line, $predicted = \beta_0 + \beta_1 \cdot actual$. Next, we performed a simultaneity test to check regression line was significantly different from the bisector of the first quadrant (y=x) (Herrero et al., 2019; Huang. et al., 2003):

- H_0: $b_0=0$ & $b_1=1$
- H_1: $b_0\neq0$ or $b_1\neq1$

Finally, we compared the AIC between the models to determine if the models fitted in site 1 are applicable to site 2 and thus, create a sound model for these variables or, on the contrary, we need to create a new model for each site.

RESULTS

TLS validation and Sites comparison

The Kolmogorov Smirnov test was not significant ($\alpha = 0.05$) for all contrasted variables, which confirms the distribution of TLS data was not significantly different from the data taken in the field. Then, CCC was tested on the two tree size variables (DBH and TH) from which, the rest of the variables derive. We obtained very high rates for both of them which corroborates the confidence (CI) of our analysis: CCC_{DBH}: 0.9766 (95% CI 0.9719 - 0.9806) and CCC_{TH}: 0.7429 (95% CI 0.6984 - 0.7817). From here, the rest of the analysis was performed with TLS data.

Firstly, descriptive statistics of all trees classified by species and pure and mixed-species plots were performed (Table 10). We have observed that oaks show similar tree heights, both in pure and mixed stands, but they are slightly thicker (DBH one cm higher) in the mix with pines than in pure conditions. Unlike pines, DBH is up to almost 3.5 cm thinner in the mix with pines but slightly taller (+0.5 m) compared to pure plots

Table 10. Mean Diameter at Breast Height (DBH) in cm and Total height (TH) in m of trees calculated with TLS separated by species and kind of plot (pure or mix). n total is the total number of trees measured.

Species	Plot	n total	DBH (cm)					TH (m)				
			Max	mean		SD	min	Max	mean		SD	min
pine	Pure	113	46.98	30.99	±	2.07	5.68	26.44	17.33	±	6.97	11.62
	Mix	84	47.34	27.51	±	2.13	13.96	22.36	18.04	±	6.33	11.31
oak	Pure	155	61.29	19.50	±	3.38	7.56	23.20	17.38	±	7.42	6.39
	Mix	107	33.52	20.53	±	2.41	10.07	20.85	17.31	±	5.20	8.73

Fitted Crown models

Pinus sylvestris and Quercus petraea

Models were hierarchized according to the lowest Akaike Information Criterion (AIC). We analyzed the residuals and made the necessary changes in the structure of the models (Table 11) to assure models met the assumptions, and in the case they did not meet the assumptions after the transformation we rejected them. The best models for each crown variable, that we selected according to these criteria are shown in Table 12. For all cases, the model selected was the model with the lowest AIC index except for the MCWH variable in both species, where models with the second AIC index were selected due to residual analyses being slightly better in the second models.

Table 11. Final equations for each species and crown response variable.

		Equation
MCWH	Pine	$MCWH = \frac{TH}{1 + e^{(-0.11 \cdot C.I. - 0.13 \cdot RatioBAL_{pine})}}$
	Oak	$MCWH = \frac{TH}{1 + e^{(-0.0.9 \cdot TH + 0.28 \cdot RatioBA_{pine})}}$
CBH	Pine	$CBH = \frac{MCWH}{1 + e^{(-22.9 \cdot \frac{BA_{total}}{DBH} - 0.1 \cdot BA_{pine} - 0.41 \cdot RAtioBAL_{pine})}}$
	Oak	$CBH = \frac{MCWH}{1 + e^{(-14.43 \cdot \frac{BA_{total}}{DBH} + 0.05 \cdot lnBA_{total} + 0.04 \cdot BAL_{total} + 0.17 \cdot RAtioBAL_{pine})}}$
CPA	Pine	$CPA = e^{0.07 \cdot DBH + 0.02 \cdot BA_{total} - 0.1 \cdot C.I.)}$
	Oak	$CPA = e^{0.9 + 0.04 \cdot DBH + 0.09 \cdot BA_{total} - 0.1 \cdot BAL._{total} + 1.15 \cdot Ratio\ n\ _{pine})}$
CV	Pine	$CV = 1.5e^{-3} \cdot d^2h + 0.44 \cdot BA_{total} - 2.35 \cdot C.I.$
	Oak	$CV = -20.28 + 0.003 \cdot d^2h + 1.03 \cdot BA_{total} - 4.29 \cdot BAL_{total} + 46.92 \cdot RatioBA_{pine})$

Table 12. The explanatory models were selected as the best fit according to their lowest Akaike index and biological criteria for each response variable (Variable) and species. r= radius of influence (5, 7.5 and 10 m); s = size; d=density; c= competition; m= mixture; α_0= Intercept; $\alpha_{1\text{-}4}$= the coefficient numbers for each explanatory variable (size, density, competition, and mixture). AIC = Akaike, K-S test = P-value of Kolmogorov Smirnov Test for residuals, R^2= coefficient of determination of the model.

Variable	**Species**	**r**	**s**	**d**	**c**	**m**	**α_0**	**α_1**	**α_2**	**α_3**	**α_4**	**AIC**	**K-S test**	**R^2**
MCWH	*P. sylvestris*	10			C.I.	Ratio BAL_{pine}				-0.11	-1.13	646.59	0.078	0.54
	Q. petraea	10	TH			Ratio BA_{pine}		-0.095			0.273	890.47	0.007	0.78
CBH	*P. sylvestris*	5	DBH		BAL_{pine}	Ratio BAL_{pine}		-22.87		0.1	-0.41	557.21	0.227	0.71
	Q. petraea	10	DBH	$\ln(BA_{total})$	BAL_{total}	Ratio BAL_{pine}		-14.43	0.05	0.04	0.17	936.91	0.543	0.74
CPA	*P. sylvestris*	10	DBH	BA_{total}	C.I.			0.0655	0.0188	-0.0964		981.45	0.194	0.66
	Q. petraea	7.5	DBH	BA_{total}	BAL_{total}	Ratio n_{pine}	0.81	0.039	0.089	-0.186	1.154	1203.11	0.001	0.70
CV	*P. sylvestris*	10	d^2H	BA_{total}	C.I.			0.0015	0.44	2.35		1491.12	0.100	0.55
	Q. petraea	7.5	d^2H	BA_{total}	BAL_{pine}	Ratio BA	-20.28	0.003	1.03	-4.29	46.92	1904.9	0.010	0.64

We observed that the size of the tree was a significant variable for all cases, with only one exception, MCWH for pines. In all the cases, tree size affected the crown shape, the bigger the tree, the higher the CBH and MCWH were, and the wider the CPA and CV too. That was, the bigger the tree, the higher and wide the crown. Competition boosted MCWH and CPA of pines, but it was observed for the rest of the variables that, the competition had a negative effect on crown shapes for both species, and crowns were shorter and narrower.

The mixture variable was always statistically significant for oaks (Table 11). The presence of pines made the height of the oaks' crowns (MCWH and CBH) smaller, by contrast, it made their crown projection and volume larger.

Pinus sylvestris and Quercus pyrenaica

Testing site 1 fitted models in site 2 (Analysis 1)

For this first analysis, we applied the models defined in Table 7 to our second experimental site, Palacio de Valdellorma. We studied how the predicted values fit against the actual values with these models. Models over estimated MCWH values of both pines and oaks, as well as oak CBH values. This was contrary to pine CBH and oak CPA values, which were underestimated. The best fit of models was for CV, nevertheless, all the simultaneous linear hypothesis tests were significantly different from zero and one (Annex 1).

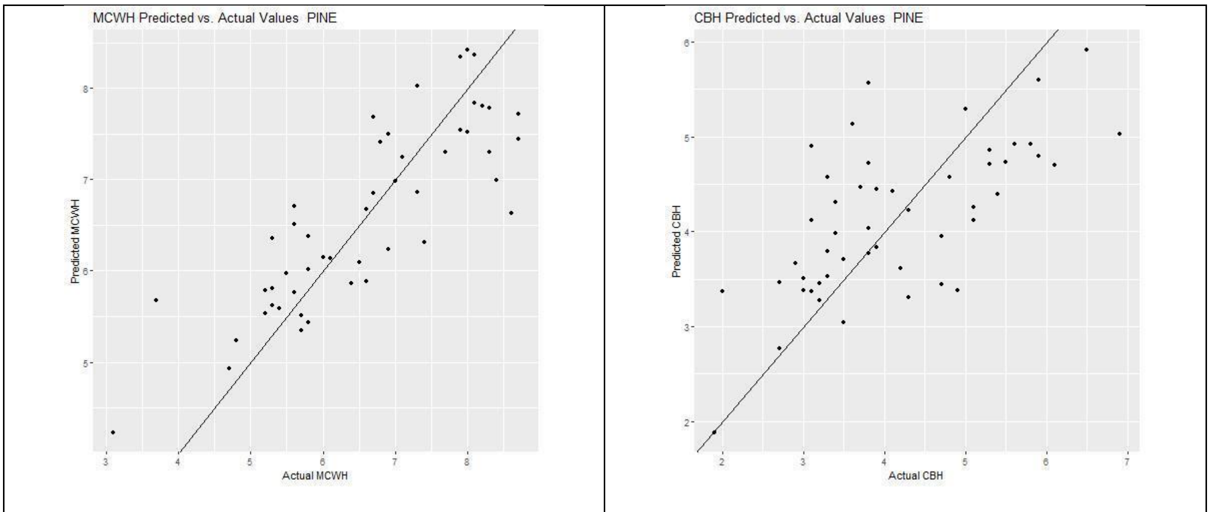
Fitting models of site 1 to site 2 (Analysis 2)

The results for the second analysis with the statistical adjustments and fitted coefficients are shown in Table 13.

Table 13. Fitted models using variables defined for the first experimental site, fitting their coefficient for this second experimental site.

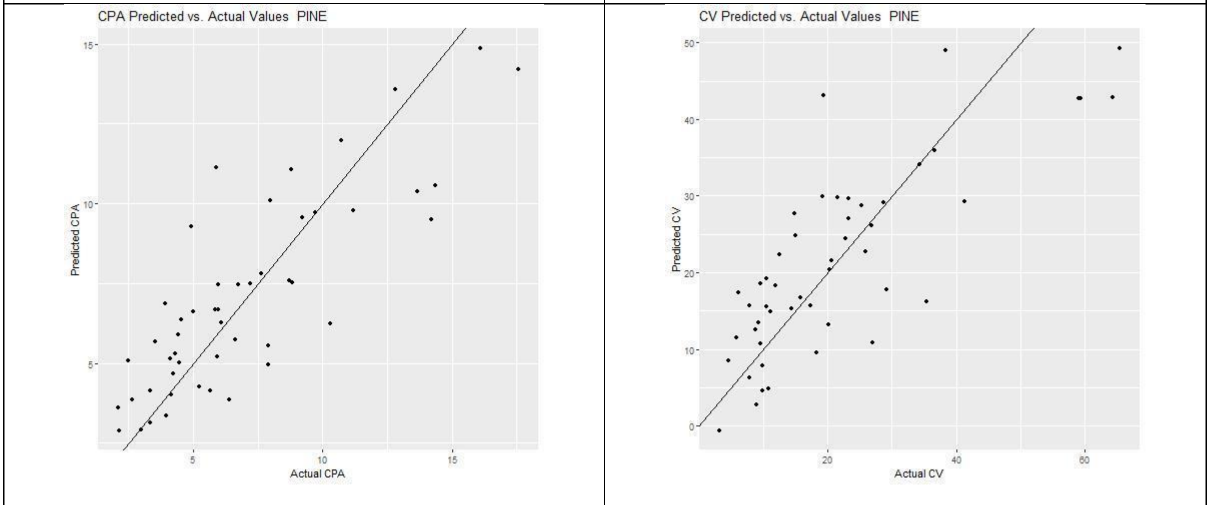
Variable	Species	r	s	d	c	m	α_0	α_1	α_2	α_3	α_4	AIC	SSE	R^2
MCWH	*P. sylvestris*	10	NA	NA	C.I.	Ratio BAL_p	NA	NA	NA	-0.02	-0.49	114.57	26.30	69.42
	Q. petraea	10	TH	NA	NA	Ratio BA_p	NA	-0.03	NA	NA	-0.99	98.68	25.50	74.30
CBH	*P. sylvestris*	5	DBH	NA	BAL_p	Ratio BAL_p	NA	3.82	NA	-1.10	0.001	132.85	36.67	44.86
	Q. petraea	10	DBH	$lnBA_t$	BAL_t	Ratio BAL_p	NA	0.77	0.22	-1.52	0.87	115.77	35.98	40.57
CPA	*P. sylvestris*	10	DBH	BA_t	C.I.	NA	NA	0.12	-0.80	0.002	NA	217.31	205.54	69.68
	Q. petraea	7.5	DBH	BA_t	BAL_t	Ratio n_p	0.15	0.02	2.46	-4.61	0.95	160.96	112.14	30.71
CV	*P. sylvestris*	10	d^2h	BA_t	C.I.	NA	NA	0.01	-21.93	0.42	NA	365.48	4227.52	62.92
	Q. petraea	7.5	d^2h	BA_t	BAL_p	Ratio BA_p	-5.84	0.001	27.87	-37.49	11.18	251.58	1217.29	34.42

In this second analysis, the new fitting for the coefficients improved the model. As shown in Figures 20 and 21. There are some large values where we performed the comparison between predicted against actual values, data follow a good correlation. In addition, the linear the multiple linear hypothesis tests we have conducted on the models show P-values > 0.05 in all cases, so the null hypothesis is accepted, slope =1 and intersection = 0.



P value = 0.47

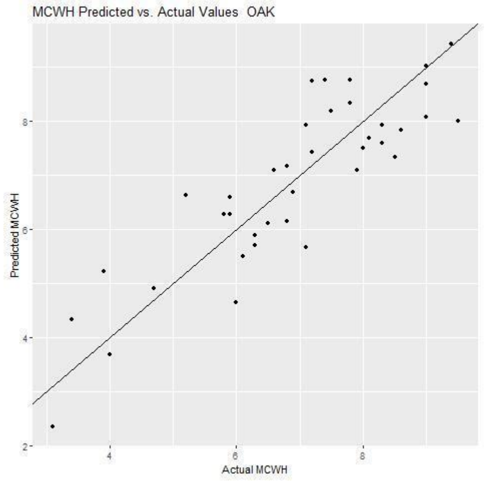
P value = 0.99



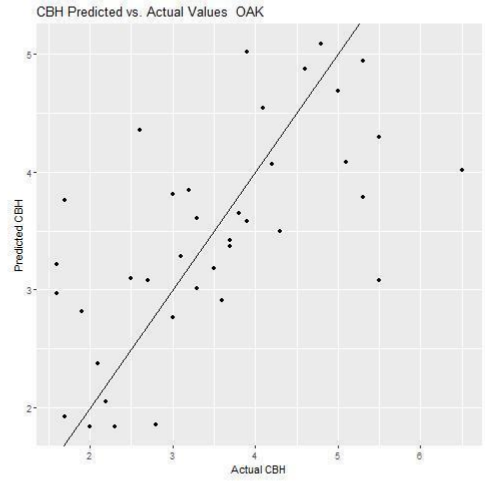
P value = 0.93

P value = 1

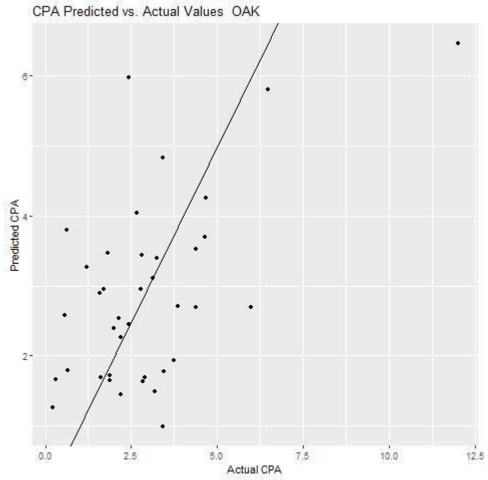
Figure 20. Predicted vs. Actual values for each variable, MCWH, CBH, CPA, and CV for *Pinus sylvestris* and its simultaneous linear hypothesis tests P-values.



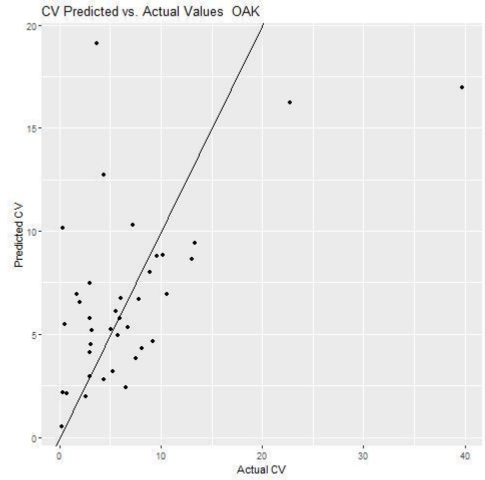
P value = 0.44



P value = 0.84



P value = 0.85



P value = 1

Figure 21. Predicted vs. Actual values for each variable, MCWH, CBH, CPA, and CV for *Quercus* sp. and its simultaneous linear hypothesis tests P-values.

Comparing the coefficient sign of the first analysis with this second analysis we observed that data coefficients had mostly kept the same sign for the oak species but not for the pines, where more than half of the coefficients changed their sign (Table 14).

Table 14. Difference coefficients for *Pinus sylvestris* and *Quercus Sp*.

Variable	analysis	Sp.	α_0	α_1	α_2	α_3	α_4	Sp.	α_0	α_1	α_2	α_3	α_4
MCWH	0	*Pinus sylvestris*	NA	NA	NA	-0.11	-1.13	*Quercus Sp.*	NA	-0.09	NA	NA	0.27
	2		NA	NA	NA	-0.02	-0.49		NA	-0.03	NA	NA	-0.99
CBH	0		NA	-22.873	NA	0.10	-0.41		NA	-14.43	0.06	0.04	0.18
	2		NA	3.823	NA	-1.10	-0.003		NA	0.77	0.22	-1.52	0.87
CPA	0		NA	0.066	0.02	-0.10	NA		0.81	0.04	0.09	-0.19	1.15
	2		NA	0.122	-0.80	0.005	NA		0.15	0.02	2.46	-4.61	0.95
CV	0		NA	0.001	0.44	-2.35	NA		-20.28	0.003	1.03	-4.29	46.92
	2		NA	0.008	-21.93	0.42	NA		-5.84	0.001	27.87	-37.49	11.18

Finally, the comparison between metrics of the models (Tables 15 and 16) shows the fit of the model was better for the model with its parameters fitted for this second experimental site. Differences between the AIC index were larger for pine than for oaks, being in both cases the variable Crown Volume the variable with less variability. The residual analysis for the selected and the model candidates is shown in Annex 2.

Table 15. Comparison of the metrics of the models for analyses 1 and 2 for *Pinus sylvestris*.

Variable	Analysis	Species	AIC	Δ AIC	% dif	SSE	R^2
MCWH	1	P. sylvestris	228.41	113.84	49.84	268.52	71.81
	2	P. sylvestris	114.57			26.30	69.42
CBH	1	P. sylvestris	270.15	137.30	50.82	604.20	47.47
	2	P. sylvestris	132.85			36.67	44.86
CPA	1	P. sylvestris	324.69	107.38	33.07	3061.64	69.97
	2	P. sylvestris	217.31			205.54	69.68
CV	1	P. sylvestris	365.48	0.91	0.24	20896.15	60.97
	2	P. sylvestris	366.39			4227.52	62.92

Table 16. Comparison of the metrics of the models for analyses 1 and 2 for *Quercus* Sp.

Variable	Analysis	Species	AIC	Δ AIC	% dif	SSE	R^2
MCWH	1	Q. petraea	134.44	35.75	26.59	65.34	34.14
	2	Q. petraea	98.68			25.50	74.30
CBH	1	Q. petraea	171.93	56.17	32.67	157.45	-160.55
	2	Q. petraea	115.77			35.98	40.57
CPA	1	Q. petraea	290.32	129.36	44.56	3374.16	-1984.64
	2	Q. petraea	160.96			112.14	30.71
CV	1	Q. petraea	253.40	1.82	0.71	18608.5	31.20
	2	Q. petraea	251.58			1217.29	34.42

Fitted models for Site 2 (Analysis 3)

We used the same approach for model selection as for the first experimental site. A total of 144 models for MCWH and CBH and 216 models for CPA and CV were fitted. Table 17 shows the variables, coefficients, and AIC values of the best resulting models. The radii of influence varied depending on the species and variable studied, but overall, we observed radii of influence were larger for oaks than for pines. Tree size and density were statistically significant variables for most of the models. Mixture variables were also significant for all the variables studied, except for CPA. Finally, the competition was only significant for oak models (except for MCWH). For pines, the competition was only significant for the CV variable. For those cases where competition was significant, the mixture was also significant with opposite sign i.e. for those cases where mixture affected negatively, competition affected positively, and the other way around. Size and density tended to appear together in the best-fitted models, with the same sign as competition and mixture for pines. Nevertheless, for oaks, density and size acted positively, i.e. the larger the oak and the higher the density of pines around the tree, the larger CPA and CV the oak had. Annex 3 shows the complete residual analysis of the first 5 models with the lowest AIC index for each variable and species for this study.

Table 17. Estimated parameter and statistical adjustment of the models.

Variable	Species	r	s	d	c	m	α_0	α_1	α_2	α_3	α_4	AIC	K-S test	R^2
MCWH	*P. sylvestris*	10	DBH	BA_t	NA	Ratio BAL_p	NA	0.03	-0.66	NA	-0.90	106.05	0.73	0.75
	Q. petraea	10	TH	NA	NA	Ratio BAL_p	NA	-0.06	NA	NA	-0.70	99.59	0.42	0.74
CBH	*P. sylvestris*	5	DBH	$\ln BA_t$	NA	Ratio BA_p	NA	12.09	-0.85	NA	-0.94	125.16	0.79	0.53
	Q. petraea	7.5	NA	NA	C.I.	Ratio n_p	NA	NA	NA	-0.05	0.53	110.91	0.53	0.42
CPA	*P. sylvestris*	5	DBH	BA_t	NA	NA	NA	0.12	-2.79	NA	NA	208.73	0.78	0.73
	Q. petraea	10	TH	$\ln BA_t$	BAL_p	NA	NA	0.26	0.43	-3.43	NA	122.43	0.86	72.1
CV	*P. sylvestris*	5	d^2h	BA_t	BAL_p	Ratio n_p	17.75	0.01	-152.77	105.53	-22.15	355.80	0.76	0.71
	Q. petraea	10	TH	BA_t	BAL_p	Ratio n_p	-20.88	1.57	31.33	-42.86	15.97	237.25	1	0. 45

Finally, the Akaike weights (AICcWt) are shown in Table 18. The best-fitted model is for CPA where the models explained 78% and 94% of the variability for pines and oaks, respectively. On the contrary, the worst fitting models were those for the Crown Volume variable, for both species where only 27% and 39% of the variability for pine and oaks were explained by the model, respectively. For MCWH, the model was best fitted for oaks than for pines, but for CBH pines CBH data were better explained by the model than for oaks.

Table 18. K: the number of parameters in the model. AICc: information score of the model. Δ_{AICc}: the difference in AIC score between the best model and the being compared. AICcWt: the proportion of the total amount of predictive power by the full set of models contained in the model being assessed. Cum.Wt: the sum of the AICc weights. LL: log-likelihood (how likely the model is, given the data).

Variable	**Species**	**Mod. Selected**	**K**	**AICc**	**AICcWt**	**Cum.Wt**	**LL**
MCWH	pine	[1]	4	106.95	0.30	0.30	-49.02
	oak	[1]	2	97.84	0.58	0.58	-46.75
CBH	pine	[1]	4	126.06	0.73	0.73	-58.58
	oak	[1]	3	111.62	0.34	0.34	-52.46
CPA	pine	[1]	3	209.26	0.78	0.78	-101.36
	oak	[1]	4	114.37	0.94	0.94	-52.58
CV	pine	[3]	5	357.50	0.27	0.27	-173.05
	oak	[1]	3	174.83	0.39	0.38	-84.03

Comparison of models: Analyses 2 Vs. 3

Comparing the two analyses, which fitted our data well, the models fitted specifically for the experimental site of Palacio de Valdellorma (Analysis 3) were always better than the models (Analysis 2) of the other experimental site with coefficients fitted for this second experimental site (Table 19). For Analysis 3, Akaike weight approaches were always up to 98% for both species, pines, and oaks.

Table 19. AIC comparison analyses 2 and 3.

Species	Variable	Analysis	K	AICc	Delta_AICc	ModelLik	AICcWt	LL	Cum. Wt
Pine	MCWH	3	4	107.2	0	1	0.98	-49.14	0.98
		2	3	115.1	7.9	0.02	0.02	-54.28	1
	CBH	3	4	126.07	0	1	0.98	-58.58	0.98
		2	4	133.76	7.69	0.02	0.02	-62.42	1
	CPA	3	3	213.8	0	1	0.9	-103.63	0.9
		2	4	218.22	4.42	0.11	0.1	-104.66	1
	CV	3	5	357.5	0	1	0.99	-173.05	0.99
		2	4	366.39	8.88	0.01	0.01	-178.74	1
Oak	MCWH	3	3	99.39	0	1	0.99	-46.34	0.99
		2	2	109.85	10.46	0.01	0.01	-52.75	1
	CBH	3	3	111.7	0	1	1	-52.5	1
		2	5	219.51	107.81	3.88E-24	3.88E-24	-103.82	1
	CPA	3	4	114.37	0	1	1	-52.58	1
		2	5	161.66	47.28	5.40E-11	5.40E-11	-74.89	1
	CV	3	3	244.93	0	1	0.996	-119.11	1
		2	6	255.8	10.87	0.004	0.004	-120.55	1

Tables 20 and 21 show the models fitted with the two analyses with the best results for pines and oaks respectively showing, (1) Analysis 2, resulting models for site 1 with the specific coefficients for Palacio de Valdellorma, and (2) Analysis 3, resulting models developed specifically for site 2. For pines (Table 20), all resulting models for site 2 (Analysis 3) were fitted with fewer variables than the resulting models from site1 (Analysis 2). Nevertheless, the differences between their AIC were small, being the largest one 8% for MCWH. On the other hand, oaks (Table 21) had a higher variability between the models, reaching a difference in AIC among models of 42% and 41% for CV and CPA, respectively.

Table 20. Comparison of analysis for Pinus sylvestris. The intercept α_0 is not shown in this table since it was not statistically significant for any of the models.

Var.	Analysis	r	s	d	c	m	AIC	Δ AIC	% dif	R^2	SSE	α_0	α_1	α_2	α_3	α_4
MCWH	3	10	DBH	BA_t	NA	Ratio BAL_p	106.05	8.52	8.04	75.33	21.22	NA	0.03	-0.66	NA	-0.90
	2		NA	NA	C.I.	Ratio BAL_p	114.57			69.42	26.30	NA	NA	NA	-0.02	-0.49
CBH	3	5	DBH	$\ln BA_t$	NA	Ratio BA_p	125.16	7.69	6.15	52.88	31.34	NA	12.09	-0.85	NA	-0.94
	2		DBH	NA	BAL_p	Ratio BAL_p	132.85			44.86	36.67	NA	3.82	NA	-1.10	0.003
CPA	3	5	DBH	BA_t	NA	NA	208.73	8.59	4.11	73.49	179.69	NA	0.12	-2.79	NA	NA
	2	10	DBH	BA_t	C.I.	NA	217.31			69.68	205.54	NA	0.12	-0.80	0.005	NA
CV	3	5	d^2h	BA_t	BAL_t	Ratio n_p	356.11	9.37	2.63	70.60	3352.25		0.01	-131.45	99.12	-5.66
	2	10	d^2h	BA_t	C.I.	NA	366.39			62.92	4227.52	NA	0.01	-21.93	0.42	NA

Table 21. Comparison of analysis for Quercus pyrenaica.

Variable	Analysis	r	s	d	c	m	AIC	Δ AIC	% dif	R^2	SSE	α_0	α_1	α_2	α_3	α_4
MCWH	3	10	NA	NA	NA	Ratio BA_p	97.50	1.19	1.22	73.74	26.05	NA	NA	NA	NA	-1.31
	2		TH	NA	NA	Ratio BA_p	98.68			74.30	25.50	NA	-0.03	NA	NA	-0.99
CBH	3	7.5	NA	NA	C.I.	Ratio n_p	110.91	4.85	4.38	41.89	35.18	NA	NA	NA	-0.05	0.53
	2	10	DBH	$\ln BA_t$	BAL_t	Ratio BAL_p	115.77			40.57	35.98	NA	0.77	0.22	-1.52	0.87
CPA	3	5	TH	NA	C.I.	Ratio BAL_p	113.16	47.80	42.24	78.12	35.42	NA	0.22	NA	-0.14	-0.49
	2	7.5	DBH	BA_t	BAL_t	Ratio n_p	160.96			30.71	112.14	0.15	0.02	2.46	-4.61	0.95
CV	3	7.5	TH		C.I.	NA	178.52	73.06	40.93	39.43	254.12		0.93		-0.35	NA
	2		d2h	BA_t	BAL_p	Ratio BA_p	251.58			34.42	1217.29	-5.84	0.001	27.87	-37.49	11.18

Fitted Wood Quality models

Following the same methodology as for the crown variables, best models (Table 22) were selected according to the lowest AIC. The analyses of the residuals of the five models with the lowest AIC are shown in Annex 4.

Table 22. Fitted models for Lean and Sweep variables, where is used Ø to represent models were the same for the three radii of influence.

Response Variable	Species	Radius of influence	Equation
Lean	Pine	10	$Lean = e^{(-1.76-0.04\cdot TH+0.003\cdot BA_t.+0.1\cdot Asym-0.26\cdot Ratio\ BA_p)}$
	Oak	5	$Lean = -1 + e^{(0.23-0.01\cdot TH-0.004\cdot lnBA_t.+0.06\cdot Asym+0.02\cdot Ratio\ BA_p)}$
Sweep	Pine	Ø	$Sweep = 0.94 + 0.002 \cdot TH - 0.013 \cdot Asym$
	Oak	Ø	$Sweep = 0.95 + 0.002 \cdot TH - 0.01 \cdot Asym$

Lean

Once the outliers are identified and removed, we work with 154 out of 190 possible outliers. With these 154 points, we fitted the linear models. We observed that the distribution of the errors followed a fan shape, in addition to other problems such as nonlinearity, as shown in Figure 22. Therefore, the resulting models were logarithmic.

$$log(Lean) = \alpha_0 + \alpha_1 \cdot size + \alpha_2 \cdot Density + \alpha_3 \cdot Competition + \alpha_4 \cdot Mixture$$

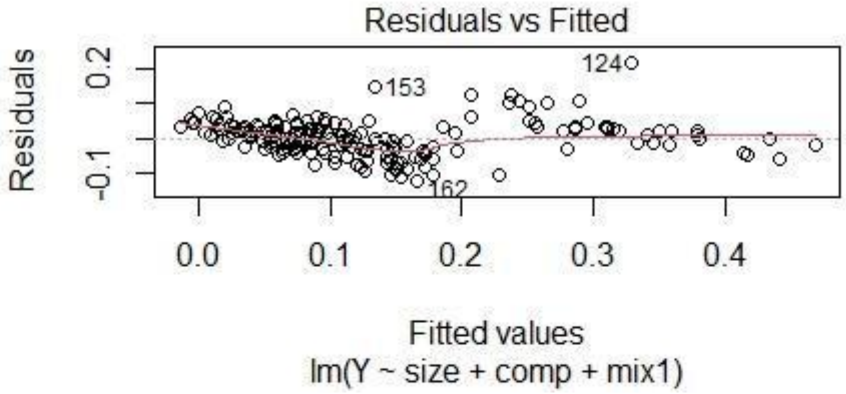


Figure 22. Residuals Vs. fitted values of the linear model for the Lean variable, violations of the equal variance and linearity assumptions.

For oaks the outlier analysis let us work with 221 out of 236 trees. For this species Lean values had values of zero, for that reason the final model is as follows:

$$log(1 + Lean) = \alpha_0 + \alpha_1 \cdot size + \alpha_2 \cdot Density + \alpha_3 \cdot Competition + \alpha_4 \cdot Mixture$$

For both, pines and oaks all variables considered (size, density, competition and mixture) were statistically significant for the fitting of the Lean variable, but the radius of influence was bigger for pine (r = 10 m) than for oaks (r = 5m) (Table 23).

Table 23. The explanatory models for the response variable Lean for each species (Sp), selected as the best fit according to their lowest AIC index and residual analysis, Pinus sylvestris (Ps) and Quercus petraea (Qp). r = radius of influence (5 and 10 m); s = size; d = density; c = competition; m = mixture; μ = intercept; β_{1-4} = the coefficient numbers for each explanatory variable (size, density, competition, and mixture); AIC = Akaike and SSE= Residual Sum of Squares.

Var	Sp	r	s	d	c	m	α_0	α_1	α_2	α_3	α_4	AIC	SSE	K-S test
Lean	Ps	10	TH	BA_t	Asym	Ratio BA_p	-1.76	-0.043	0.003	0.096	-0.256	-547.5	0.24	0.2
	Qp	5	TH	$lnBA_t$	Asym	Ratio BA_p	0.22	-0.012	-0.004	0.062	0.017	-646.1	0.66	0.7

The significant variable for size and competition were the total height of the tree and the asymmetry of the crown, respectively. The sign of the parameters for each variable indicated that the higher the tree and the less asymmetrical the crown, the more straight the stem for both pines and oaks. The density variable was different for each species, total basal area for pines, and the logarithm of total basal area for oaks. Nevertheless, the effect on the lean was the same, the higher the density around the tree, the straighter the tree. Finally, both species were affected by the mixture but in a different sense and radius of influence. For pines the bigger ratio of BA of pines within a radius of 10m the straighter the pine, but for oaks, it was the other way around, the bigger the ratio of Basal Area of pines in a radio of 5m the leaner were the oaks.

Sweep

For this variable, the residual analysis indicated a good model fit for the linear models. In this case, and after the outlier analysis we have worked with 178 pine trees out of 190 and with 202 oak data, out of 236 data. The best model selected is shown in Table 24.

For this response variable, the resulting models were the same for all three radii of influence studied, r= 5, 7.5, and 10m. The sweep of the tree was only affected by the total height of the tree (size) and the asymmetry of the crown (competition), for both, pines and oaks, in the same way. The higher the tree and the more asymmetric the crown concerning its trunk center, the less bent (sweep) the tree was.

Table 24. The explanatory models for the response variable, Sweep, for each species (Sp), were selected as the best fit according to their lowest AIC index and residual analysis. *Pinus sylvestris* (Ps) and *Quercus petraea* (Qp). r = radius of influence (5 and 10 m); s = size; d = density; c = competition; m = mixture; μ = intercept; β_{1-4} = the coefficient numbers for each explanatory variable (size, density, competition, and mixture); AIC = Akaike and SSE= Residual Sum of Squares.

Var	**Sp**	**r**	**s**	**d**	**c**	**m**	α_0	α_1	α_2	α_3	α_4	**AIC**	**SSE**	**K-S test**
Sweep	Ps		TH	NA	Asym	NA	0.94	2.11E-03	NA	-0.013	NA	-965.83	0.04	0.44
	Qp		TH	NA	Asym	NA	0.95	2.37E-03	NA	-0.013	NA	-1128.36	0.04	0.8

DISCUSSION

Fitted Crown models

In this study, we analyzed four crown variables: MCWH, CBH, CPA, and CV on a total of 242 Scots pines and 294 oaks Sp. through TLS in two experimental sites located in two different climate conditions (Atlantic and Continental Mediterranean climate) and analyzed them by linear and non-linear regression using as explanatory variables tree size, stand density, competition, and mixture proportion. Our results showed these variables affect significantly crown shape (Table 13, 20, and 21), creating a complex structure where the crown of pines are higher and narrower and the crown of oaks is shorter but wider, tending to occupy the gaps in the stand.

Stand dynamics model development is a breakthrough in sustainable forest management (Lizarralde, 2008b) within the last years, many studies have focused on mixed forests dynamics searching for a better understanding of forest species interactions (Aldea, 2018; Cattaneo et al., 2020; Himes & Puettmann, 2020; Juchheim et al., 2020; Riofrio, 2018; Rodríguez De Prado et al., 2022) to understand mixing effects and develop more precise forest practice applications (del Río et al., 2019). Within this regard, the characterization of crown species is crucial, because it gives us information on how species tend to occupy the stand canopy and helps to quantify their plasticity (Cattaneo et al., 2018). Moreover, the crown characterization is a fundamental element in the development of forest dynamics models (Fichtner et al., 2013; Lizarralde, 2008b). On the one hand, the crown provides us with information about the health of the forest, large dense crowns have been associated with vigorous growth rates, while trees with small and sparsely foliated crowns show a declining state with little or no growth (Zarnoch et al., 2004). On the other hand, the response of tree crowns to changes in canopy structure or competition occurs over a shorter period (del Río et al., 2019), thus a comprehensive understanding of crown structure can give us an insight into tree species interaction determination and thus, in decision-making and forest planning. Del Río et al. (2019) stated that the admixed species-dependent effects on tree allometry highlight the importance of considering species composition instead of species diversity since tree allometry can be influenced by between-species interactions. For this reason, in this study we have characterized the crown of one pine species (*Pinus sylvestris* L.) in combination with two oak species (*Quercus petraea* L. and *Quercus pyrenaica* Willd), considering each study individual neighbors within three radii of influence (5,7.5 and 10m), i.e. the species composition affecting the target tree within three specific circular plots. In this way, we have been able to analyze the inter and intra-interaction as a continuous variable and not based on pure and mixed stand assumptions as has been done traditionally (e.g. (Aldea, 2018; Cattaneo, 2018; del Río et al., 2019; Riofrío et al., 2017). Developing tree allometry models depending on intra- and inter-specific interaction is crucial when evaluating mixing effects (Forrester and Pretzsch 2015), as they allow upscaling of results from tree to stand level (del Río et al., 2019).

The value of this study is based on the analysis of costly measurement of tree crown variables in inventories, which usually relies on the human ability to identify precisely where the crown begins on individual trees, most of the time, this difficulty in obtaining crown data limits the studies to a specific DBH size of the tree (Zarnoch et al., 2004). Traditionally, crown data availability comes from studies that measure the crown height with a hypsometer and the crown diameter with a tape by standing under the estimated drip-line of the crown at the ends of each of these axes and measuring the horizontal distances (Zarnoch et al., 2004). Other crown studies are based on National Forest Inventories (NFI) average data, to develop crown models for species-specific crown shapes (Pretzsch, 2009). Although NFI data are a good first approach providing valuable insight, it is important to consider certain limitations inherent to them, as not all species are considered (del Río et al., 2019). Most of the important references we have nowadays to understand crown dynamics are based on these approaches (e.g. Assmann, 1961; Badoux, 1946), creating a compact geometric form in two-dimensional space (Ritter & Nothdurft, 2018) and developing Weibull distribution or non-linear regressions to quantify the crown profile. More recent studies formulated models that track vertical crown development. All of them are acknowledged to be smoothed and simplistic approximations of crown shapes that, in reality, are more irregular with fractal dimensions (Pretzsch, 2009; Ritter & Nothdurft, 2018). Thanks to TLS, we have been able to obtain more accurate crown metrics (Barbeito et al., 2017), and represent a much more efficient usage of the growing space than the maps derived from the traditional allometric models enabling us to develop more complex approaches like quantitative structure models (QSMs) (Ritter & Nothdurft, 2018) and consequently, to gain deeper insight into tree crowns' response to pines and oaks mixture, focusing on the crown structural pattern in great detail fitting our models considering the real three-dimensional shape of the crowns.

Within the last two decades, many studies have focused on analyses of the mixture of certain species with *Pinus sylvestris* e.g. (Cattaneo, 2018; Jacobs et al., 2019; Juchheim et al., 2020; Lizarralde, 2008; Riofrío et al., 2017; Seidel et al., 2013) and *Quercus petraea* e.g (Bicl-Sorlin & Bell, 2000; Petritan et al., 2014) both in pure and mixed stands, but only recently studies have been focused on *Quercus petraea* together with *Pinus Sylvestris*(Forrester, 2017; Michelot, et al., 2012; Perkins et al., 2018; Pretzsch et al., 2020; Steckel et al., 2020) despite their great distribution throughout Europe. On the other hand, little is known about both mixed and pure conditions of the crown structure of *Quercus pyrenaica* (e.g. Adame et al., 2010; Condés & Sterba, 2005; del Río & Sterba, 2009), a very important species in Spain due to forestry vocation as multiple-use forest systems (Pedrosa Meca Ferreira de Castro, 2004).

Our results suggest there is an inter and intra-specific interaction that modifies the crown shapes of pines and oaks (Table 13, 20, and 21). The differences we found between the mixtures (*Pinus sylvestris-Quercus Petraea* and *Pinus sylvestris-Quercus pyrenaica*) support what has been noted in previous studies, mixture effect on species productivity in temperate mixed deciduous-coniferous forests can depend more on species composition than on functional type (Toïgo et al., 2018).

Structural complexity necessarily involves the interaction between many different attributes (variables) (McElhinny et al., 2005). Tree DBH, stand density, and stand age are known to be correlated with the crown diameter and other crown parameters (Zarnoch et al., 2004). For that reason, in this study, we have expanded and fitted the crown models fitted by Pain & Hann, 1982; Hann et al., 2003; Sanquetta et al., 2015; and Ritter & Nothdurft, 2018 for other species. In agreement with (Lizarralde, 2008) we observed the general structures of the models were robust enough to be used on our studied species at different locations. Nevertheless, in accordance with Ritter & Nothdurft (2018), It became evident that each study site needs its own allometric models since the models fitted for Site 1, did not fit for Site 2. (Annex 1). After having adjusted the coefficients we observed the data were better fitted to the models (Figures 20 and 21) but when comparing these models with new coefficient vs. models fitted specifically for Site 2, the AIC index (Table 19) showed us clearly that data were better explained by models developed for each site.

Size effect

The relationship between crown diameter (CPA and CV) and tree size was positive in all the cases; the bigger the tree the bigger the crown diameter. Similar to Bonnor (1964) and Sprinz & Burkhart (1987), who found a strong relationship between crown diameter and DBH for *Pinus contorta* Dougl, our results showed that DBH was a good predictor together with BA for *Pinus sylvestris*. This relationship was also found for *Quercus petraea* but for *Quercus pyrenaica* the wider crown dimensions were related to the TH of the tree.

Smith (1986) found that trees exhibiting the greatest height growth are usually the largest in all dimensions, including crown size. Pommering & Grabarnik (2019) found that, the more growing space a tree is granted, the longer is its crown and the smaller its height diameter ratio. Our models suggest the same, as we found a positive effect in the crown width (CPA and CV) of every tree species when increasing the DBH or TH of the tree, but a negative effect for crown length (MCWH and CBH), i.e. the smaller the tree, the larger their crowns but wider.

Density and Competition effect

Our results are partially in agreement with Pretzsch & Biber (2016) who found that due to a better supply and more efficient use of resources, maximum stand density can be larger in mixed species. An increase in stand density had a positive effect for *Quercus petraea* when growing with *Pinus sylvestris* but not the opposite. Nevertheless, *Pinus sylvestris* did show a positive effect on its crown when in mixture with *Quercus pyrenaica*.

The relationship between density and competition we found for the mixture *Pinus sylvestris-Quercus petraea*, in line with Pretzsch et al. (2017) interspecific competition effect on tree allometry was more relevant for crown projection area and Crown Volume than for the other allometric relationships. These two variables were opposite for both species, which suggests increased inter-competition when decreasing total density. For *Quercus petraea,* this same relationship was also found for the CBH variable.

This apparent rapport between oaks growing together with pines may agree with relaxing resources competition in mixed forests that lead tree species to temporal diversification and spatial niche partitioning as suggested by Williams et al. (2017) and Aldea (2018). Juchheim et al. (2017), found in a mixture between *Pinus sylvestris* with *Picea Abies* and *Fagus sylvatica* lower BA exhibited a greater Stand Structural Complexity Index. For the Pine-oak mixture, we found, the same results for pines, a decrease in BA resulted in wider crowns increasing the inter-competition. Nevertheless, our results suggest the mixture benefits *Quercus petraea* where we found the opposite relationship, crowns were wider when increasing the mixture with pines and thus, their BA, decreasing the competition, creating a more heterogeneous and complex stand structure agreeing with (del Río & Sterba, 2009), which found that Scots pine-oak mixed stands support higher volume increment per occupied area compared to pure stands, i.e. pine did not act as a real competitor and, therefore, the oak had larger crown dimension when mixed with pine (del Río et al., 2019).

The seeming complementarity between density and competition showed in our models are in line with other studies (Hemery et al., 2005; Jucker et al., 2015; Ritter & Nothdurft, 2018), which have shown that, especially in mixed-species stands, crown plasticity enables trees to optimize canopy packing, to reduce inter-tree competition, and to maximize the utilization of available photoactive radiation. The competition reduction and facilitation mechanisms found in these mixtures lead to admixture positive effects on forest productivity and are commonly interpreted on the basis of complementarity (Ammer, 2019).

McElhinny et al. (2005) found the density of shade-intolerant tree species to be the most significant explanatory variable in multiple regression, this statement seems to be fulfilled for the mixture *Pinus sylvestris-Quercus petraea* but not for the mixture *Pinus sylvestris-Quercus pyrenaica,* our models did not show a significant relationship between density and competition but they were in line with del Río et al. (2019), showing that, oak competition did not affect *Pinus sylvestris* and, density did no result significant for *Quercus pyrenaica*. But oak crowns were wider the less competition for any of the crown studied variables. A plausible explanation for this result can be found in Muñoz-Gálvez et al. (2021) who stated that *Quercus pyrenaica* increased its competitive ability under non-limited water availability. Due to the Mediterranean climate characteristics of the experimental site, water availability is an important factor to consider.

Muñoz-Gálvez et al. (2021) stated competition reduction usually occurs through niche partitioning, due to inter-specific differences in physiology, morphology, and phenology. Our models show these differences also occur at the intra-specific level. A result of this inter and intra-specific relation leads to disparate resource acquisition strategies (Forrester & Bauhus, 2016).

Mixture effect

Pines and oaks are classified as species with high morphological plasticity (Pretzsch & Rais, 2016) and changes in crown structure due to mixing effects have previously been reported for different mixtures (Barbeito et al., 2017; Martin-Ducup et al., 2016; Pretzsch, 2014). Inter-specific interaction was studied for oaks in combination with pines and it was found the presence of pines made oaks CBH lower but higher MCWH. the mixture affected differently on CPA of *Quercus petraea* and *Quercus pyrenaica*, making crowns wider for the first one and narrower for the second one. For pines, the intra-specific interaction was studied. We found this relation is significant for CBH and MCWH resulting in higher crowns the more pines with a Larger Basal Area around the target pine. Crown expansion (CV and CPA) was only significant for the Crown volume of the pines for the mixture *Pinus sylvestris – Quercus pyrenaica*.

Our findings suggest that crown oaks, in presence of pines, remain under the crown pines, occupying the space between pine stems, that may be the reason why crown oaks are shorter but wider, contrary to pines where crowns start at a higher point when growing together with oaks. This way, it seems species mixing modify the crown size and shape, and thereby the canopy space-filling (Bauhus et al., 2017). Some researchers have hypothesized differences in crown shape between deciduous broadleaves and evergreen conifers are the origin of a positive mixture effect on species productivity in broadleaved-conifer mixed stands (Pretzsch & Schütze, 2009). Fitted models suggested that mixture increases stand structural complexity index as pointed out in Juchheim et al. (2020) due to better use of the available light, and thus, both species benefit from mixing (Cattaneo et al., 2020; Jucker et al.,

2014) when growing species with functional differences as shade tolerance, leaf habit and rooting depth (del Castillo et al., 2016). Shade-tolerant species tend to have a crown shape optimized for the capture of light under limiting conditions (Aiba & Nakashizuka, 2009), and within mixtures, force non-tolerant species to grow to reach the upper canopy level. Additionally, a resource use complementarity appears when in winter the lack of leaves in oak allows pine trees to capture light and photosynthesize. These complementary functionalities between study species can lead to a higher resource use efficiency in mixed stands (Forrester & Bauhus, 2016). Our results suggest interactions in these pine-oak mix forests which reduced competition, which may involve a complementary and efficient use of resources over time (Forrester, 2014) between shade-tolerant and shade-intolerant species (McElhinny et al., 2005; Pretzsch et al., 2016). Also, explained by differences in foliage persistence during the year (Bravo et al., 2021), which may also cause changes in tree species' crown allometry (Toïgo et al., 2018), creating inter-specific variations in crown architecture and height, when combining species with different shade tolerances or vertically-oriented species with more laterally expanding tree species (Ammer, 2019; Pretzsch & Schütze, 2014).

Within this context, it seems, that shade-tolerant oak species develop safer life strategies (Cuny et al., 2012) and we hypothesize that pine-oak mixture leads to the facilitation of oak over pine, as pine seemed to increase the performance of the coexisting species (Pretzsch et al., 2017). Species interactions such as facilitation or reduced competition between species can enable the use of more site resources and with greater efficiency (Forrester, 2014). Pretzsch & Zenner, 2017 found the complementary use of resources – mixing light-demanding with shade-tolerant species, deep-rooting with shallow-rooting species, or evergreen with deciduous species – to be the main cause of over-yielding from mixed stands. Our findings seem to meet all these requirements, respectively. Pine species may have a more advantageous growth strategy, as they are fast-growing in springtime, pioneering, light-demanding, and may experience autumn growth (cell enlargement or xylem differentiation for maritime pine). The growth of dominant pine trees might be accelerated permanently thanks to reduced competition from oak (the effect of a rather translucent species) or facilitation (hydraulic water redistribution), and this superiority may extend over the entire tree lifespan (Pretzsch et al., 2017). On the other hand, the shallow rooting and shade tolerance provide also oak with a competitive advantage due to temporal diversification of space occupation, which may relax resource competition via morphological and physiological trait differences (Mallo, 2018).

The apparent reducing competition found in *Quercus petraea* suggests that the asynchronous growth responses of mixed tree species can also decrease abiotic stress, diminish temporal growth variation and stabilize productivity over time (del Río et al., 2017; Jucker et al., 2014; Sterba et al., 2014). This crown complementarity has been proved to be greater when there are greater differences in the functional traits of the species such as growth rate or crown structure (del Río et al., 2019; Williams et al., 2017).

Site effect

The radii of influences we set to study each variable were different, but it was observed a slight tendency for the mixture *Pinus sylvestris-Quercus pyrenaica* to be smaller than *Pinus sylvestris-Quercus petraea.* We hypothesized this could be related to the site conditions rather than the mixture. Since in the first mixture, trees were located in terraces due to the strong slope of the terrain, which may cause more changes in a smaller radius, this fact can also be related to the similarity between species across sites. Our expectations were, that developed models for both experimental sites would be more similar between pines than oaks, as pines were the same species, *Pinus sylvestris* in both sites, and oaks species were different. *Quercus petraea* for the first experimental site 1 (Valberzoso), and *Quercus pyrenaica* for the second experimental site (Palacio de Valdellorma). However, our results were the opposite, more similar among oaks and less among pines. These differences might be explained by different external factors. Del Río et al. (2019) found the higher the elevation the smaller the crown diameter for different species combinations, among them *Pinus sylvestris* and *Quercus petraea.* In this study, we had 400 m of differences across sites. And the models fitted for the higher experimental site *(Pinus sylvestris-Quercus petraea*) presented more constraints, i.e. they used more explanatory variables, than for the lower site (*Pinus sylvestris-Quercus pyrenaica*). On the other hand, positive interactions among species are more common in areas with high environmental stress, which is the case of drought-limited forests in Mediterranean mountains (Muñoz-Gálvez et al., 2021) as occurred in our *Pinus sylvestris-Quercus pyrenaica* mixture located in a Mediterranean climate.

We hypothesized this difference was due to the dominance of pines species, similarly influencing their neighborhood regardless of the oak species, while oaks affect pines differently since they are different species and sites. So we can conclude there is a site condition effect. Some studies in mixed stands showed that conifers have access to shallower water resources while oak species can access deeper ones due to a more extensive and deep root system (del Castillo et al., 2016; Muñoz-Gálvez et al., 2021; Poyatos et al., 2008).

Ecology of species

Toïgo et al. (2018) pointed out that it exists either a competitive advantage of *Quercus petraea* over a more light-demanding species, like *Pinus sylvestris* or a result of the complementary use of resources in the mixture. For *Quercus pyrenaica*, competitive capacity could allow this species to maximize light and nutrient capture in mixed stands under non-limited water conditions (Longuetaud et al., 2013; Muñoz-Gálvez et al., 2021). Unlike other deciduous species, which have a remarkable capacity to adjust their morphology and physiology to a particular set of light conditions (Delagrange et al., 2006). Mediterranean oaks present low plasticity as a result of a conservative resource-use strategy (Valladares & Niinemets, 2008). However, it has been found that shade-tolerant species strongly depend on the availability of other natural resources (Sánchez-Gómez et al., 2006).

On the other hand, *Pinus sylvestris* is likely to benefit from increased nutrient availability, competition for light could offset positive admixture effects under moderate to high water availability conditions due to larger leaf areas (Jucker et al., 2014). However, in this context, *Quercus pyrenaica* could be favored over *Pinus sylvestris* due to its broad-leaved habit and higher tolerance to shade (Valladares & Niinemets, 2008).

Fitted Wood Quality models

Our results suggest that there are physiological and morphological differences. A total of 49 pines and 38 oaks were analyzed. Our results (Tables 23 and 24) suggest both *Pinus sylvestris* and *Quercus petraea*. Opposite to Höwler et al. (2017) who found these variables to be significant in smaller radii of influence (5 and 7.5), we found the radius of influence does not affect the fitted models.

Our models suggest, that the shorter the tree the less lean (bent), and the higher the tree, the more sweep (crooked). Benneter et al. (2018) found no influence of species diversity on wood quality, however, our results suggest this is true only for the sweep variable, suggesting tall trees imply higher relative allocation and, hence, reduced allocation to branches and photosynthetic biomass (Sierra-de-Grado et al., 2022)

Density, Competition, and Mixture effect

It has been reported stem forms in forests depend on tree genetics (White et al. 2007) but our study seems to be more in line with Sierra-de-Grado et al., 1997 who stated, that the straightness of trees could be also due to mechanical stress responses. The straightness of pines and oaks, were related to the BA (Density) which oppositely affected each species, being pines leaner as the surrounding BA increased and oaks as the surrounding BA decreased. Within this regard, coefficients of the models showed this effect to be greater in pines than in oaks, which can be explained since deciduous trees shed their leaves in winter and thereby reduce the wind resistance of the crown (Pommerening & Grabarnik, 2019).

Competition, seen as the asymmetry of the crown, also played a piece of significant information to this variable, showing for both species the more asymmetry the leaner is the stem but also less sweep. Different authors (e.g. Moulia et al., 2019; Moulia & Fournier, 2009; Schüler et al., 2015), found the asymmetry of trees is a consequence of a physiological response of the tree when a stem is tilted provoking a curvature in them (Sierra-de-Grado et al., 2022).

Finally, mixture and density affect only the lean variable, in an opposite and complementary way. For pines, the more density and less proportion of pines, the straighter is the stem. On the contrary, the less density and bigger proportion of pines the leaner is the oak. We argue, as Höwler et al. (2017) found for beech trees, that higher stem qualities for oaks are pure rather than in mixed conditions. Therefore, the straightness of a tree trunk depends not only on external factors inducing curvature but also on intrinsic factors (Sierra-de-Grado et al., 2022).

Asymmetry of the crown

According to our results, we hypothesize, as found in other studies where they studied saplings of other species (Apiolaza et al., 2011; Lachenbruch et al., 2010; Sierra-de-Grado et al., 2022) there was an intraspecific variation of the trunk regarding the sweep of the stems. Since only the height of the tree and the asymmetry of the crown were the significant variables in our fitted models. Reinforcing the hypothesis of Höwler et al. (2017), intraspecific competition is much stronger than interspecific interference.

The opposite relation in Lean and Sweep we found regarding the asymmetry of the crown may be in line with Sierra-de-Grado et al. (2022), who found straight-type plants dedicated comparatively more biomass to the main stem, while crooked-type plants dedicated more resources to leaves, hence the crooked-type plants ‘ignored’ to some extent the function of mechanical support.

Final remarks

As a final remark, it should be noted our study plots had not been thinned in the last 10 years but previous silviculture could have been caused a residual effect in our findings due to the memory effect found in the forest stand dynamic (Lara et al., 2013; Pretzsch, 2009) as modified structure then affects the processes in the forest ecosystem (Pommerening & Grabarnik, 2019). The origin of the forest, i.e., plantation or natural regeneration may affect trees and associated vegetation relative to those in monocultures (Himes & Puettmann, 2020), the same way we are seeing in our study combining pine plantation with natural oak resprouting where we have found trees' neighborhood seems to be affecting crown allometry.

Long-term records of forest cover and change are needed across a broad range of investigations (Feng et al., 2016). Within this regard, observation of mixed forests and general findings are still rare (Pretzsch et al., 2017) especially when involving individual tree analysis (Pommerening & Grabarnik, 2019). Thanks to TLS we have been able to fit new crown models and develop new quality models through the analysis of more than 500 individual trees, providing accurate information on species interactions that can be implemented in forest simulators. This information will help forest managers to design more effective silvicultural prescriptions to select the most suitable frame of plantation between species combinations, considering the size, density, competition, and mixture effect within species. Thanks to this, our forests will be not only more productive but also more resistant and resilience face to extreme and unexpected events.

CONCLUSIONS

1. TLS is very useful for nondestructively examining external crown and stem characteristics of this tree species, which can substantially reduce fieldwork data collection. TLS is very easy to use and capable of adapting to any kind of terrain with batteries that last a long time. It was proven that not much resolution is needed to obtain good data, although they should be taken during periods of dormancy to ensure good visualization of the tree canopy. However, its greatest limitation to being perfectly incorporated as a forest management tool remains in the data processing time, which is still very time consuming and still only semi-automatic making manual intervention needed. This need for manual intervention grately limits the advantages that this device has in terms of data acquisition. In the last two years, much new software has been developed that can maybe help to solve this limitation, and thus, TLS will be perfectly integrated as a tool in forest management, but, for now, TLS is a great research tool as it allowed us to assess and quantify the crown and timber quality of three tree species.
2. It was shown, that fitted crown models should be specific for every site and mixture. However, models of one site can work for other sites. When comparing the models with the AIC index, we saw models for each of the sites were able to explain in all cases more than 90% of data and adjusted coefficient no more than 5%.
3. Our results suggest a complementarity in canopy space occupation, which creates a multi-layered canopy (stem diameter and height variety) in oak-pine stands in Northern Spain. We hypothesize that multi-layered canopies are produced by the mixture complementarity of crown shapes of pines and oaks due to their differential crown architecture and the combination of shade-tolerant and shade-intolerant, resulting in oaks with wider crowns and pines with larger stems to be able to capture the light above oaks.
4. This research has given us a comprehensive work focused on the crown structure of *Pinus sylvestris* – *Quercus petraea* and *Pinus sylvestris* – *Quercus pyrenaica* mixture. Showing more positive effects for oaks due to the mixture than for pines, and proving inter and intra-specific relations between species. Similarities between *Quercus* Sp. were bigger than *Pinus sylvestris* across sites, we hypothesize this is due to site conditions.
5. We developed two models for analyzing wood quality in *Pinus sylvestris* and *Quercus petraea* through Lean and Sweep of stems. We found crown asymmetry is an important factor that compromises the straightness of the stem, adding, this way, another important value to the crown architecture of trees. Finally, based on our results, we hypothesized the Lean of the stems is determined by an interspecific relationship, but the Sweep of the stems seem to be an intrinsic condition of the tree.

CONCLUSIONES

1. El TLS resulto ser un aparato muy útil para examinar las características externas de la copa y el tronco sin tener que apear el árbol y además reduce significativamente el trabajo de toma de datos en campo. Es muy fácil de usar y, capaz de adaptarse a cualquier tipo de terreno con baterías muy duraderas, y quedó comprobado que no se necesita mucha resolución para obtener buenos datos, aunque deben tomarse en periodos de letargo para asegurar una buena visualización del dosel arbóreo. Si bien, su gran limitación para incorporarse perfectamente como herramienta de gestión forestal sigue estando en el tiempo de procesado de los datos, que es muy lento ya que se trata todavía de un proceso semiautomático por lo que se necesita la intervención manual, descompensando totalmente la gran ventaja que tiene este dispositivo en cuanto a la adquisición de datos. En los dos últimos años se han desarrollado muchos programas informáticos nuevos que puede que ayuden a incorporar de forma definitiva el TLS en la gestión forestal, pero, por ahora, es una gran herramienta de investigación, ya que nos permitió evaluar y cuantificar los efectos de la interacción de tres especies arbóreas en su copa y en la calidad de la madera.
2. Quedó demostrado que los modelos ajustados de copa deben ser específicos para cada sitio y mezcla. Aunque los modelos de un sitio pueden funcionar bastante bien para otros sitios, al comparar los modelos con el índice AIC vimos que los modelos para cada uno de los sitios eran capaces de explicar en todos los casos más del 90% de los datos y el coeficiente ajustado no superaba el 5%.
3. Nuestros resultados sugieren una complementariedad en la ocupación del espacio del dosel, que crea un dosel complejo con diferentes alturas y tamaños (variedad en el diámetro y altura del árbol) en las masas mixtas de pino y roble del norte de España. Nuestra hipótesis es que esta diferencia de alturas en el dosel arboreo mixto de pinos y robles se producen por la complementariedad de sus formas de, debido a su arquitectura diferencial de copas y a la combinación temperamentos, tolerantes y no tolerantes a la sombra, lo que da como resultado robles con copas más anchas y pinos con troncos más largos para poder captar la luz por encima de los robles.
4. Esta investigación nos ha proporcionado un trabajo exhaustivo centrado en la estructura de la copa de la mezcla *Pinus sylvestris* - *Quercus petraea* y *Pinus sylvestris* - *Quercus pyrenaica*. Mostrando efectos más positivos para los robles debido a la mezcla que para los pinos, y probando las relaciones inter e intraespecíficas entre las especies. Las similitudes entre *Quercus* Sp. fueron mayores que las de *Pinus sylvestris* en todos los emplazamientos, lo que, según nuestra hipótesis, se debe a las condiciones del lugar.

5. Desarrollamos dos modelos para analizar la calidad de la madera mediante la inclinación y el retorcimiento de los troncos. Encontramos que la asimetría de la copa es un factor importante que compromete la rectitud del tronco, añadiendo, de esta manera, otro valor importante a la arquitectura de la copa de los árboles y que asi como la inclinacion de los troncos si que viene determinada por la relacion interespecifica, el retorcimiento de los troncos parece ser una condicion intrinseca del arbol.

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ANNEX 1

Crown models of the mixture *Pinus Sylvestris - Quercus Petraea* applied in the mixture *Pinus Sylvestris - Quercus Pyrenaica*.

Annex 1.

CROWN MODELS OF THE MIXTURE *PINUS SYLVESTRIS-QUERCUS PETRAEA* APPLIED IN THE MIXTURE *PINUS SYLVESTRIS-QUERCUS PYRENAICA*.

Pinus sylvestris

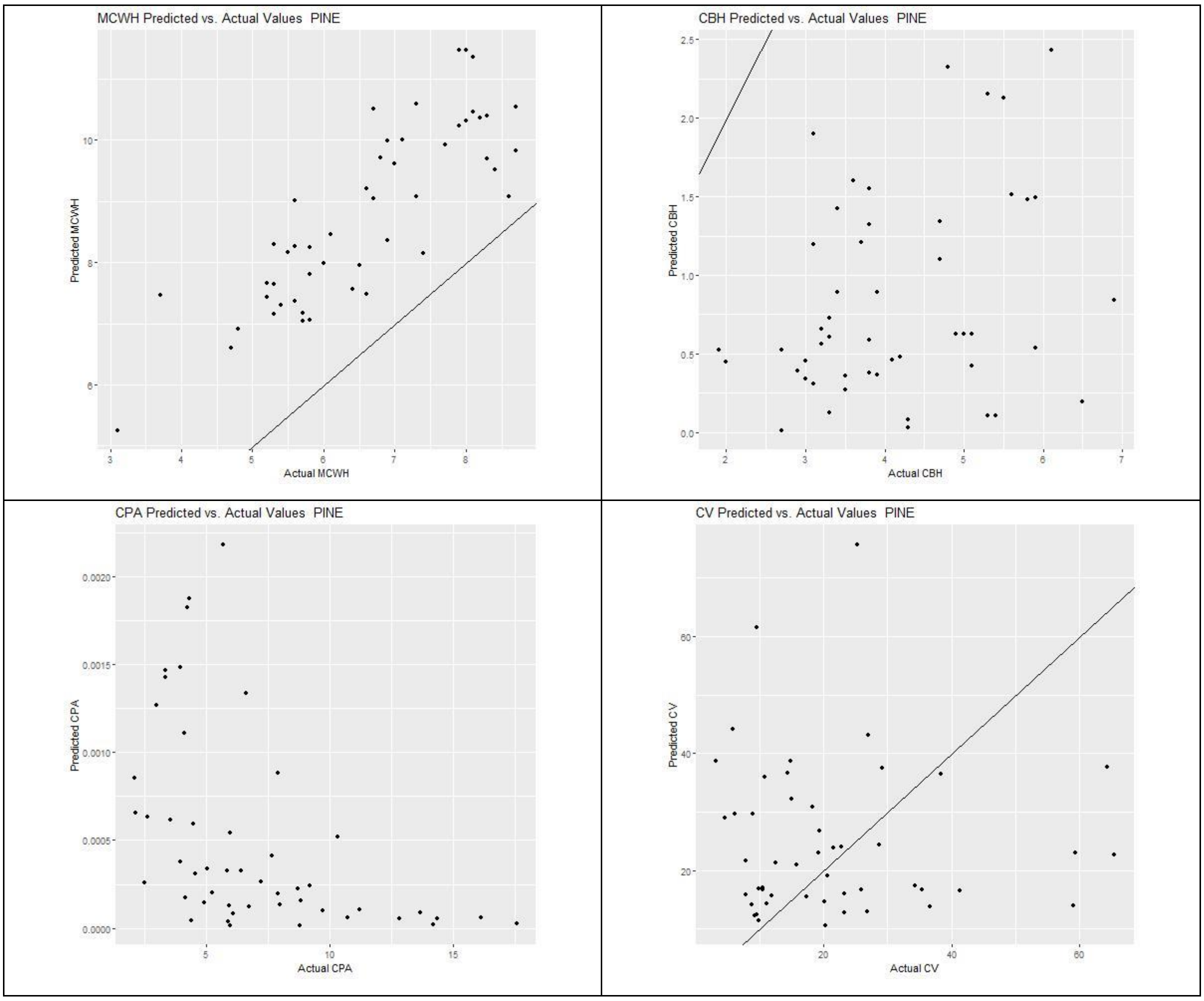

Figure 1. Predicted Vs Actual values for pines.

Quercus pyrenaica

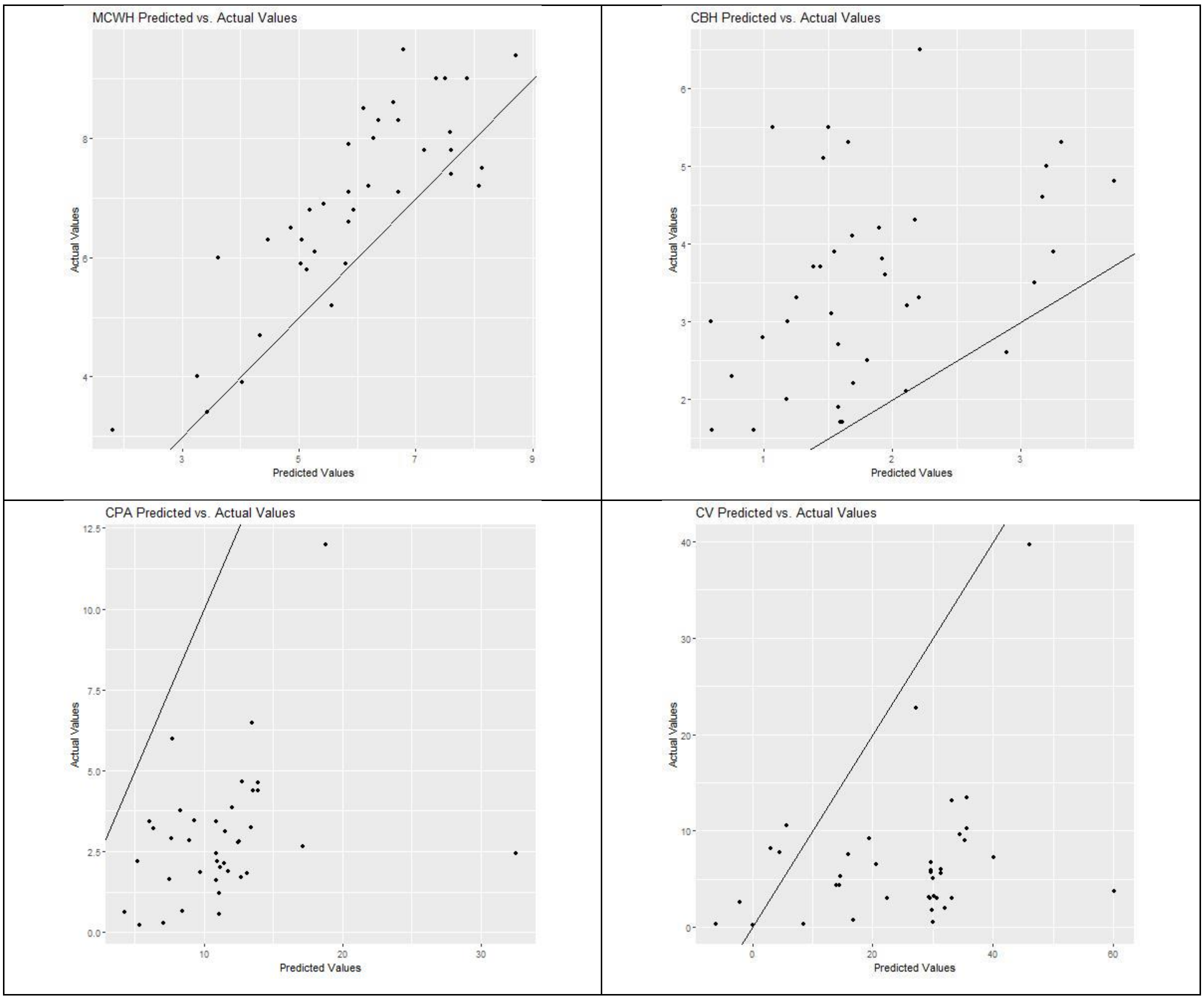

Figure 2. Predicted Vs Actual values for oaks

ANNEX 2

Residual analysis for the mixture *Pinus Sylvestris – Quercus Pyrenaica* (Analysis 2)

Annex 2

RESIDUAL ANALYSIS FOR THE MIXTURE PINUS SYLVESTRIS – QUERCUS PYRENAICA (ANALYSIS 2)

1. PINE: Maximum Crown Width Height (MCWH)

$$MCWH = \frac{TH}{1 + e^{(-0.02 \cdot CI - 0.49 \cdot Ratio\ BAL)}}$$

Table 1. MCWH pine analysis 2

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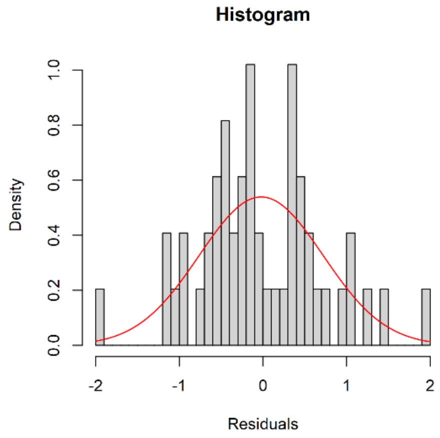
Histogram

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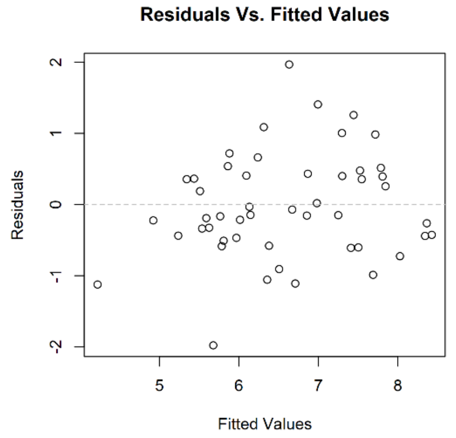
Residuals Vs. Fitted Values

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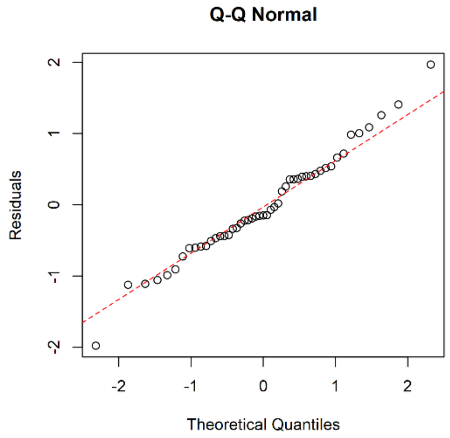

Q-Q Normal

</td>
<td>
Residual standard error: 0.7481 on 47 d.f.
R^2 = 69.41915
p-value = 0.5662
SSE = 26.30116
AIC = 114.5678
</td>
</tr>
</table>

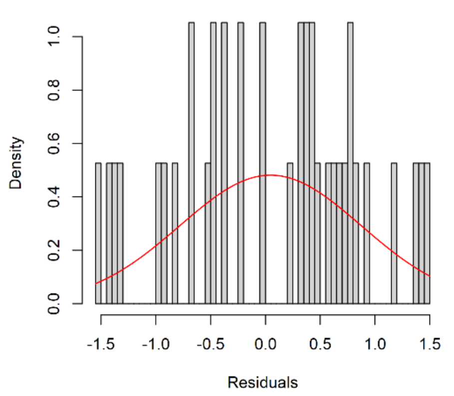
2. OAK: Maximum Crown Width Height (MCWH)

$$MCWH = \frac{TH}{1 + e^{(-0.03 \cdot TH - 0.99 \cdot Ratio\ BA)}}$$

Table 2. MCWH oak Analysis 2

<table>
<tr>
<td>

Histogram



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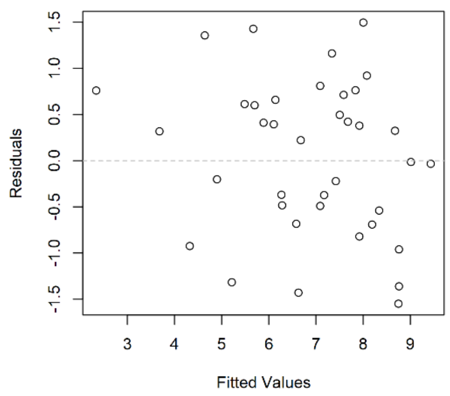
Residuals Vs. Fitted Values



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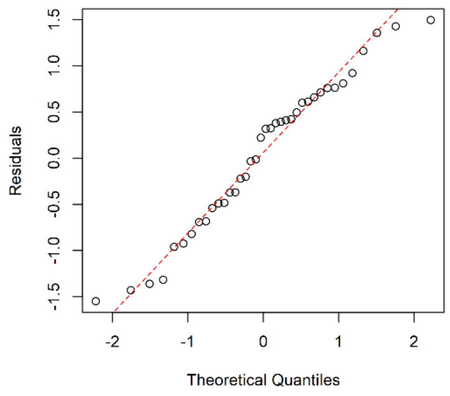
Q-Q Normal



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<td>

Residual standard error: 0.8417 on 36 degrees of freedom
R^2 = 74.29618
p-value = 0.3323
SSE = 25.50258
AIC = 98.68469

</td>
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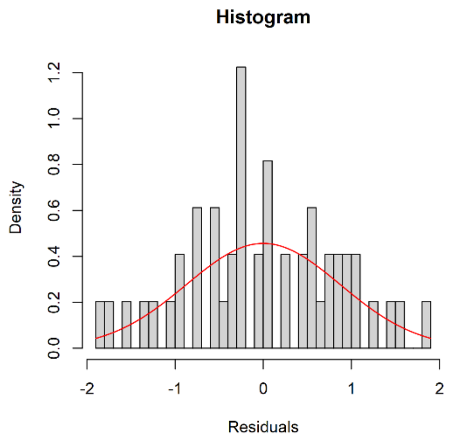
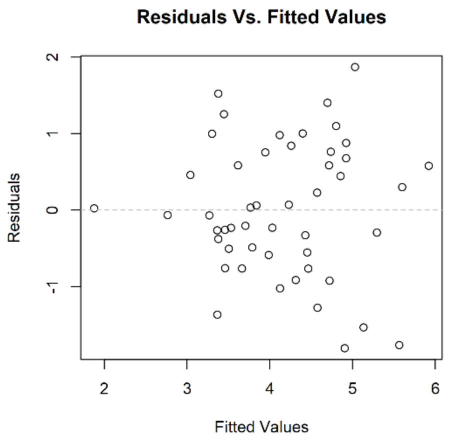
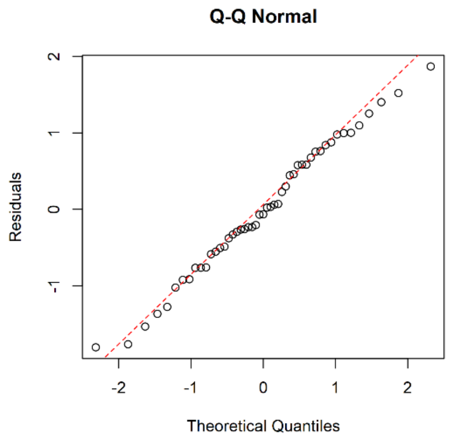
</table>

3. PINE: Crown at Base Height (CBH))

$$CBH = \frac{MCWH}{1 + e^{\left(3.82 \cdot \frac{DBH}{lnBA} - 1.1 \cdot BALp + 0.001 \cdot Ratio\ BAL\right)}}$$

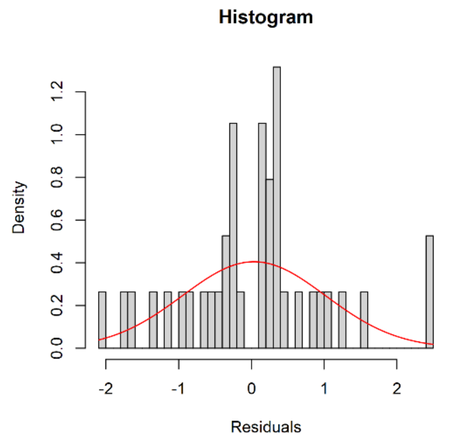
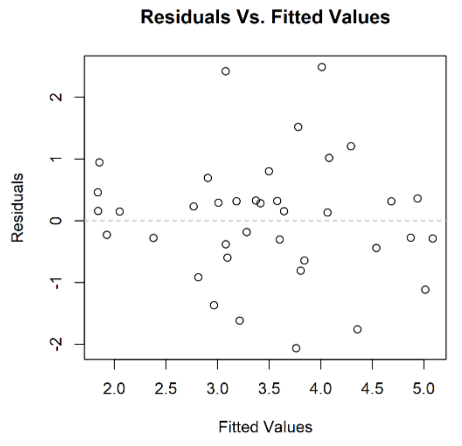
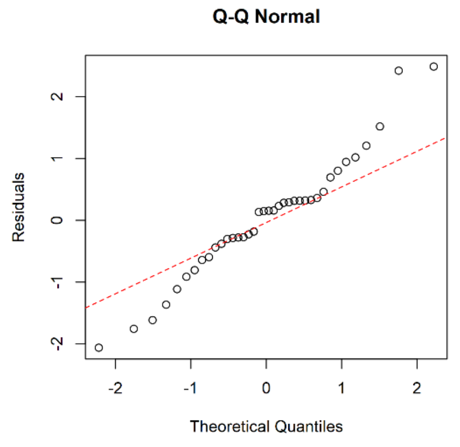
Table 3. CBH pine analysis 2

	
	Residual standard error: 0.8928 on 46 degrees of freedom R^2 = 44.86449 p-value = 0.9422 SSE = 36.66646 AIC = 132.848

4. OAK: Crown at Base Height (CBH)

$$CBH = \frac{MCWH}{1 + e^{\left(0.77\cdot\frac{DBH}{lnBA} + 0.22\cdot lnBA - 1.52\cdot BALt + 0.87\cdot Ratio\ BAL\right)}}$$

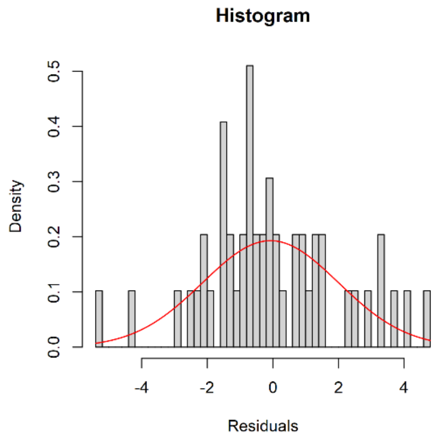
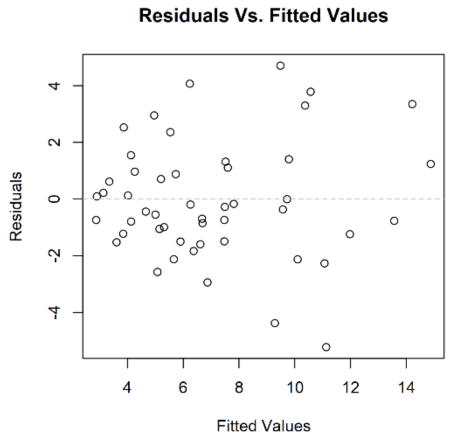
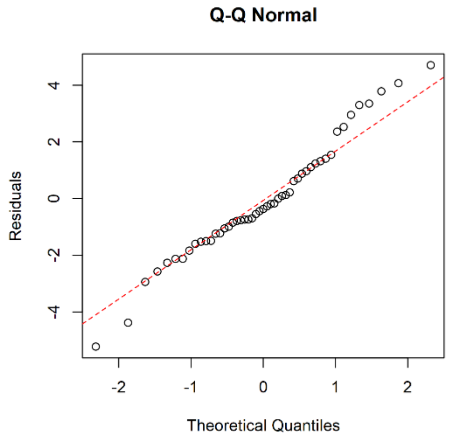
Table 4. CBH Oak Analysis 2

	
	Residual standard error: 1.029 on 34 degrees of freedom R^2 = 40.57473 p-value = 0.5979 SSE = 35.98185 AIC = 115.7656

5. PINE: Crown Projection Area (CPA)

$$CPA = e^{(0.12\cdot DBH - 0.8\cdot BA_t - 0.002\cdot CI)}$$

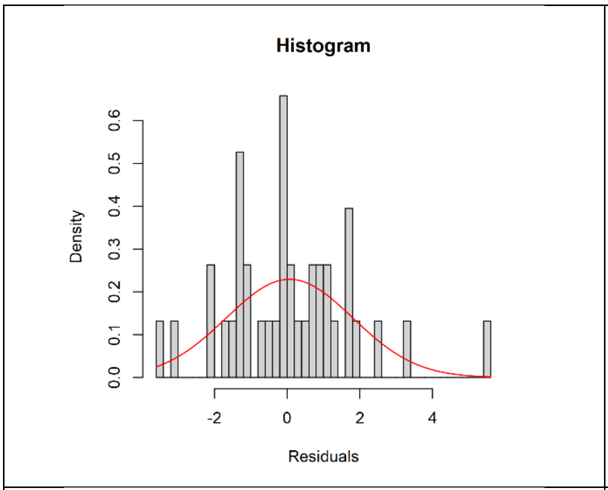
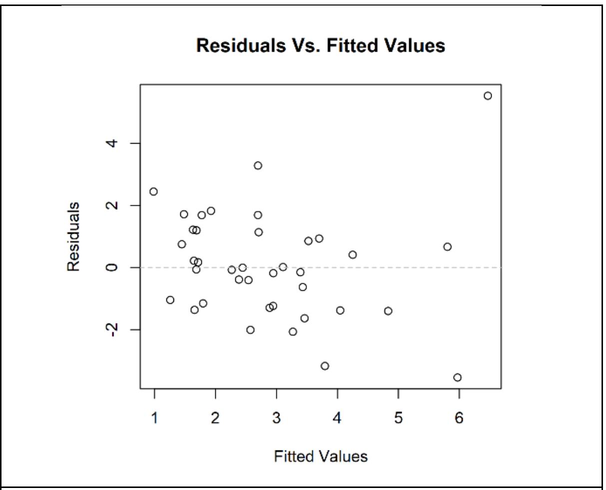
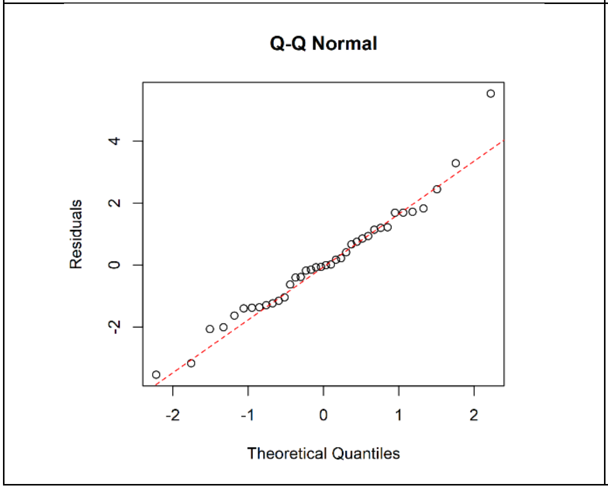
Table 5. CPA pine analysis 2

	
	Residual standard error: 2.114 on 46 degrees of freedom R^2 = 69.67994 p-value = 0.5437 SSE = 205.5402 AIC = 217.3132

6. OAK: Crown Projection Area (CPA)

$$CPA = e^{(0.15+0.02 \cdot DBH+2.46 \cdot BA-4.61 \cdot BAL+095 \cdot Ratio\ n)}$$

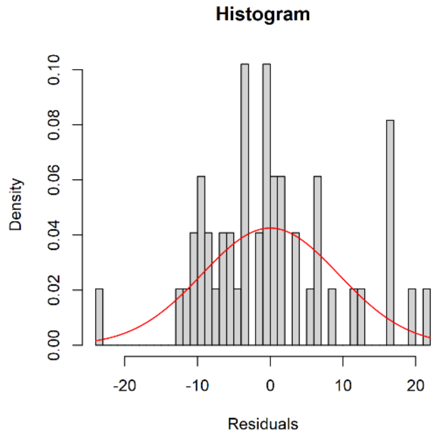
Table 6. CPA Oak Analysis 2

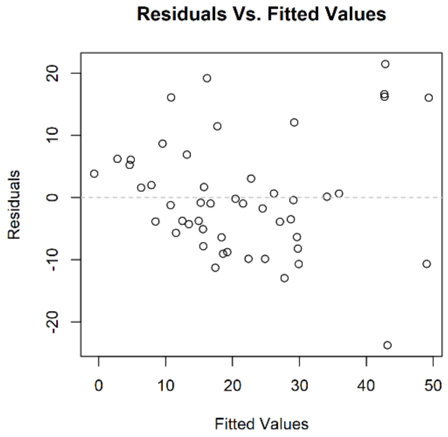
	
	Residual standard error: 1.843 on 33 degrees of freedom R^2= 30.71497 p-value = 0.958 SSE = 112.1433 AIC = 160.9626

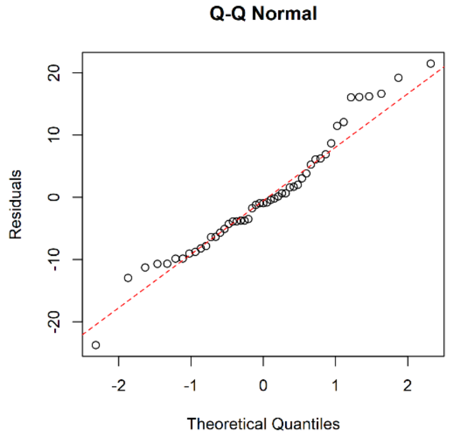
7. PINE: Crown Volume (CV)

$$CV = 0.01 \cdot d^2 h - 21.93 \cdot BA_t + 0.42 \cdot CI$$

Table 7. CV pine analysis 2







Residual standard error: 9.587 on 46 degrees of freedom

Multiple R-squared: 0.8755, Adjusted R-squared: 0.8674

R^2 = 62.92323

p-value = 0.5593

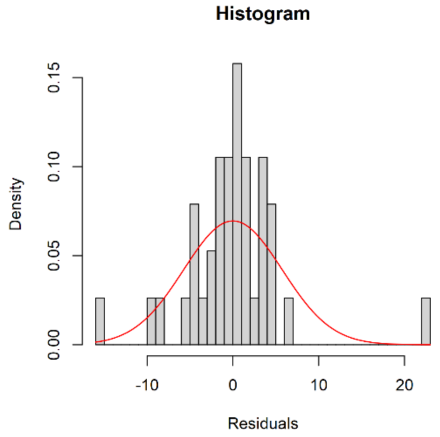
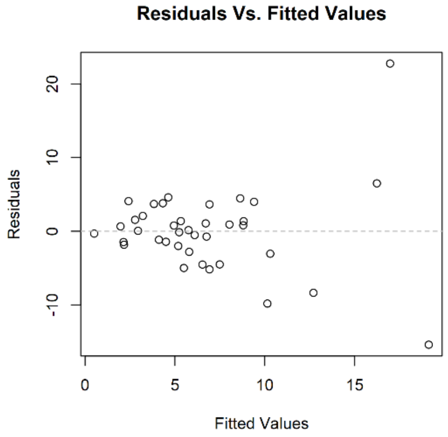
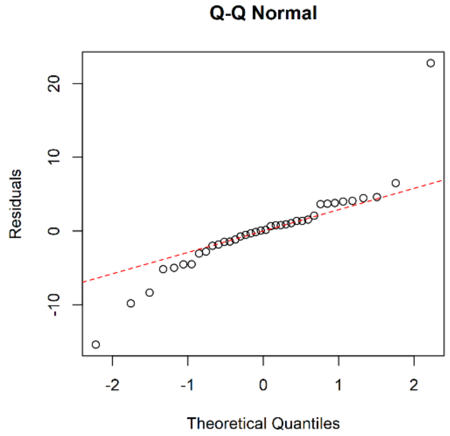
SSE = 4227.516

AIC = 365.4759

8. OAK: Crown Volume (CV)

$$CV = -5.84 \cdot DBH + 0.001 \cdot lnBA_t + 27.87 \cdot BAL_t - 37.49 \cdot \ Ratio\ BAL$$

Table 8. CV Oak Analysis 2

	
	Residual standard error: 6.074 on 33 degrees of freedom Multiple R-squared: 0.3442, Adjusted R-squared: 0.2647 R^2 = 34.41954 p-value = 0.2659 SSE = 1217.285 AIC = 251.5774

ANNEX 3

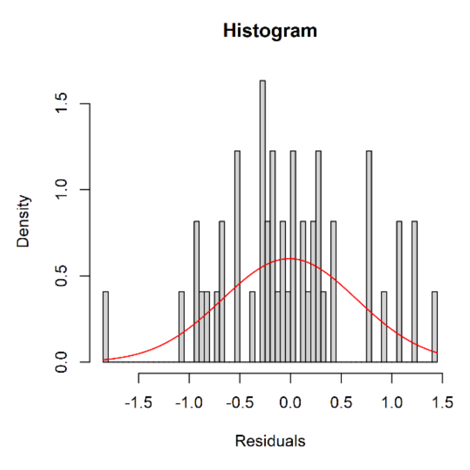
Residuals analyses of the first 5 models with lower AIC that were developed for the mixture *Pinus Sylvestris – Quercus Pyrenaica* (Analysis 3)

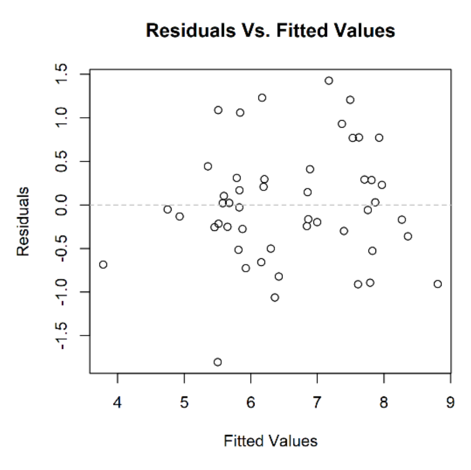
Annex 3.

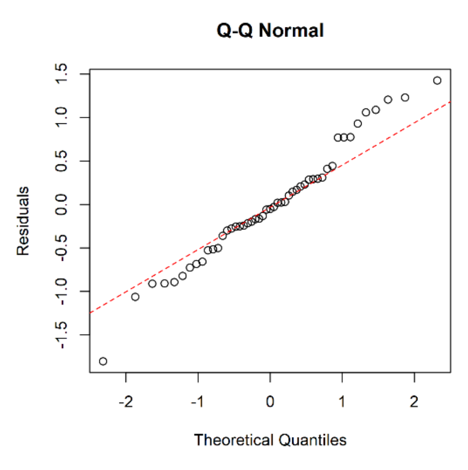
RESIDUALS ANALYSES OF THE FIRST 5 MODELS WITH LOWER AIC THAT WERE DEVELOPED FOR THE MIXTURE *PINUS SYLVESTRIS- QUERCUS PYRENAICA* (ANALYSIS 3)

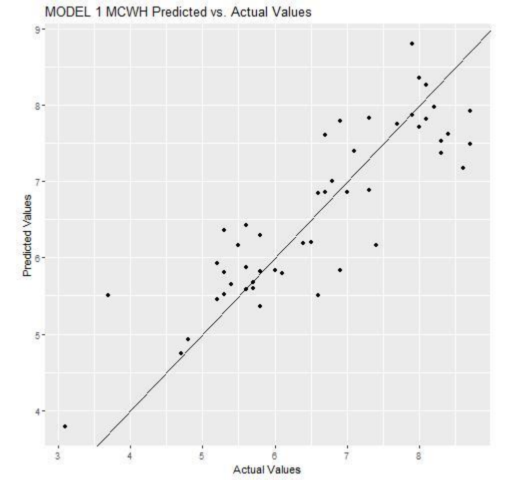
1. PINE: Maximum Crown Width Height (MCWH)

Model 1 (Radius = 10) $MCWH = \frac{TH}{1+e^{(0.03\cdot DBH-0.66\cdot BA_t-0.9\cdot Ratio\ BAL)}}$

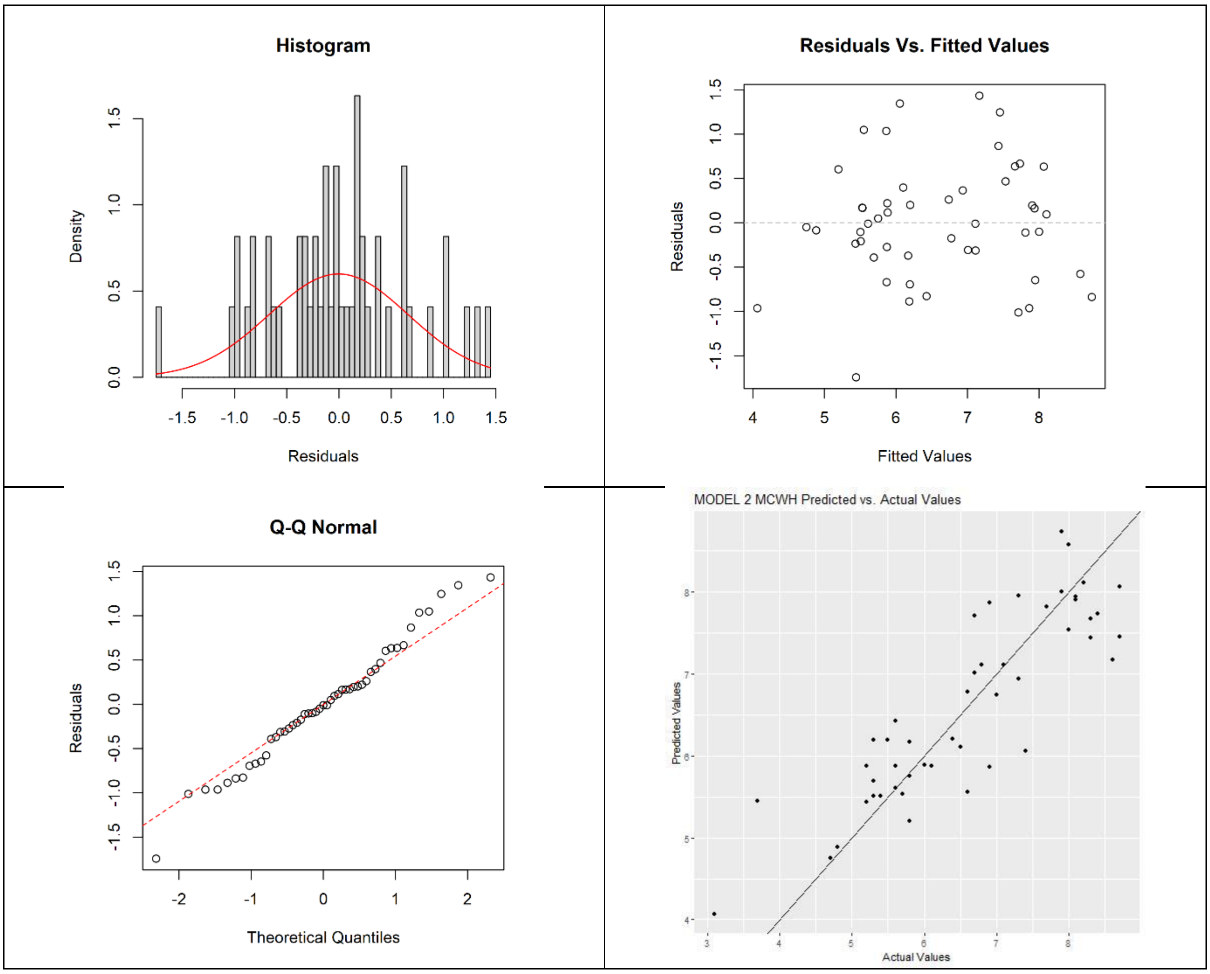

Histogram


Residuals Vs. Fitted Values

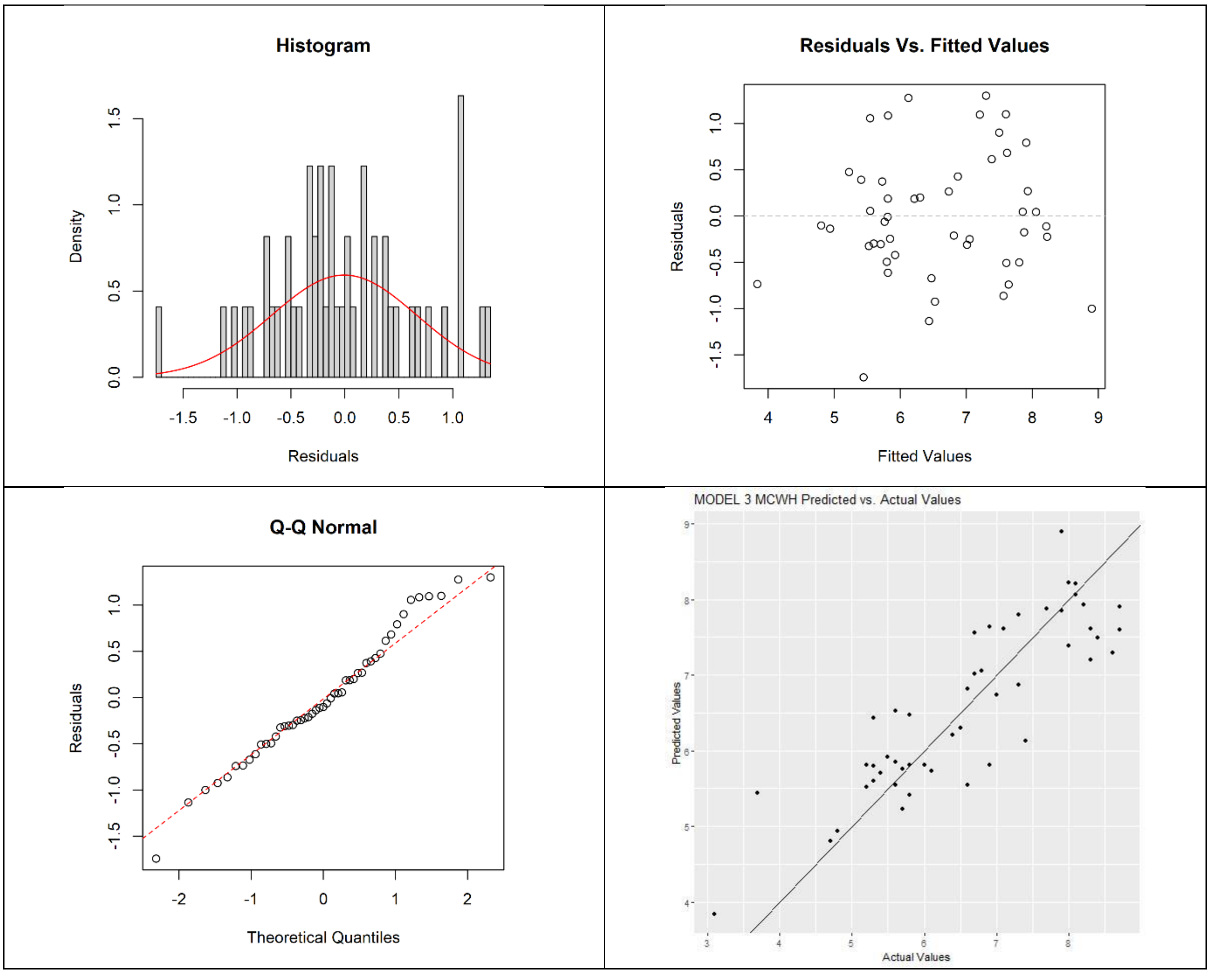

Q-Q Normal


MODEL 1 MCWH Predicted vs. Actual Values

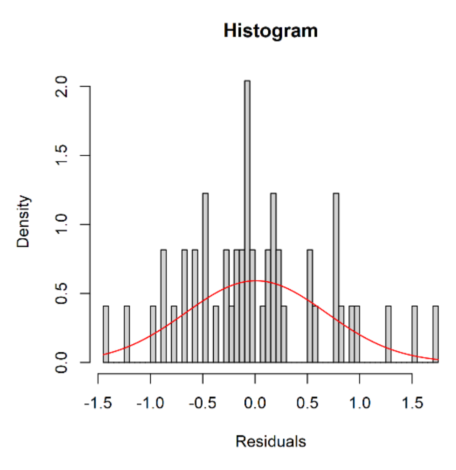
Model 2 (Radius 10) $MCWH = \frac{TH}{1+e^{(0.03 \cdot DBH - 0.78 \cdot BA_t - 0.82 \cdot Ratio\ BA)}}$

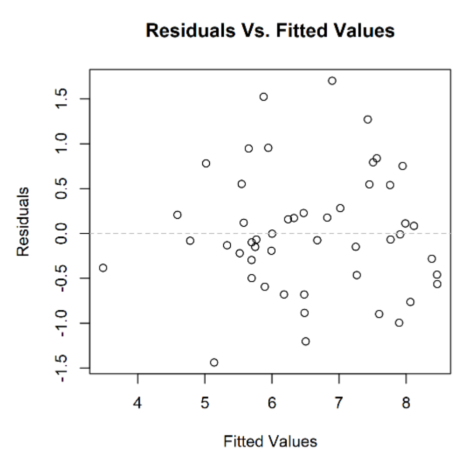


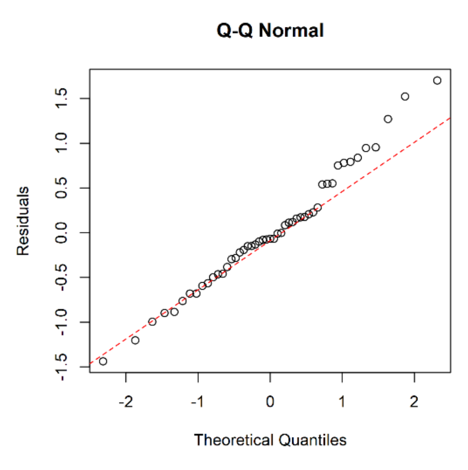
Model 3 (Radius 7.5) $MCWH = \frac{TH}{1+e^{(0.03\cdot DBH-1.06\cdot BA_t-0.95\cdot Ratio\ BAL)}}$

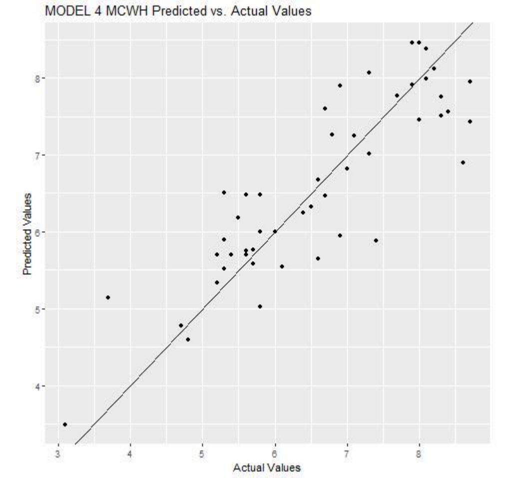


Model 4 (Radius 10) $MCWH = \frac{TH}{1+e^{(0.02\cdot DBH-0.31\cdot lnBA_t-1.38\cdot Ratio\ BAL)}}$

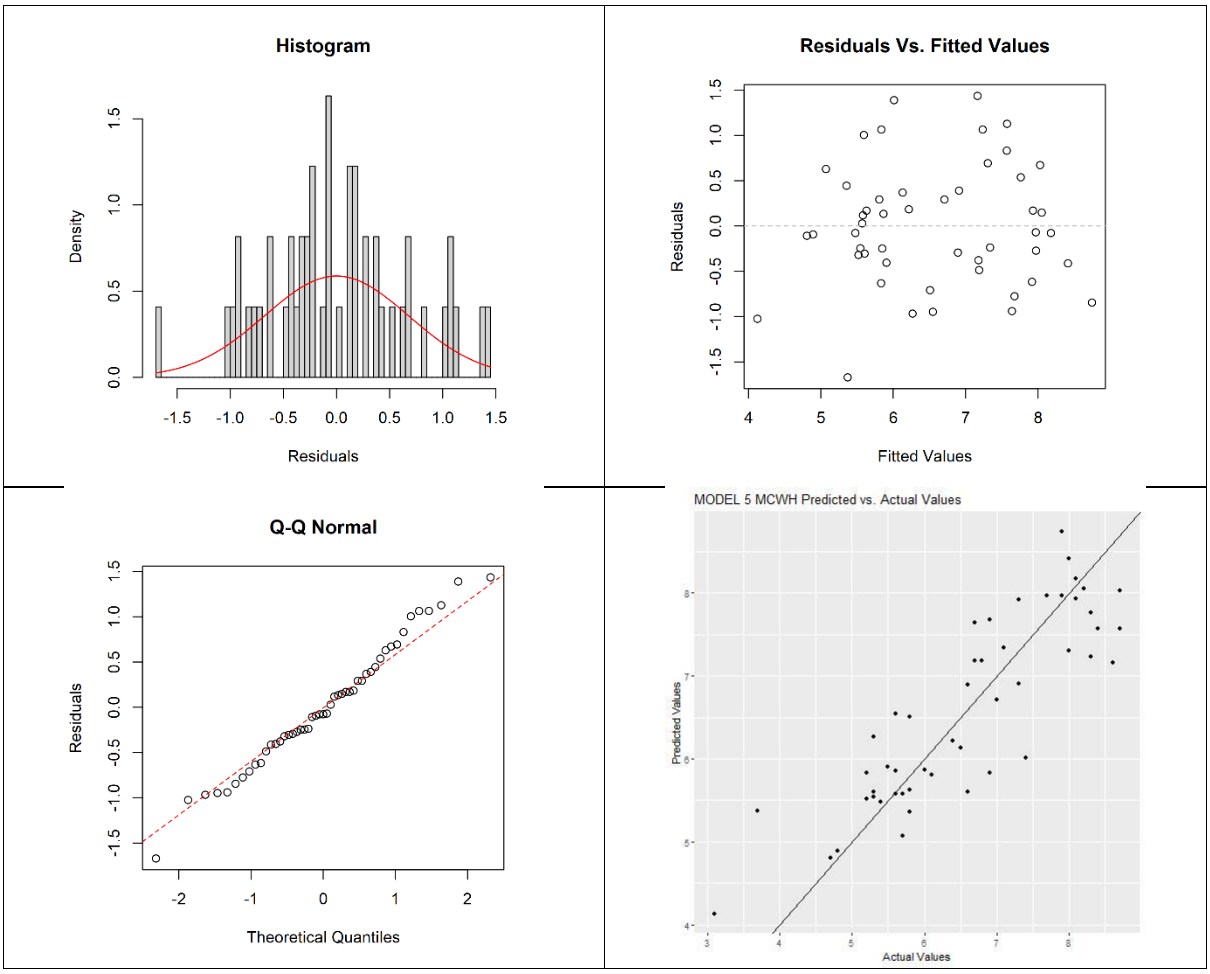








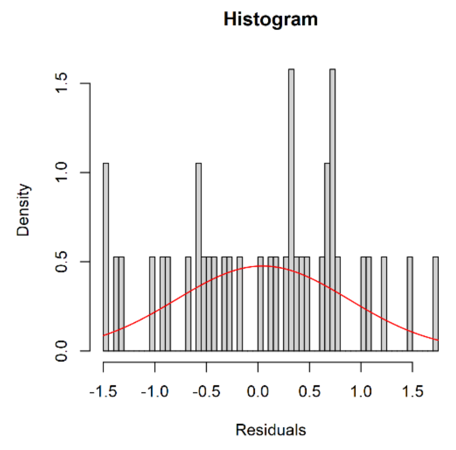
Model 5 (Radius 7.5) $MCWH = \frac{TH}{1+e^{(0.03\cdot DBH-1.24\cdot BA_t-0.87\cdot Ratio\ BA)}}$



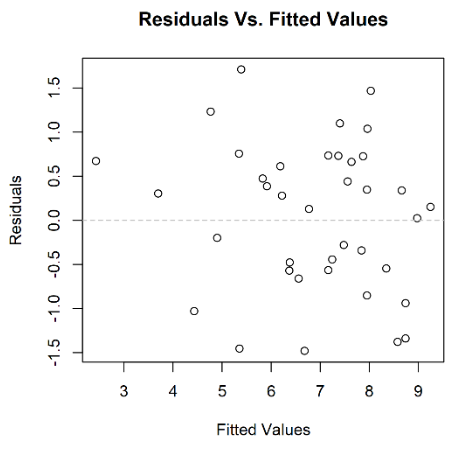
2. OAK: Maximum Crown Width Height (MCWH)

Model 1 (Radius = 10) $MCWH = \frac{TH}{1+e^{(-1.31 \cdot Ratio\ BA)}}$

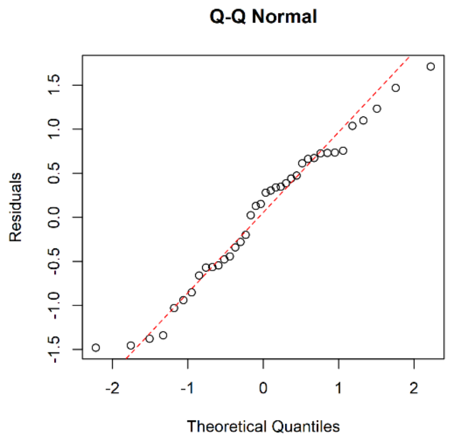
Histogram



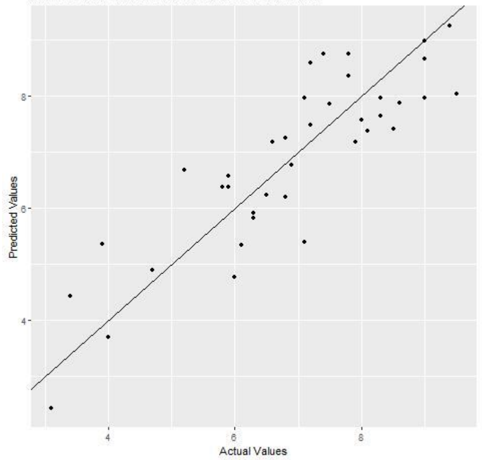
Residuals Vs. Fitted Values



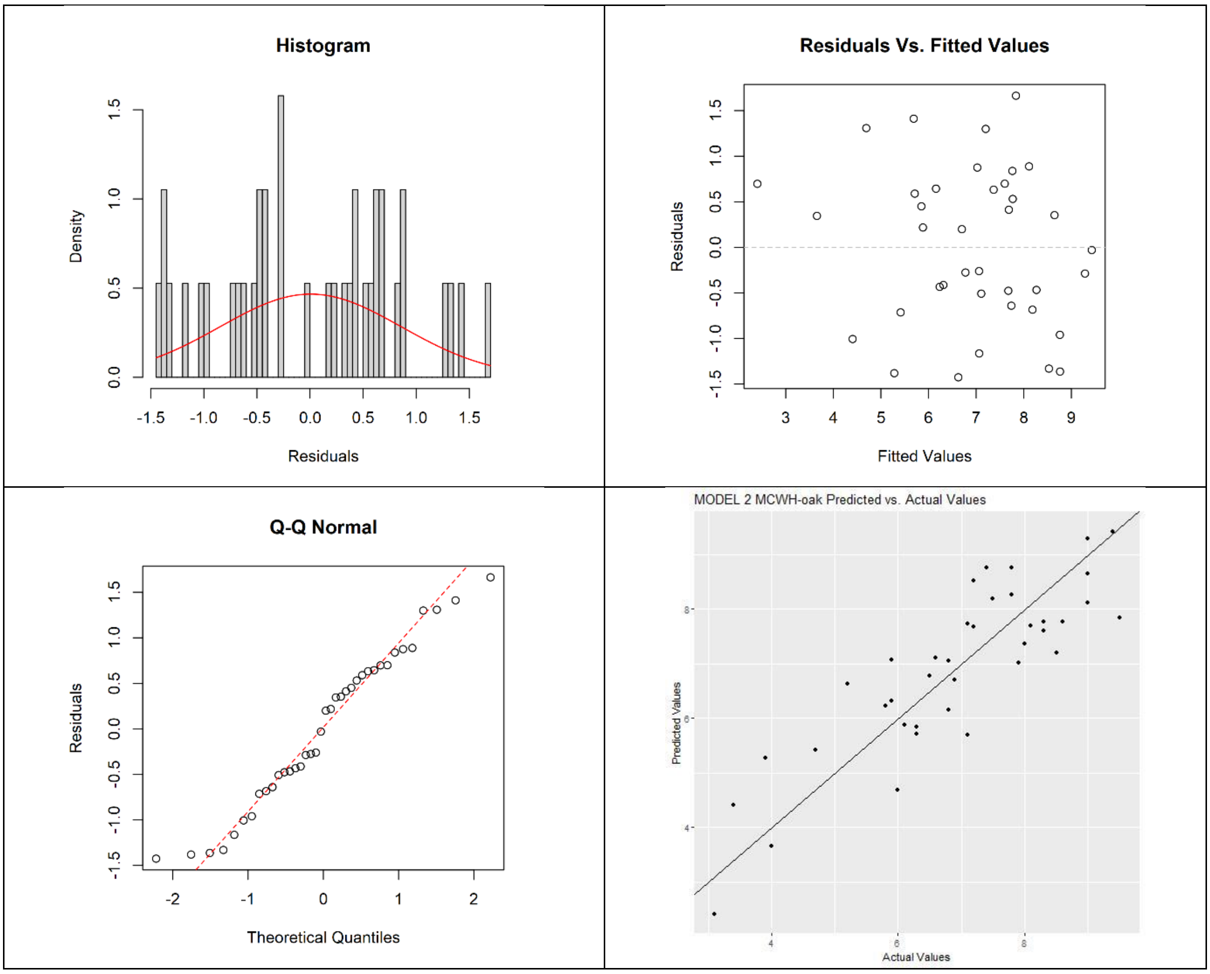
Q-Q Normal



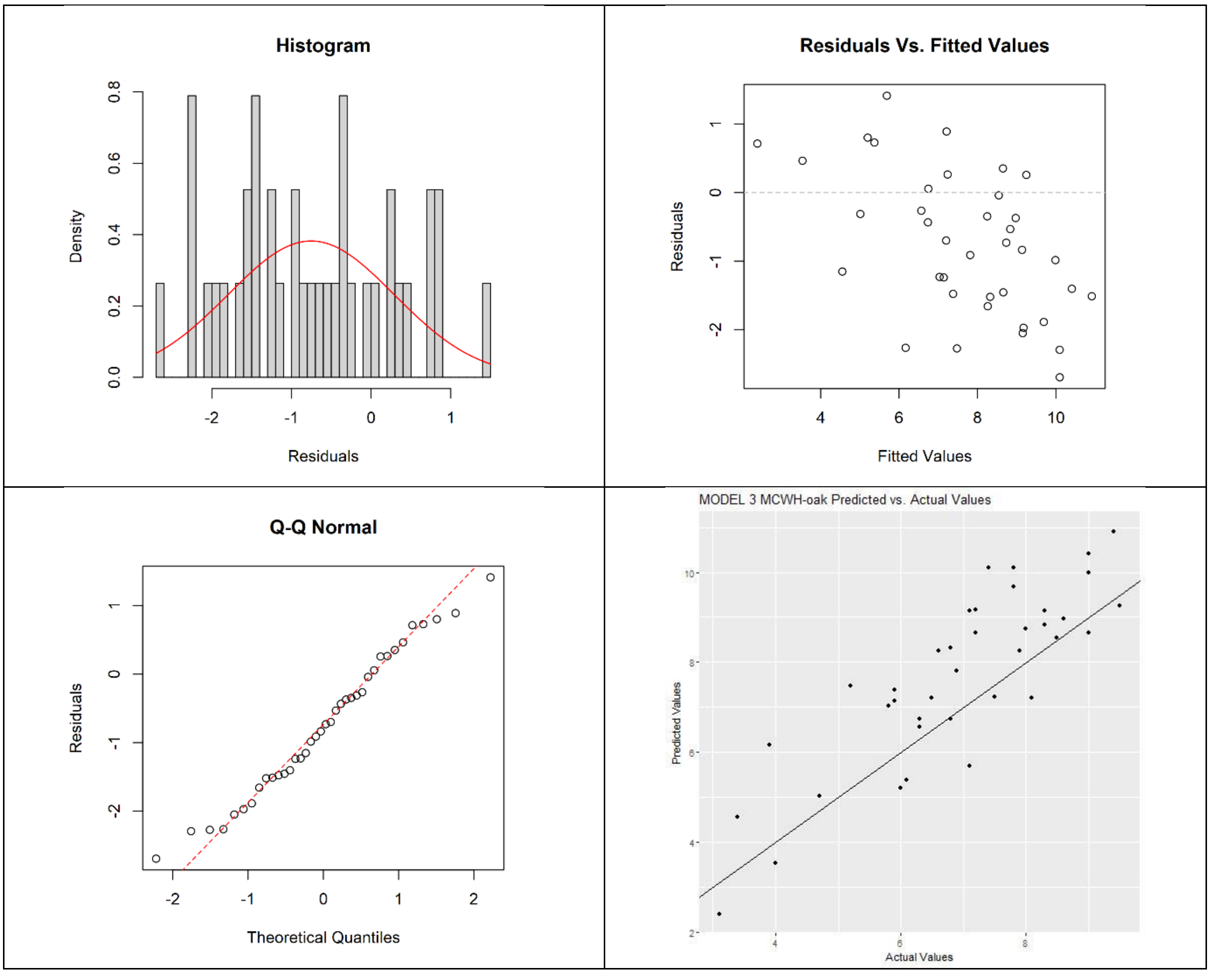
MODEL 1 MCWH-oak Predicted vs. Actual Values



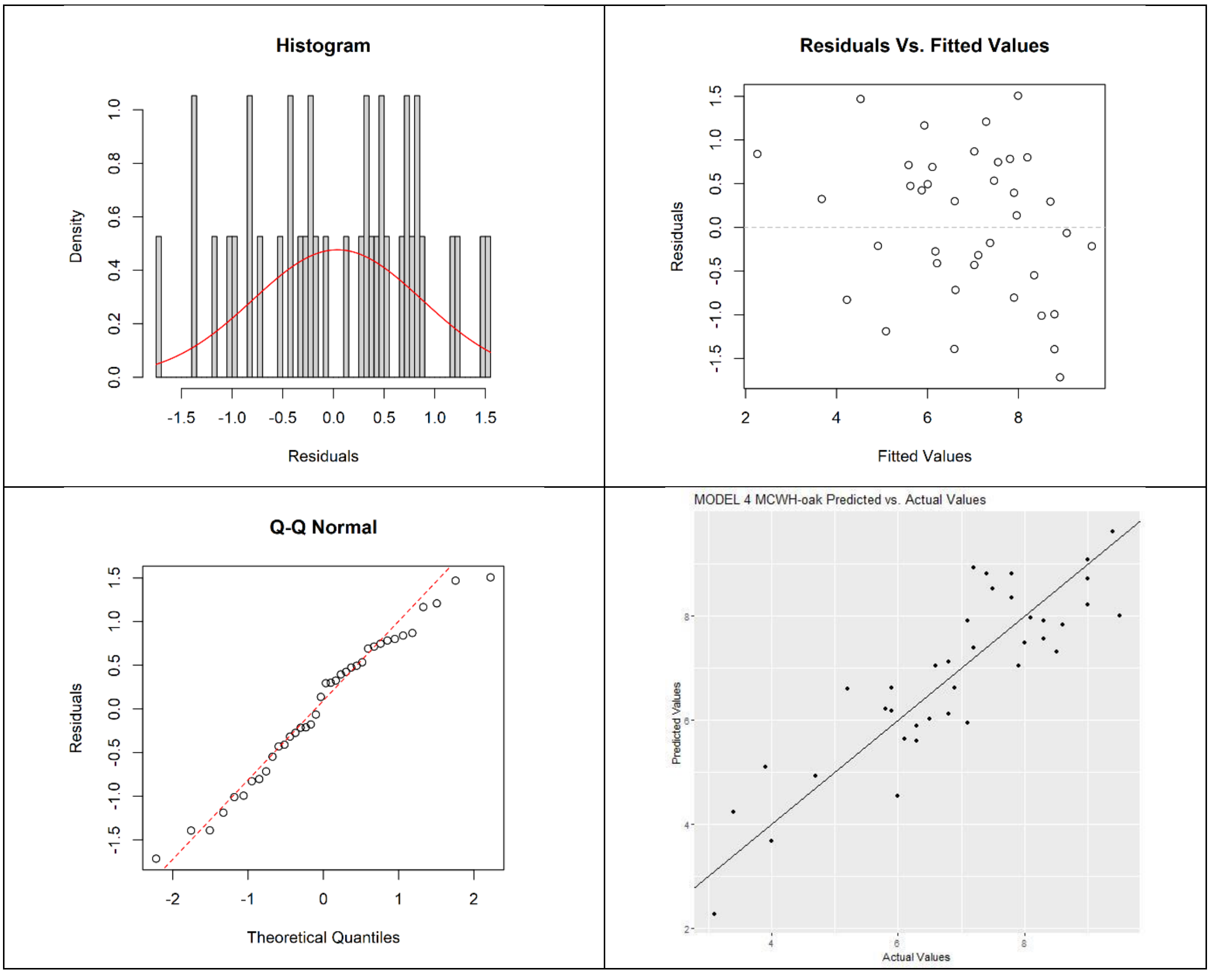
Model 2 (Radius = 10) $MCWH = \frac{TH}{1+e^{(-0.02\cdot DBH-0.94\cdot Ratio\ BAL)}}$



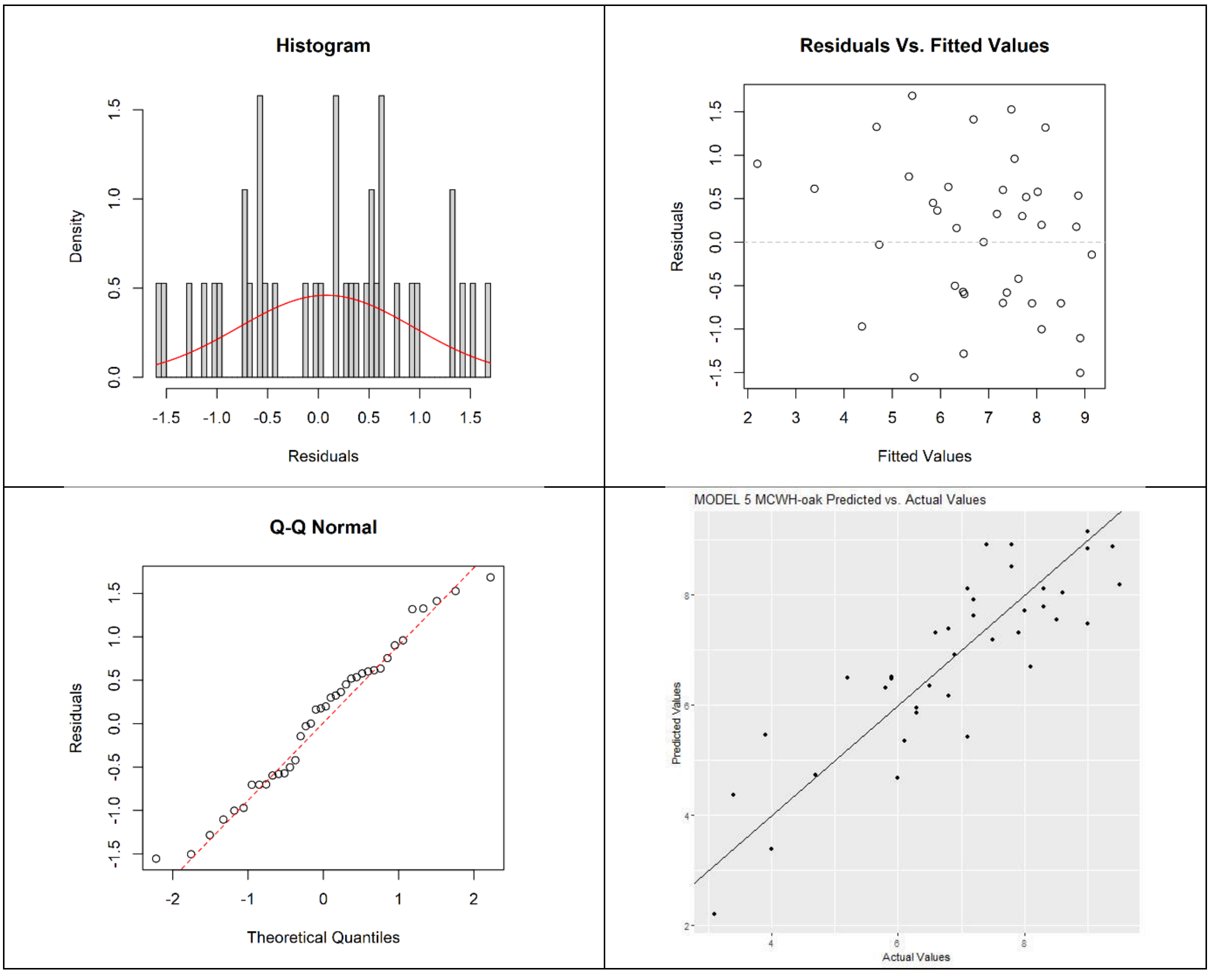
Model 3 (Radius = 7.5) $MCWH = \frac{TH}{1+e^{(0.49\cdot BAL_t - 2.36\cdot Ratio\ n)}}$



Model 4 (Radius = 10) $MCWH = \frac{TH}{1+e^{(-0.06 \cdot TH - 0.70 \cdot Ratio\ BAL)}}$

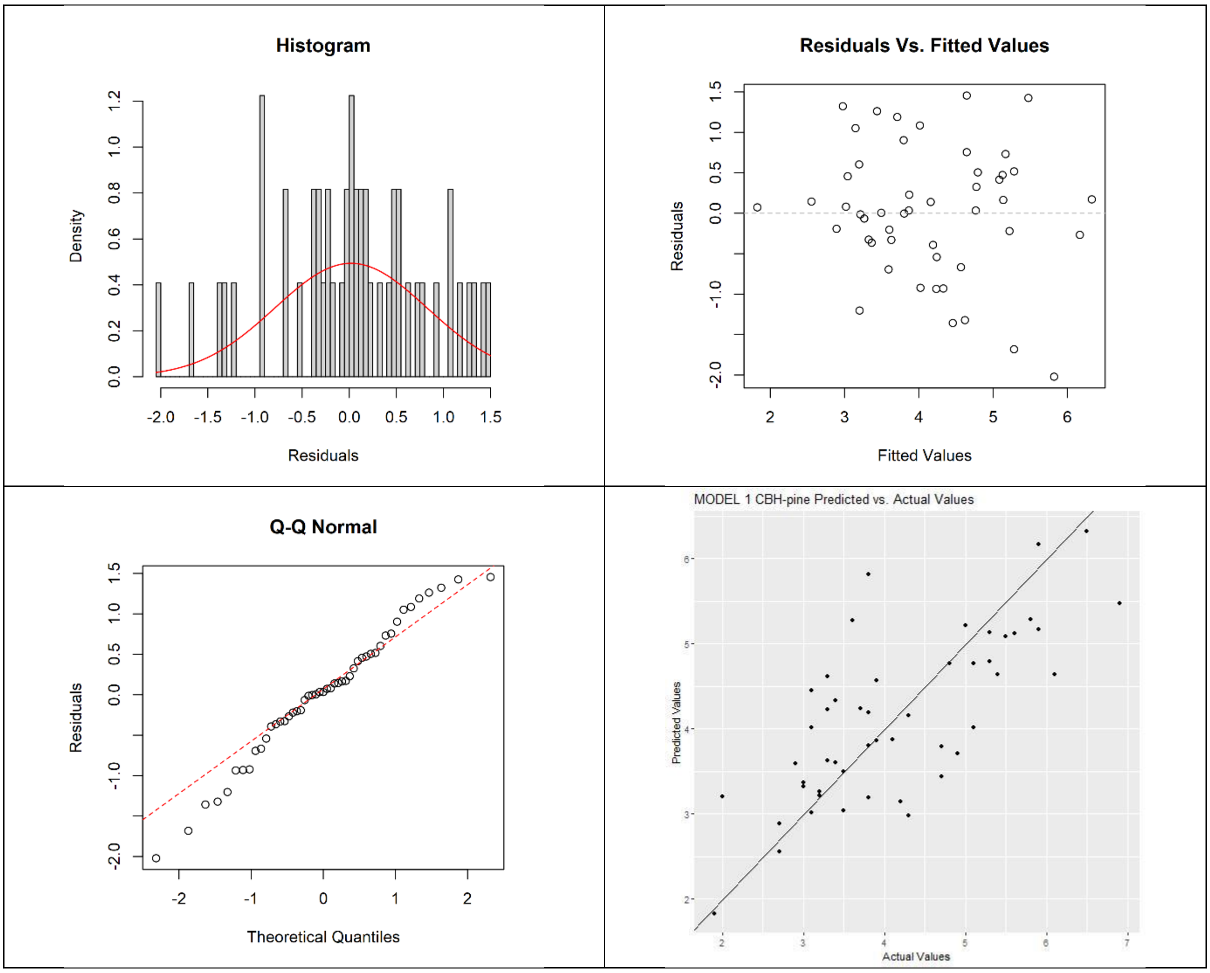


Model 5 (Radius = 10)) $MCWH = \frac{TH}{1+e^{(-1.40 \cdot Ratio\ n)}}$

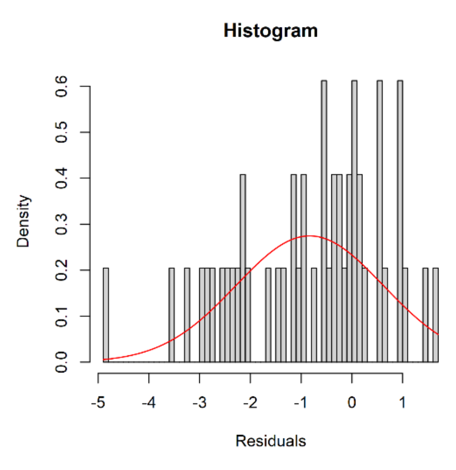


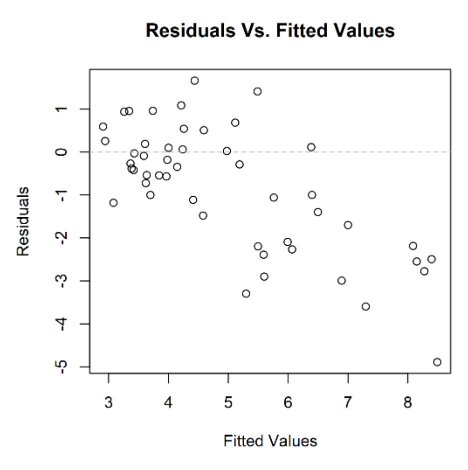
3. PINE: Crown at Base Height (CBH))

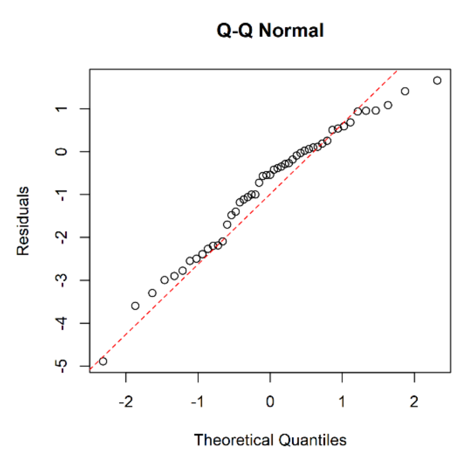
Model 1 (Radius = 5) $CBH = \frac{MCWH}{1+e^{(12.09 \cdot DBH/lnBA - 0.85 \cdot lnBA - 0.94 \cdot Ratio\ BA)}}$

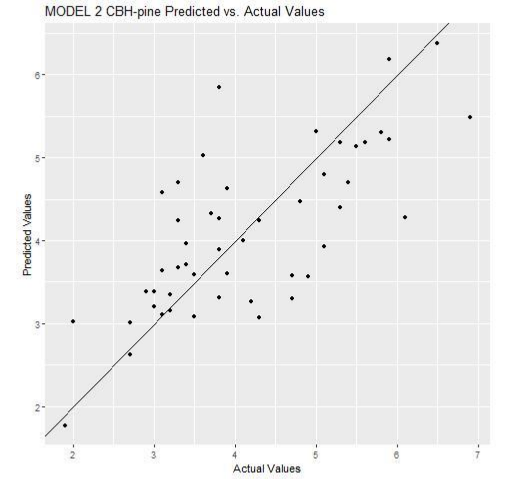


Model 2 (Radius = 5) $CBH = \frac{MCWH}{1+e^{(11.44\cdot DBH-0.77\cdot lnBA-0.90\cdot Ratio\ n)}}$

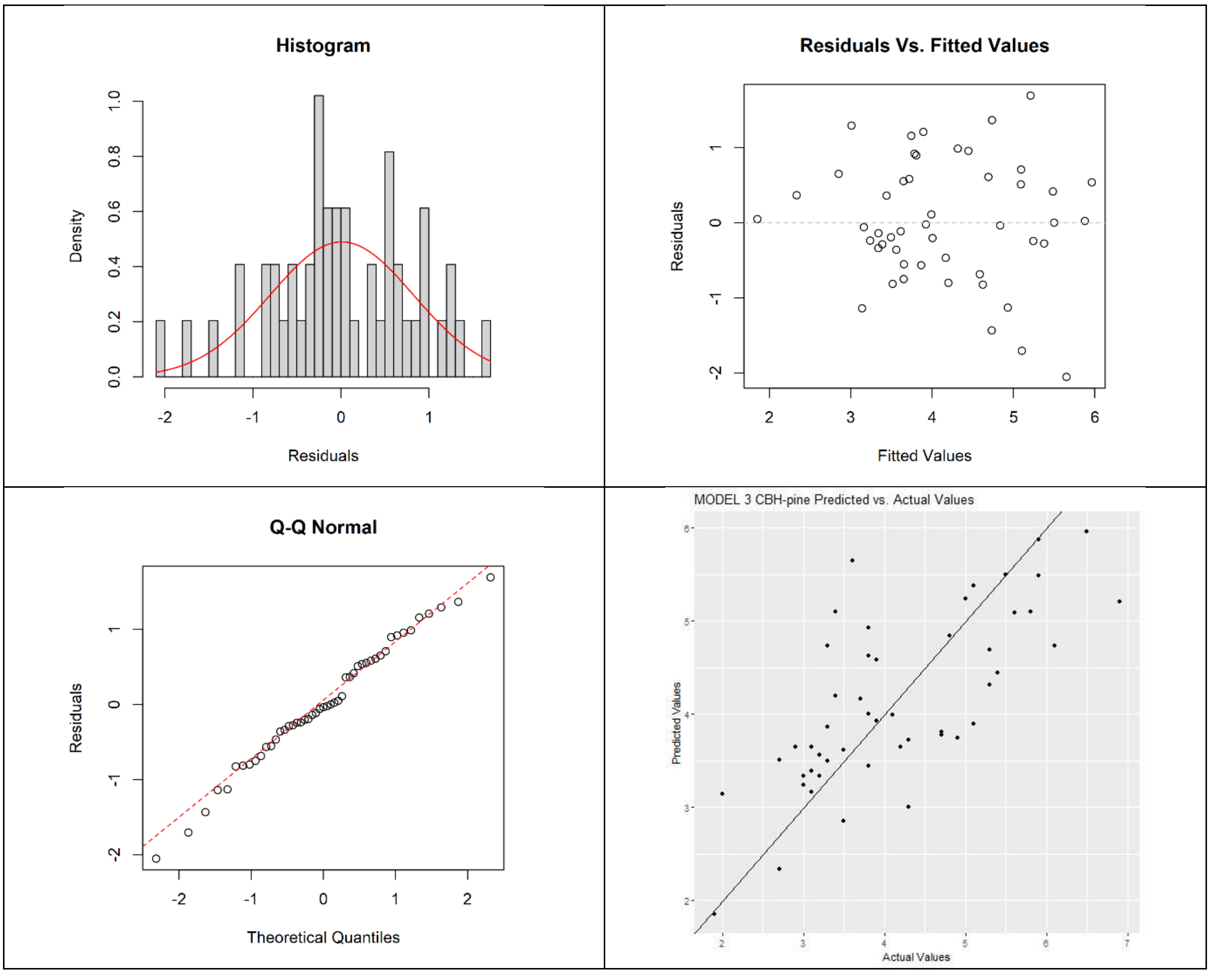

Histogram


Residuals Vs. Fitted Values

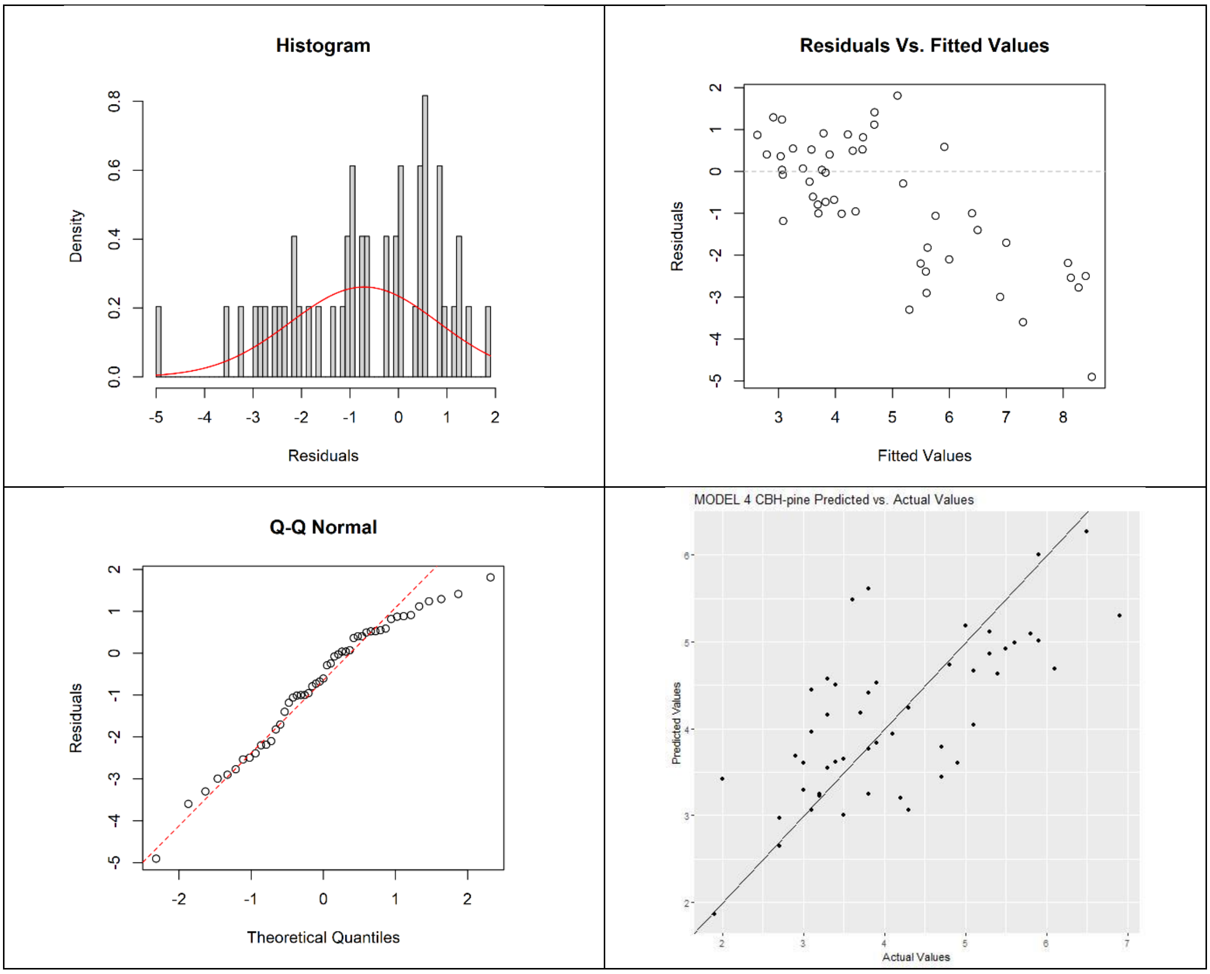

Q-Q Normal


MODEL 2 CBH-pine Predicted vs. Actual Values

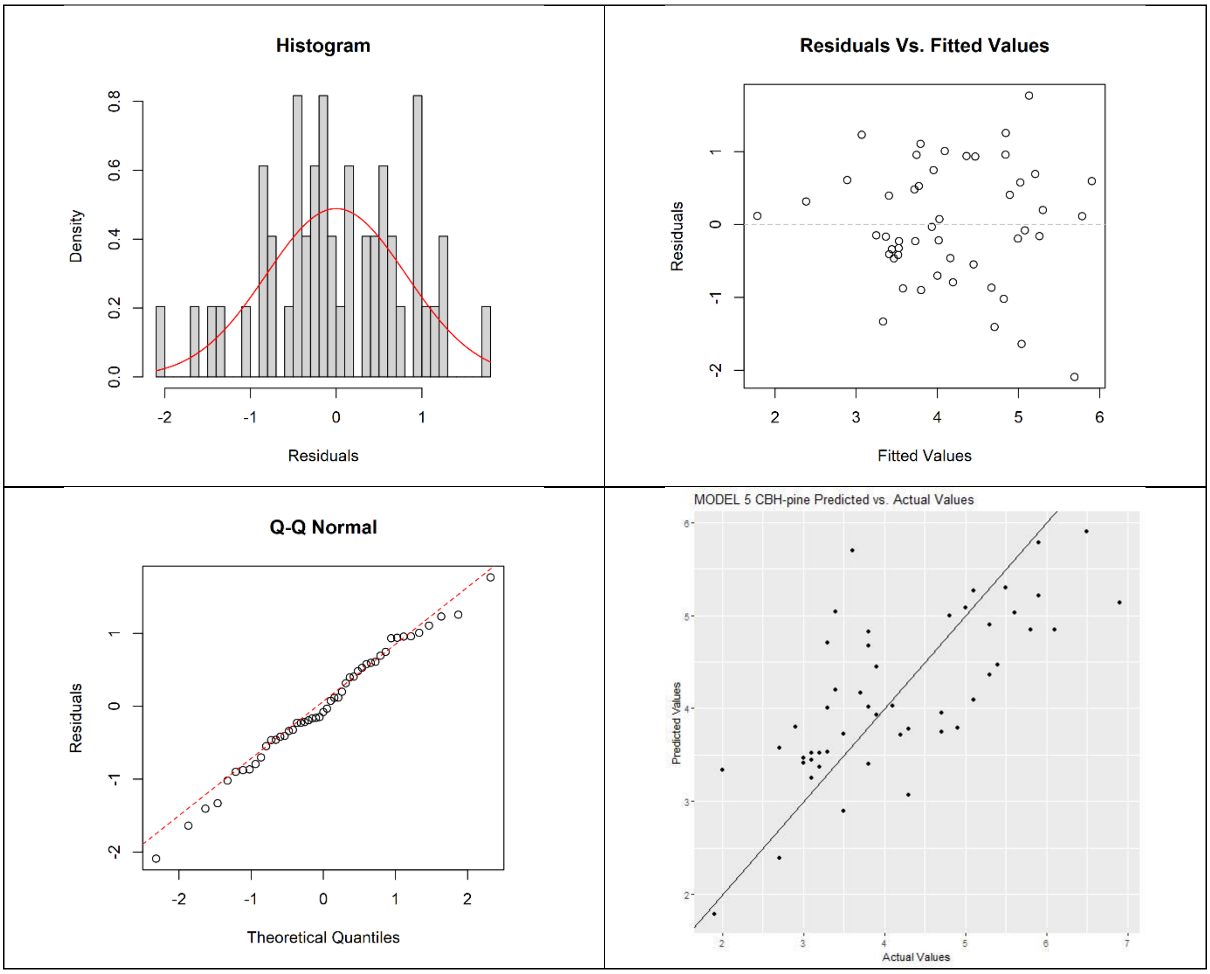
Model 3 (Radius = 7.5) $CBH = \frac{MCWH}{1+e^{(-78.55\cdot DBH+2.82\cdot BA+2.22\cdot BAL_p-0.53\cdot Ratio\ n)}}$



Model 4 (Radius = 5) $CBH = \frac{MCWH}{1+e^{(11.15 \cdot DBH - 0.69 \cdot lnBA - 0.69 \cdot Ratio\ BAL)}}$

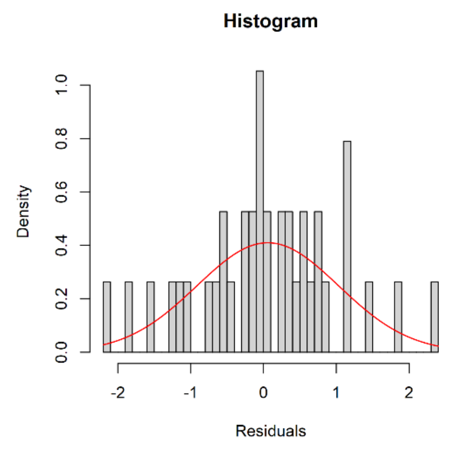


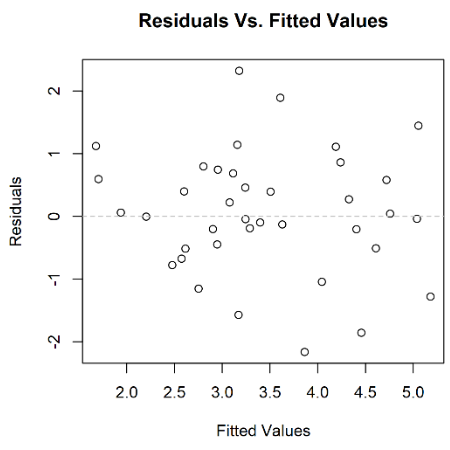
Model 5 (Radius = 10) $CBH = \frac{MCWH}{1+e^{(-44.57 \cdot DBH + 1.91 \cdot BA + 1.12 \cdot BALp - 0.6 \cdot Ratio\ BAL)}}$

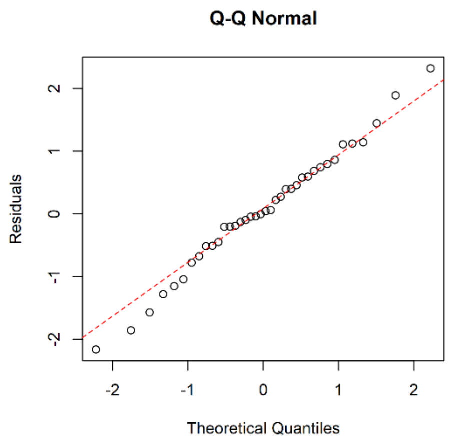


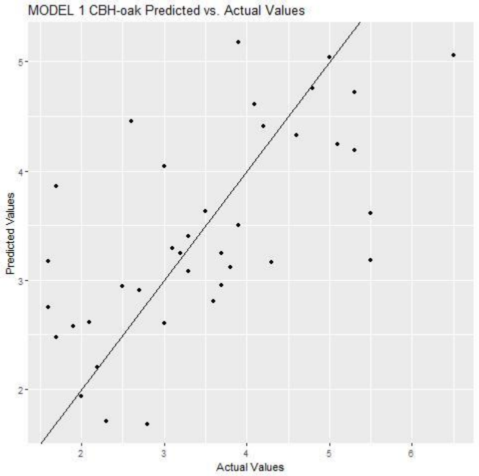
4. OAK: Crown at Base Height (CBH)

Model 1 (Radius = 7.5) $CBH = \frac{MCWH}{1+e^{(-0.05\cdot C.I.+0.53\cdot Ratio\ n)}}$

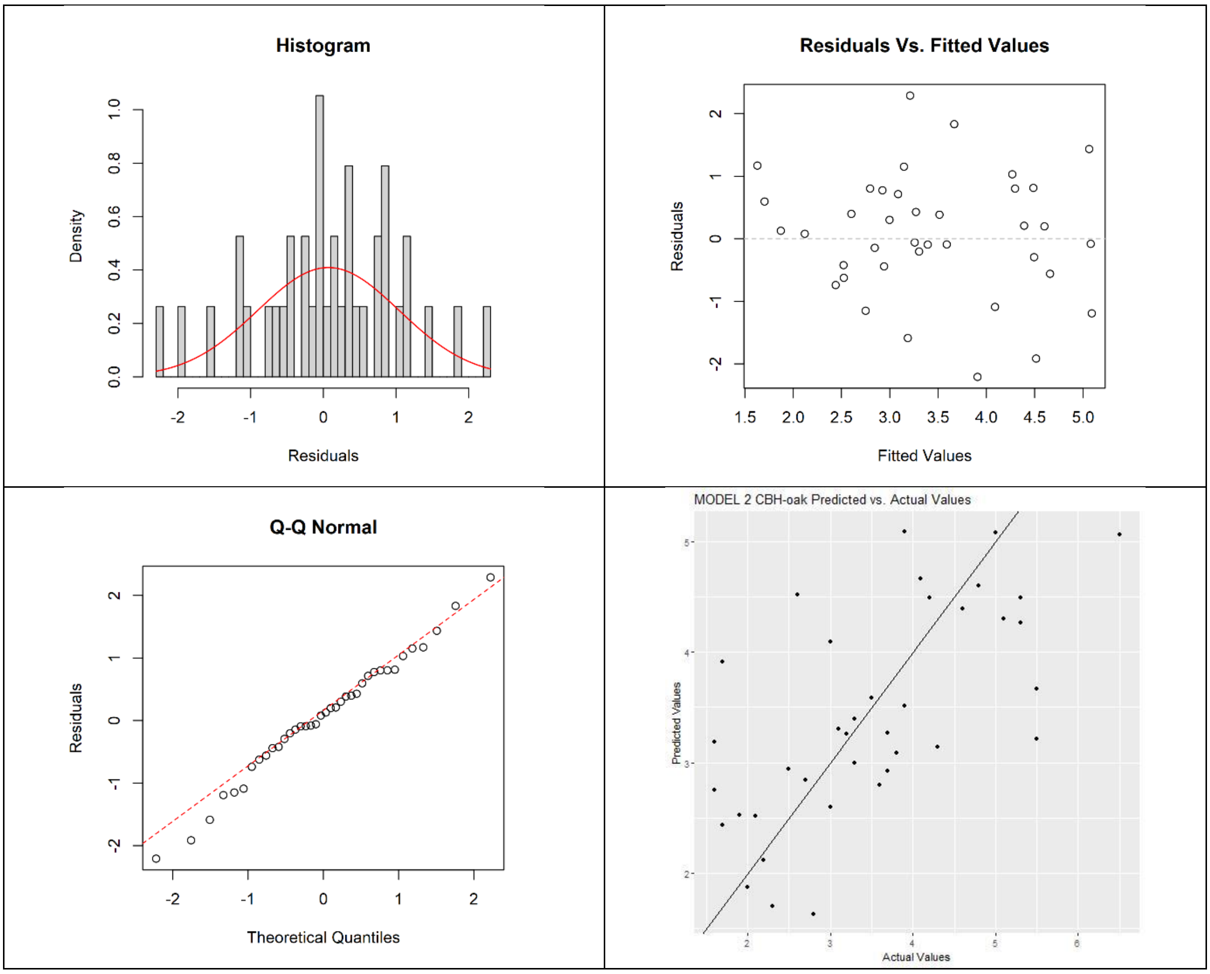




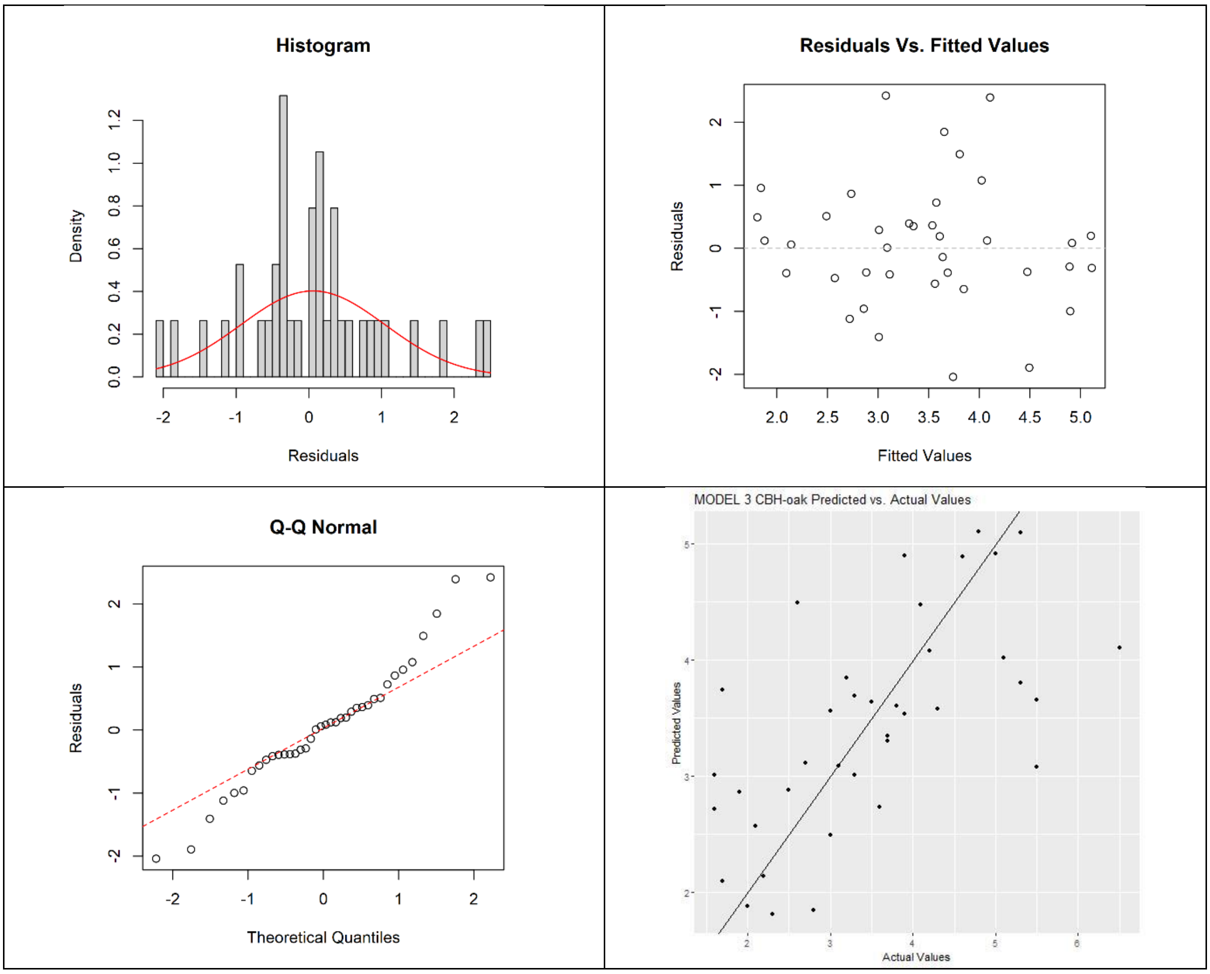




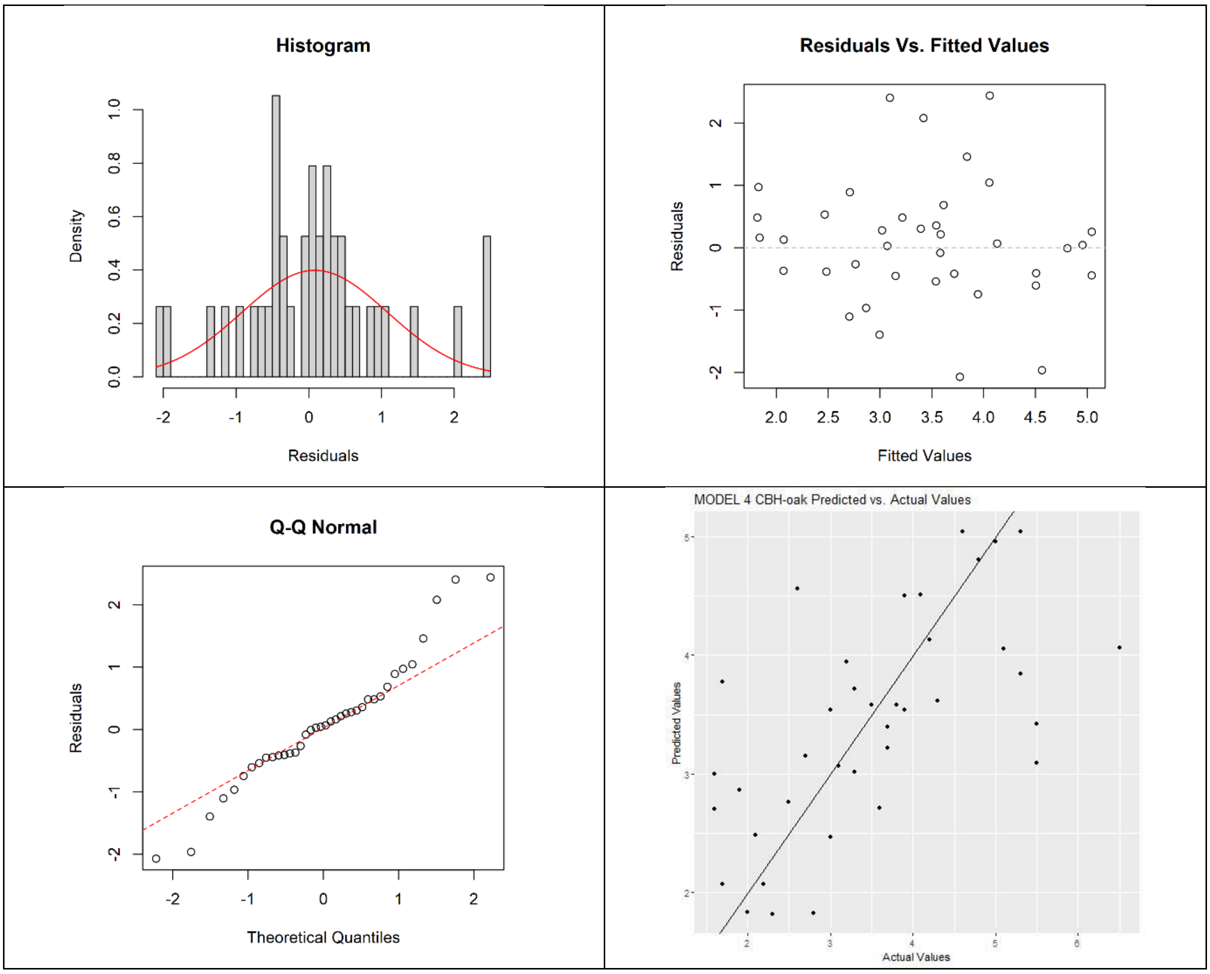
Model 2 (Radius = 7.5) $CBH = \frac{MCWH}{1+e^{(-0.06 \cdot C.I.+0.53 \cdot Ratio\ n)}}$



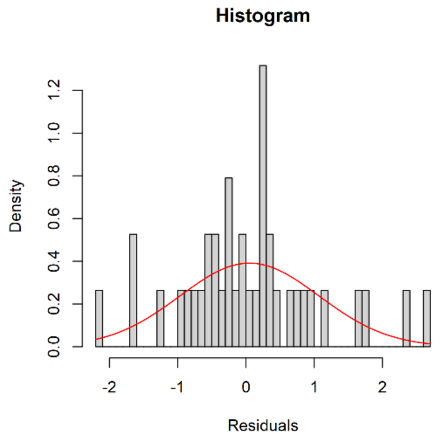
Model 3 (Radius = 10) $CBH = \frac{MCWH}{1+e^{(-1.01\cdot BAL_t+0.42\cdot Ratio\ n)}}$

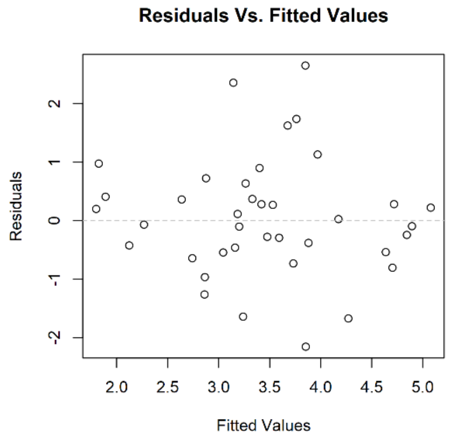


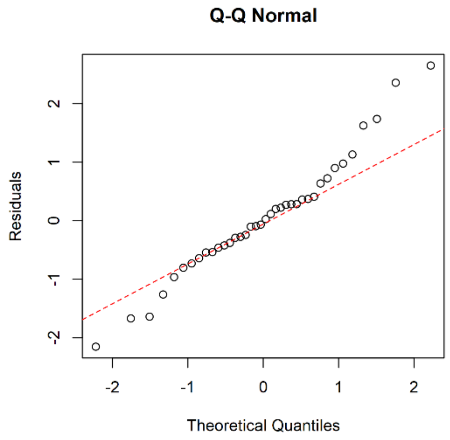
Model 4 (Radius = 10) $CBH = \frac{MCWH}{1+e^{(-1.16\cdot BAL_p+0.46\cdot Ratio\ n)}}$

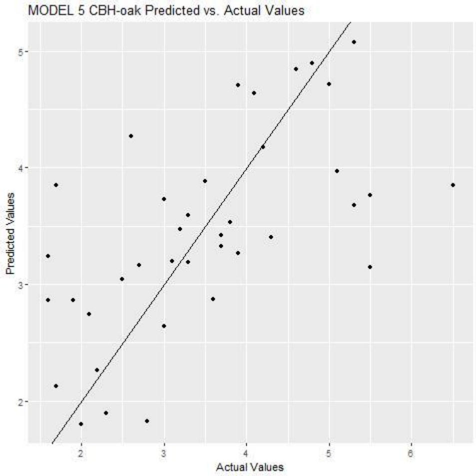


Model 5 (Radius = 7.5) $CBH = \frac{MCWH}{1+e^{(-1.44\cdot BAL_t+0.33\cdot Ratio\ n)}}$



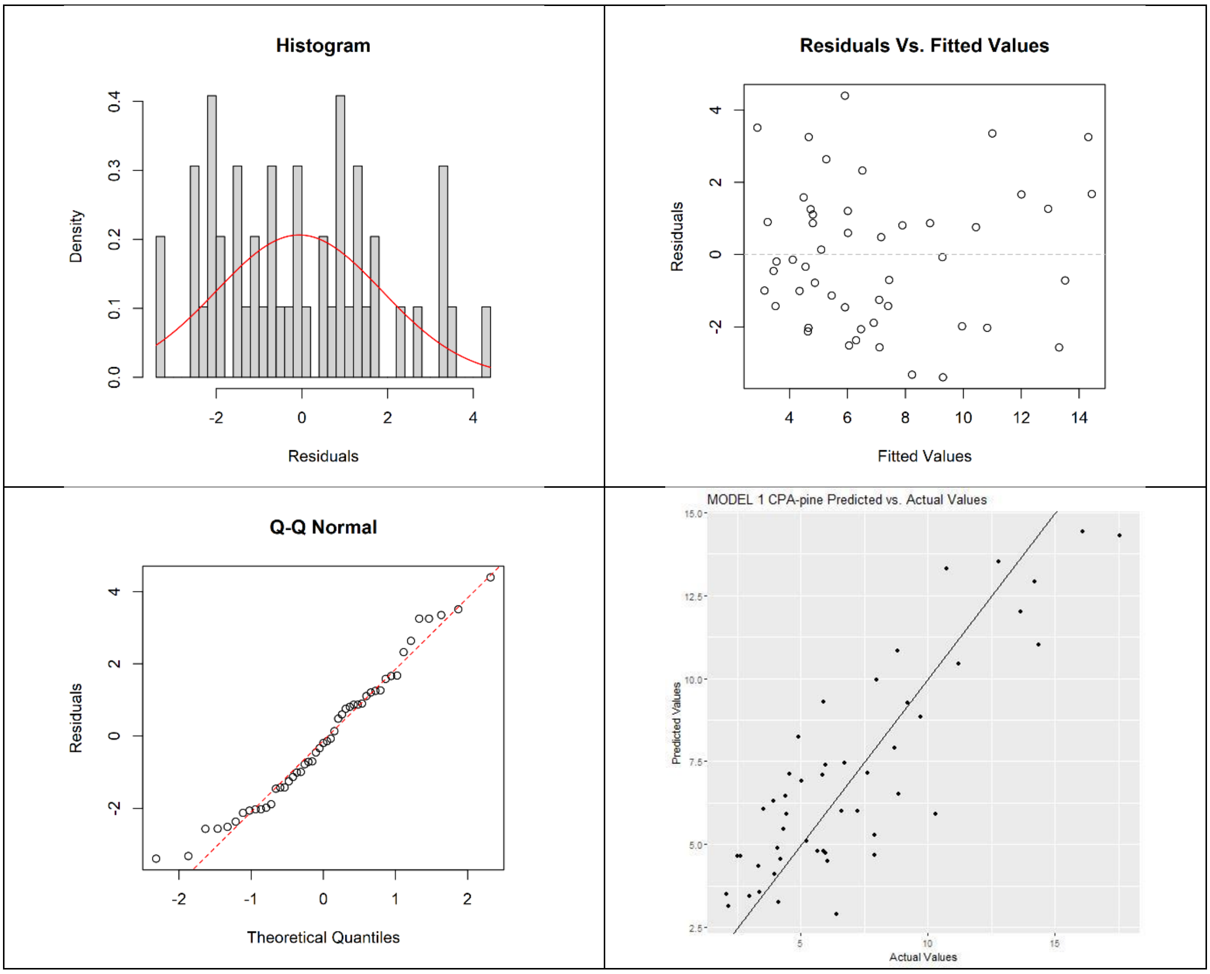




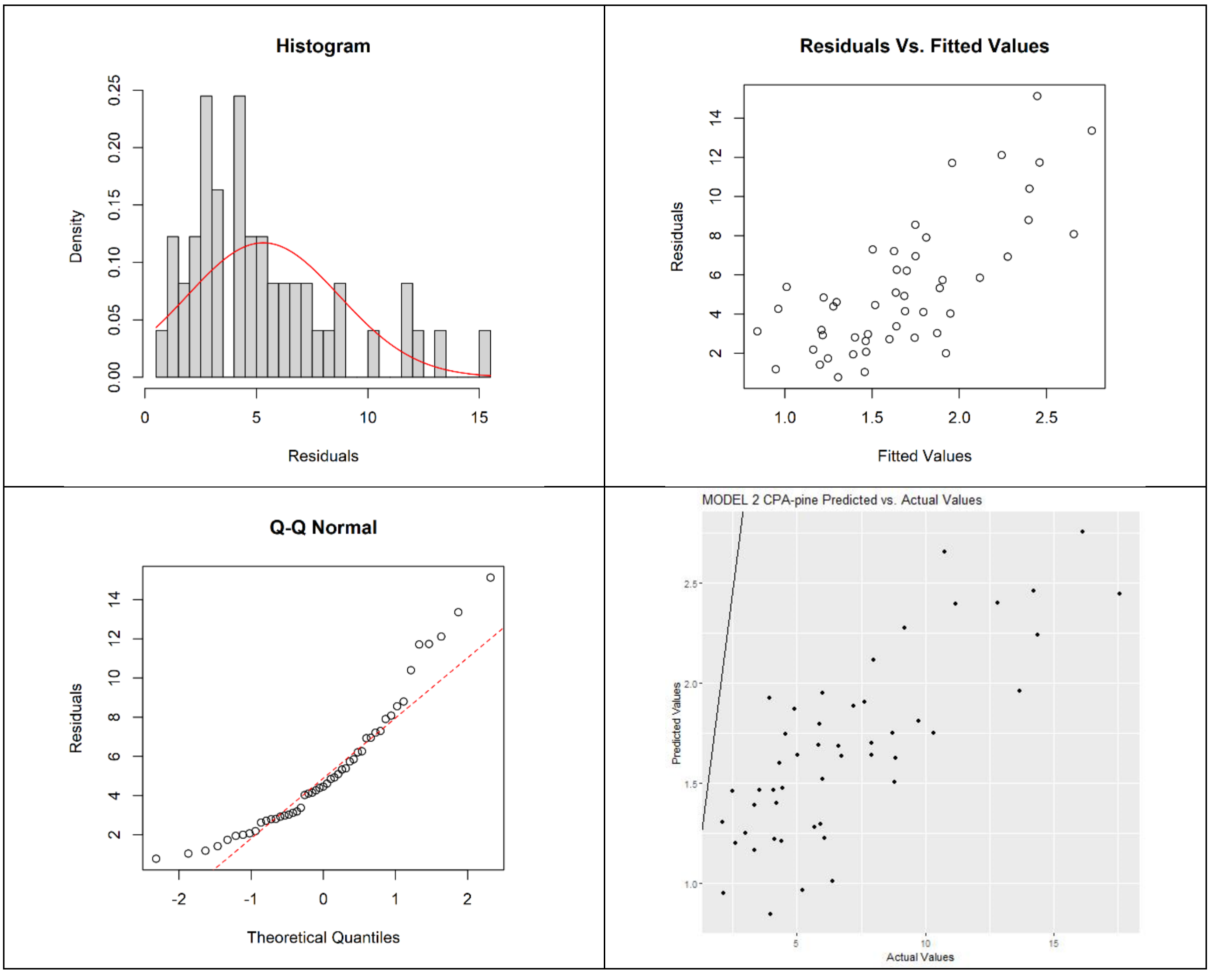


5. PINE: Crown Projection Area (CPA)

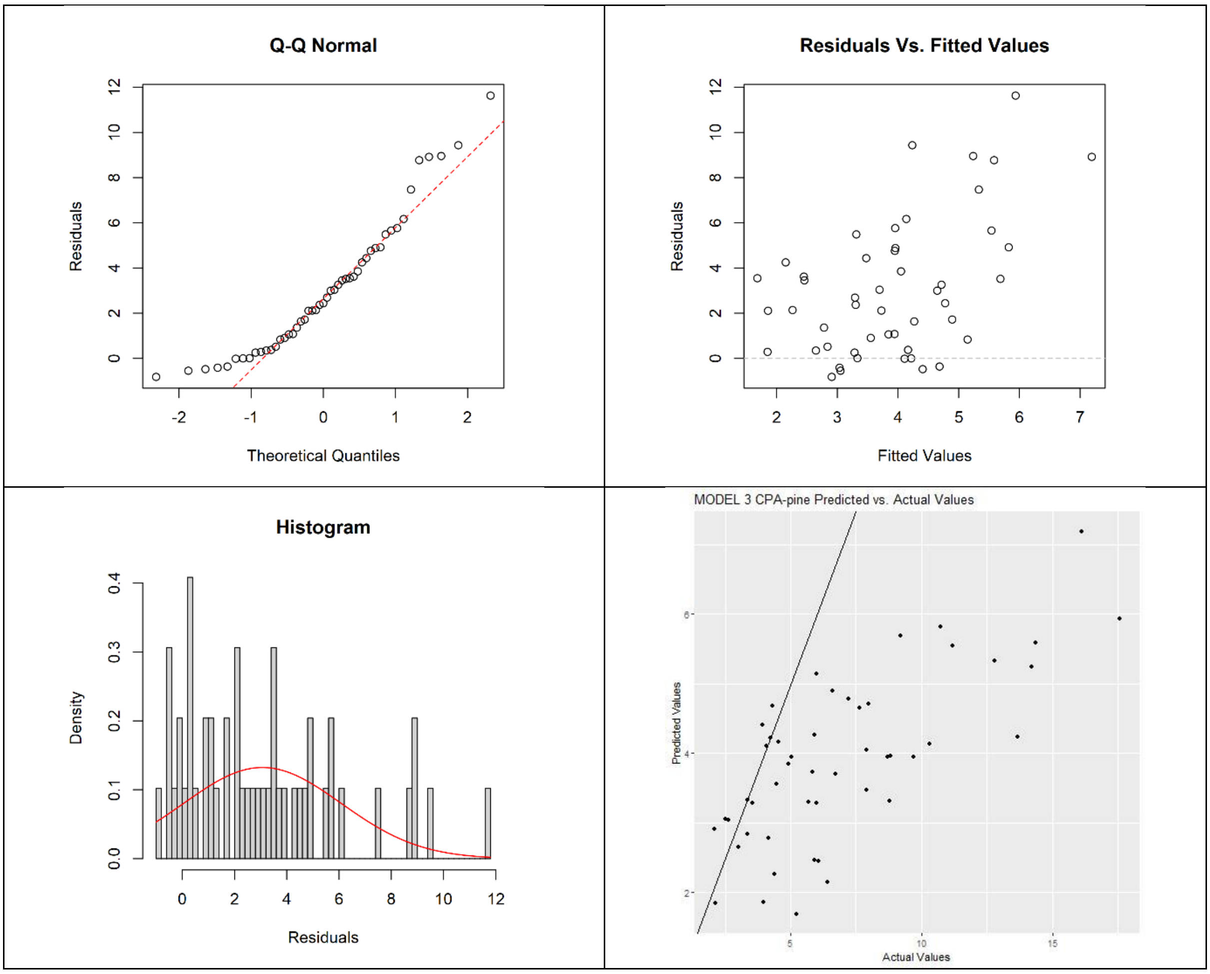
Model 1 (Radius = 5) $CPA = e^{(0.12 \cdot DBH - 1.79 \cdot BA_t)}$



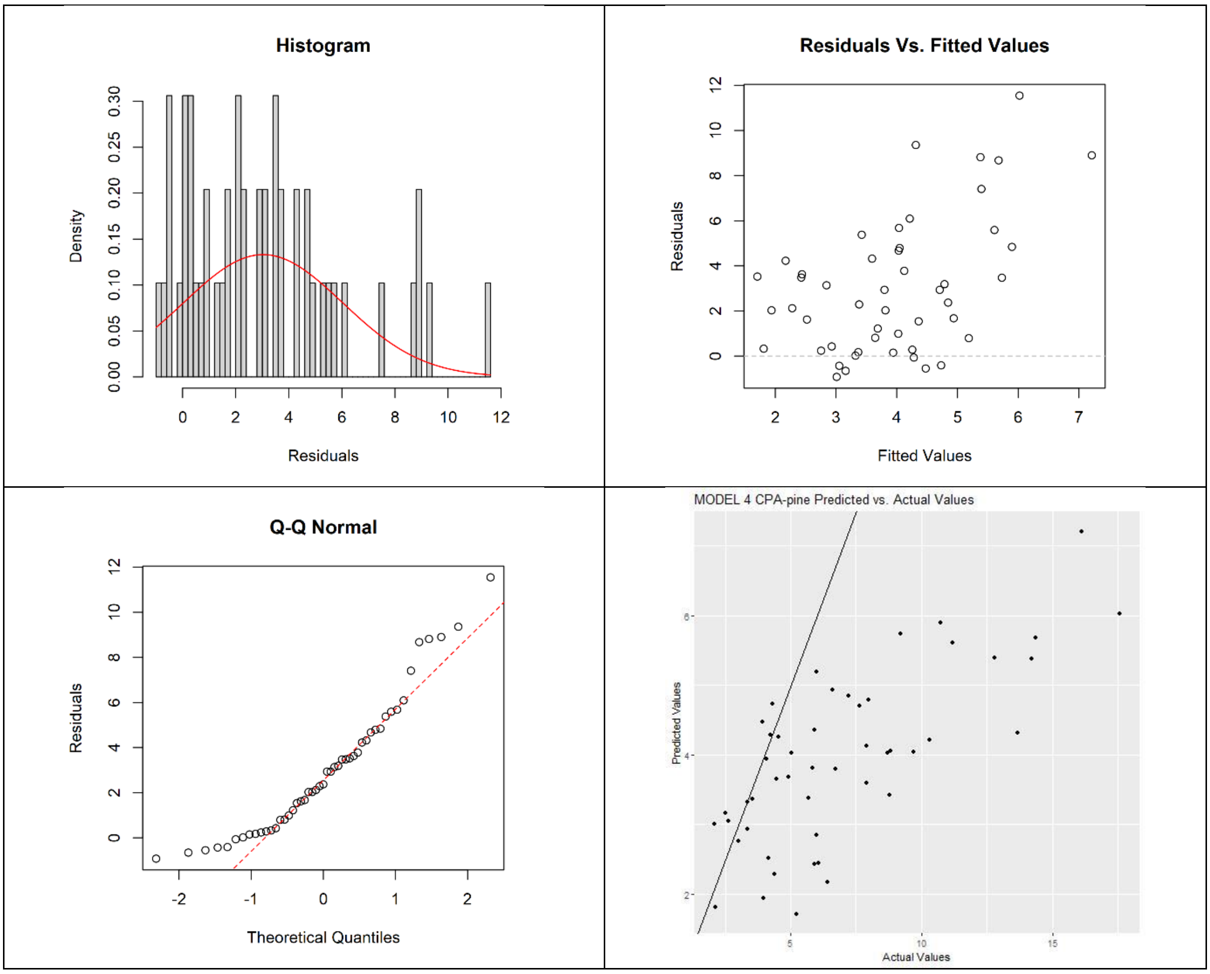
Model 2 (Radius = 10) $CPA = e^{(-0.54+0.07 \cdot DBH - 1.10 \cdot BA_t + 0.80 \cdot BAL_p)}$



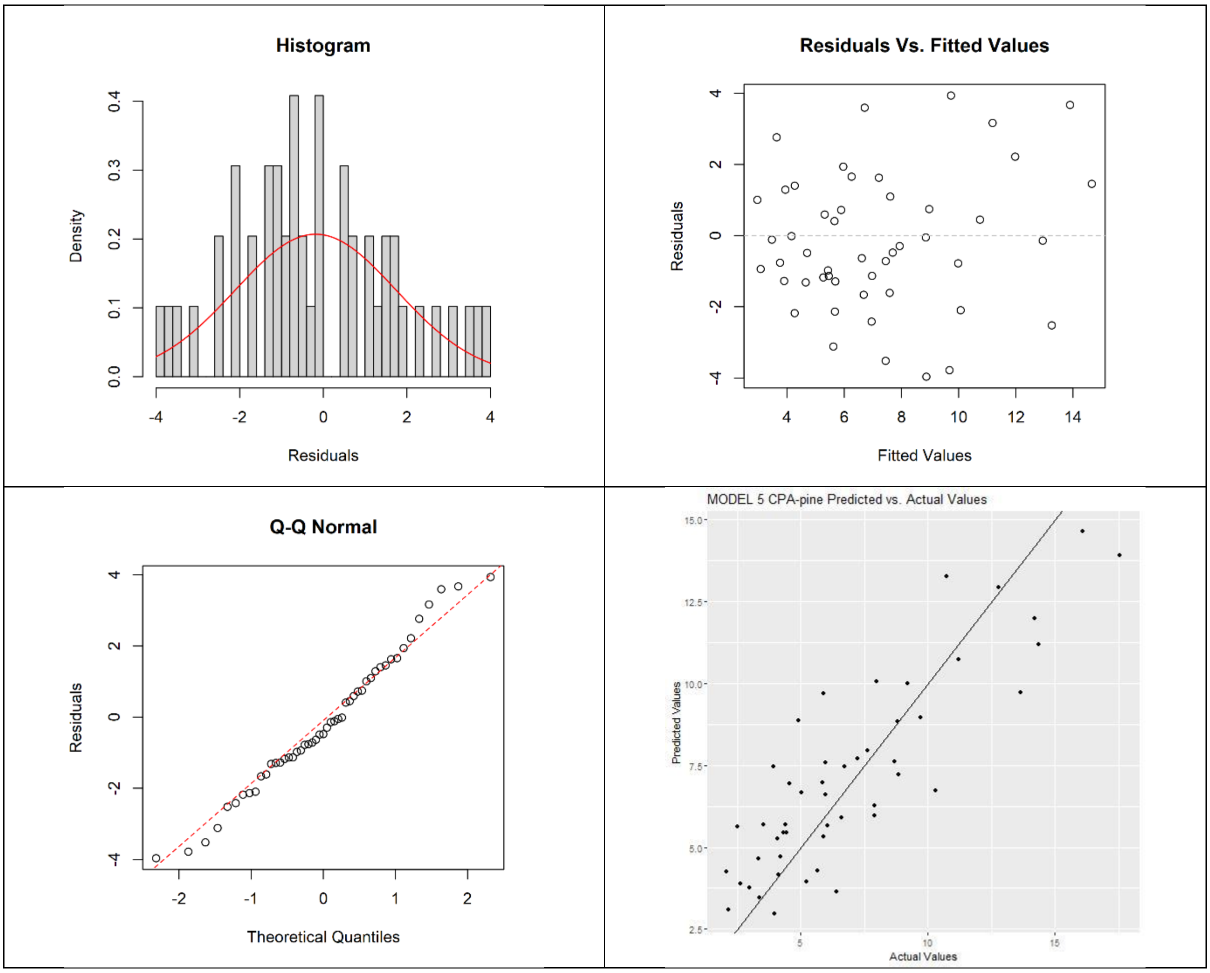
Model 3 (Radius = 10) $CPA = e^{(1.4+0.0001\cdot d^2H-1.65\cdot BA_t+0.77\cdot BAL_t)}$



Model 4 (Radius = 10) $CPA = e^{(1.41+0.0001\cdot d^2H-1.595\cdot BA_t+0.76\cdot BAL_p)}$



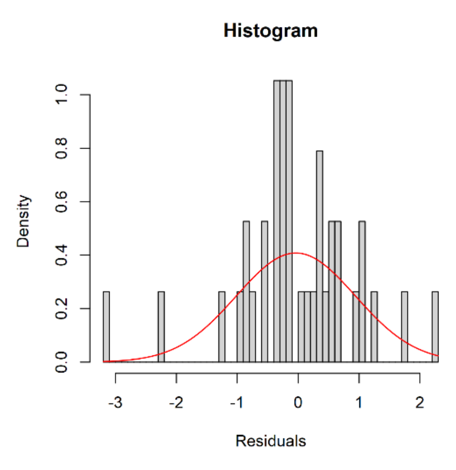
Model 5 (Radius = 10) $CPA = e^{(0.12\cdot DBH - 1.06\cdot BA_t + 0.64\cdot BAL_p)}$



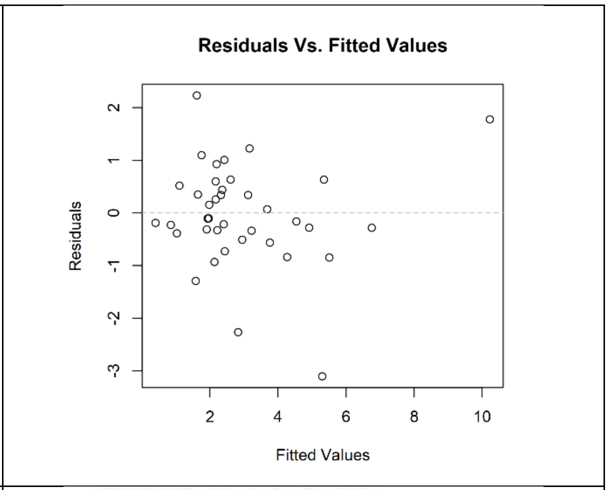
6. OAK: Crown Projection Area (CPA)

In this case, extremely large data observed in the graphs were analyzed to see if they are very influential points. We did not find any influence. For this reason, we decided to keep this data to fit our models.

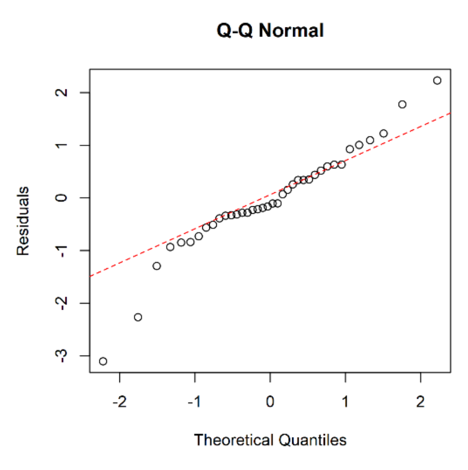
Model 1 (Radius = 5) $CPA = e^{(0.22\cdot TH - 0.14\cdot C.I. - 0.49\cdot Ratio\ BAL_p)}$



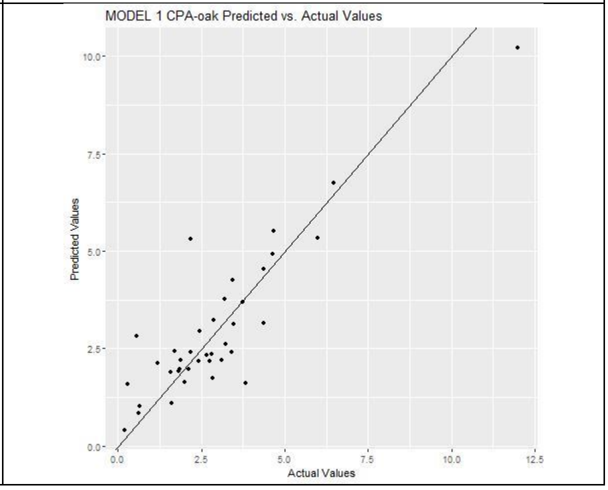
Histogram



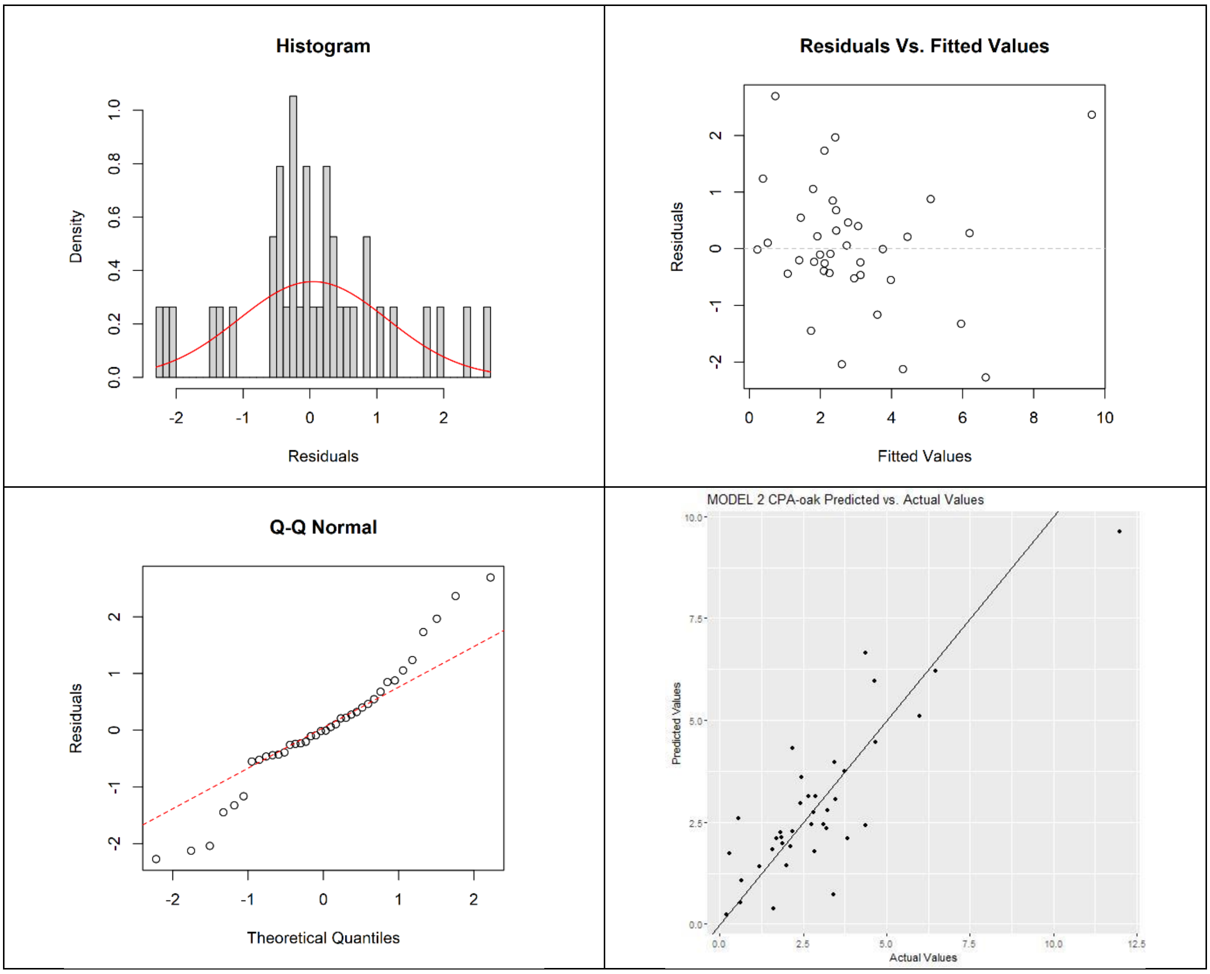
Residuals Vs. Fitted Values



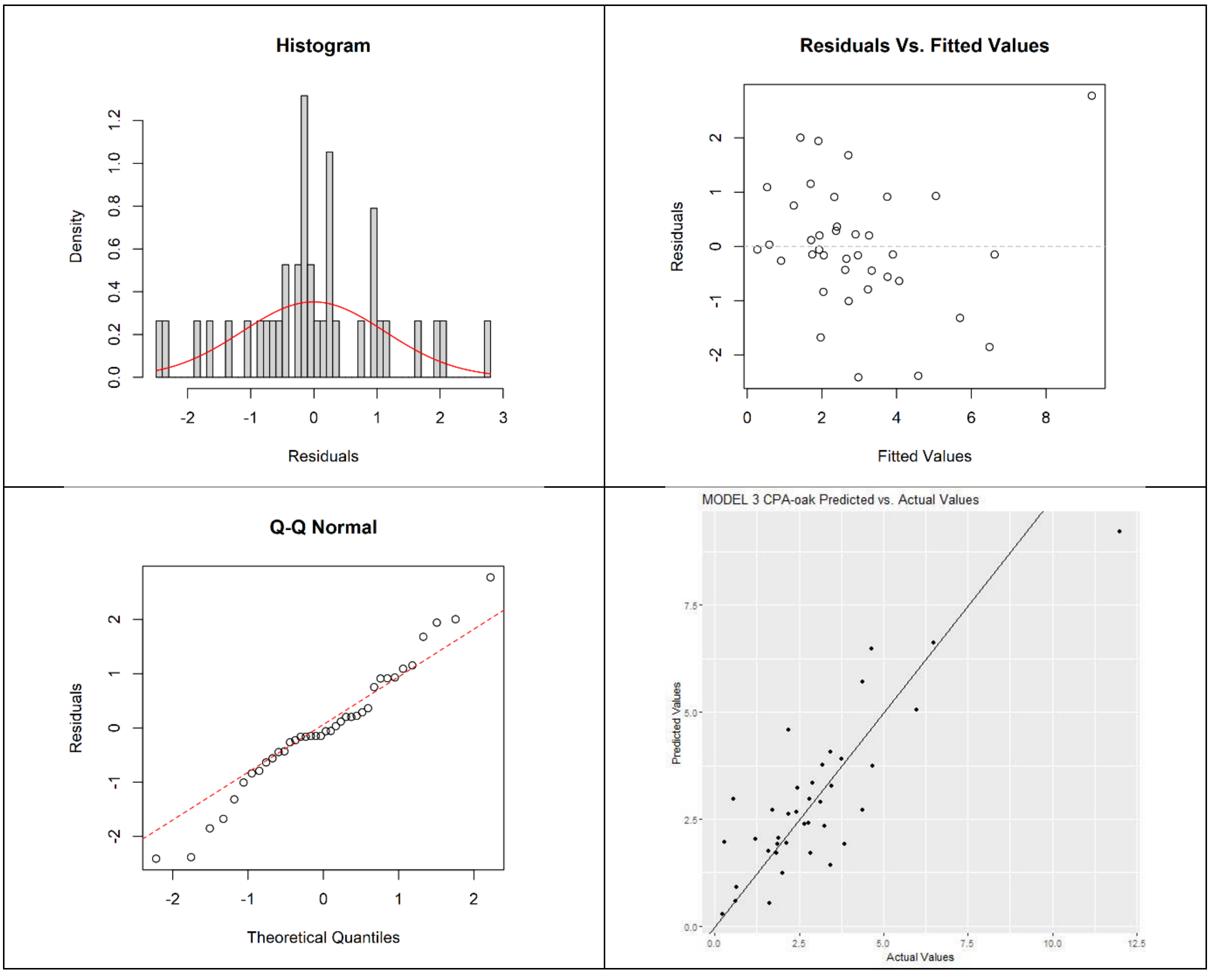
Q-Q Normal



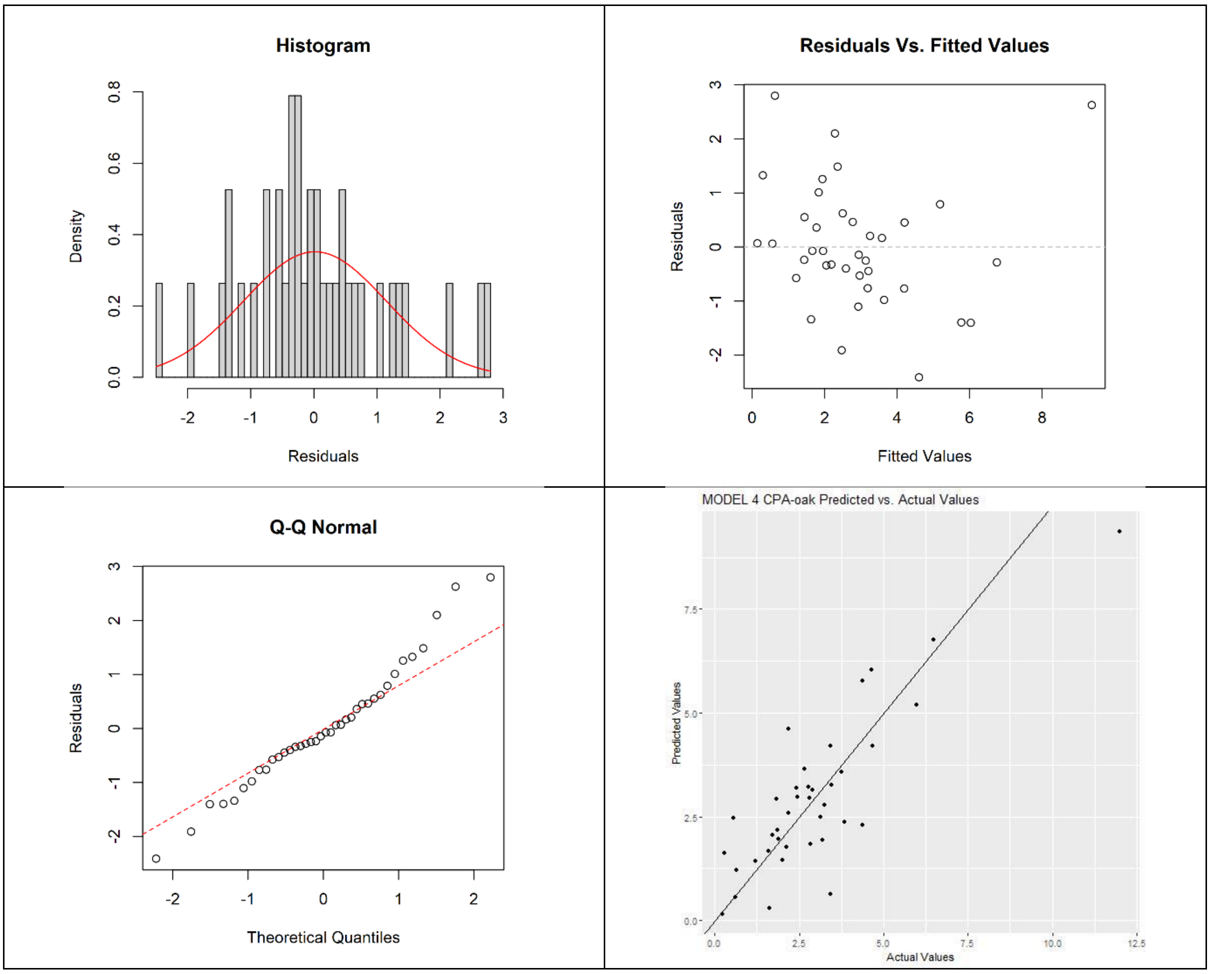
Model 2 (Radius = 7.5) $CPA = e^{(0.24 \cdot TH - 0.16 \cdot C.I.)}$



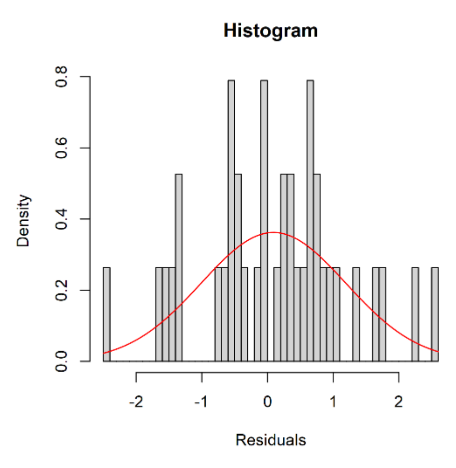
Model 3 (Radius = 5) $CPA = e^{(0.23 \cdot TH - 0.22 \cdot C.I.)}$

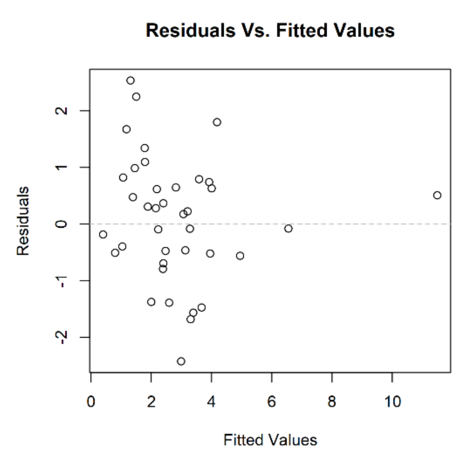


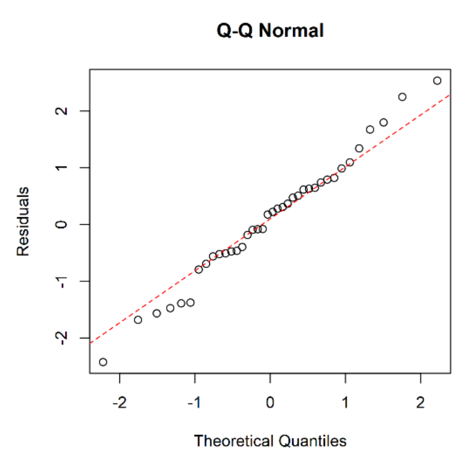
Model 4 (Radius = 10) $CPA = e^{(0.25 \cdot TH - 0.13 \cdot C.I.)}$

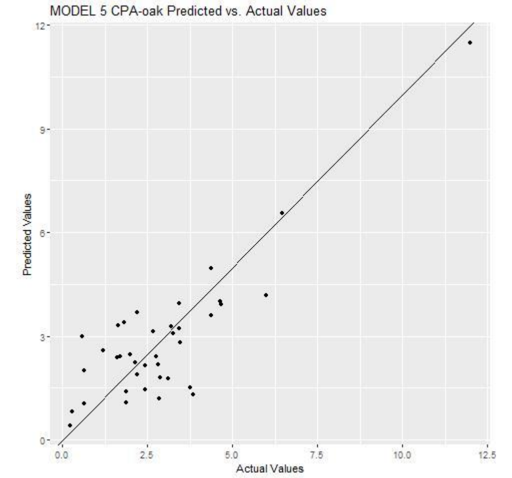


Model 5 (Radius = 10) $CPA = e^{(0.26 \cdot TH + 0.43 \cdot lnBA_t - 3.43 \cdot BAL_p)}$


Histogram

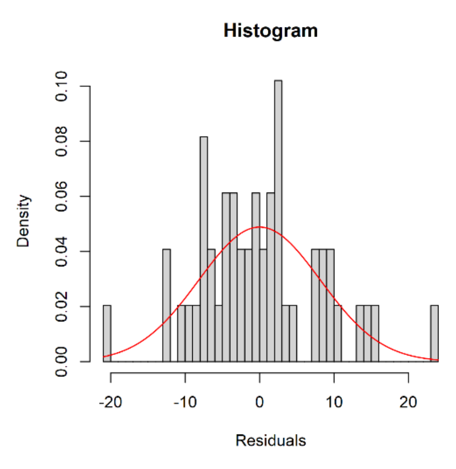

Residuals Vs. Fitted Values

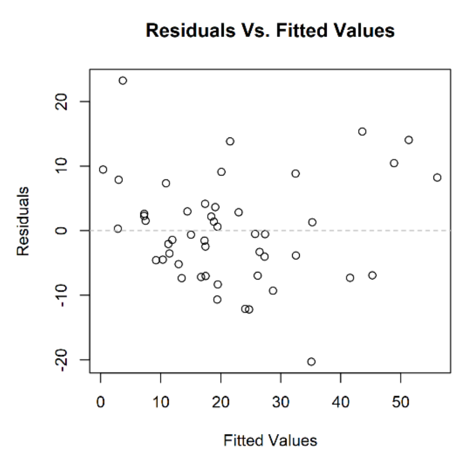

Q-Q Normal

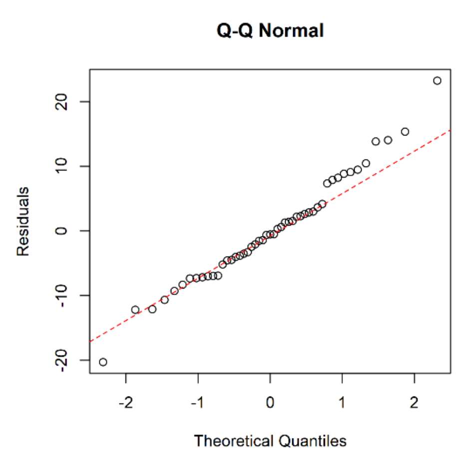

MODEL 5 CPA-oak Predicted vs. Actual Values

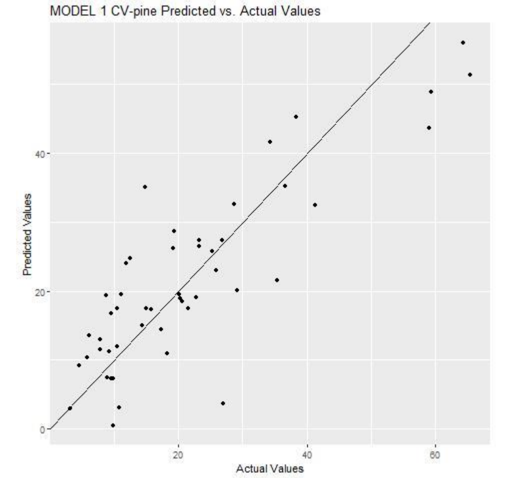
7. PINE: Crown Volume (CV)

Model 1 (Radius = 5) $CV = 17.75 + 0.01 \cdot d^2h - 152.77 \cdot BA_t + 105.53 \cdot BAL_p - 22.15 \cdot Ratio\ n_p$

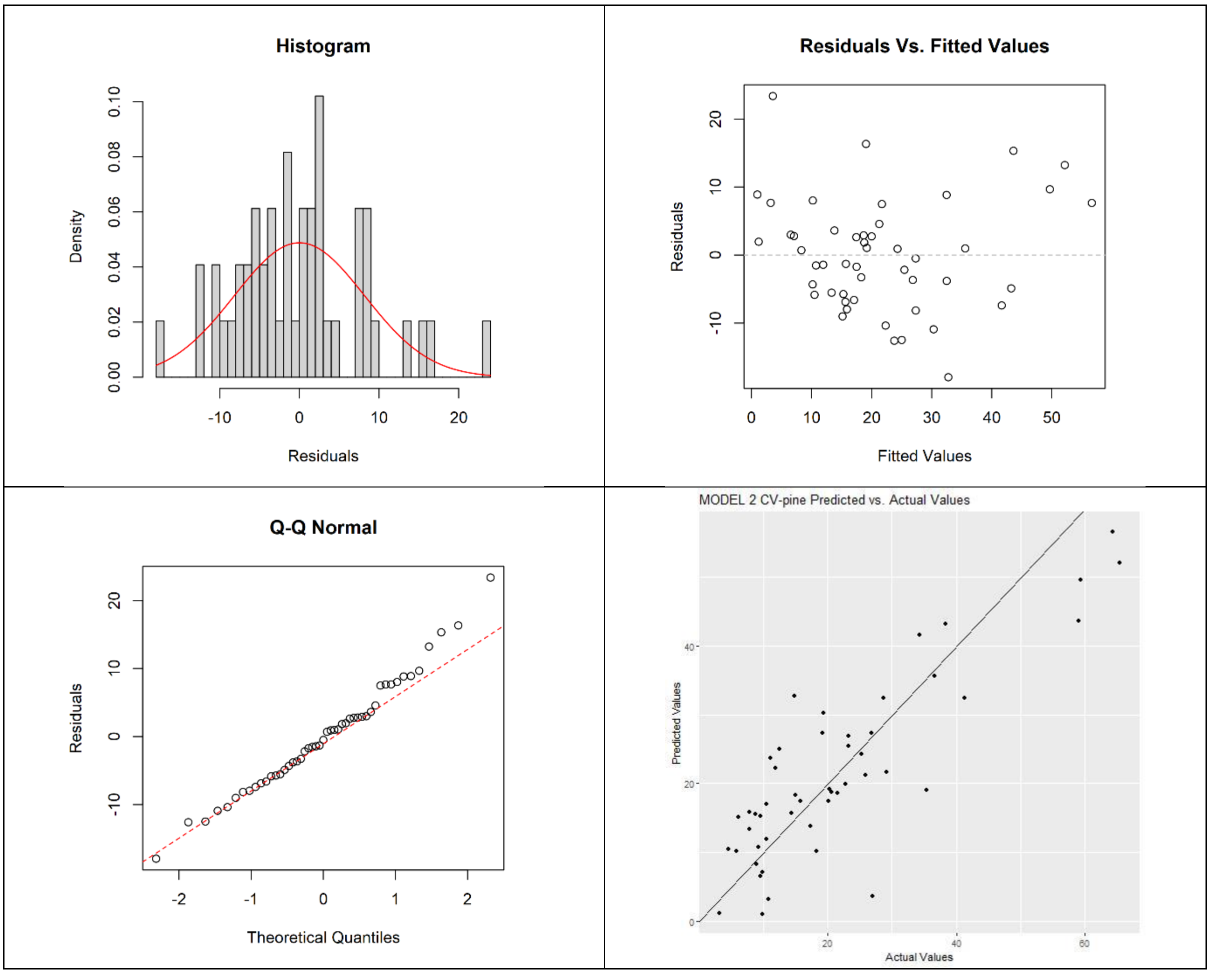




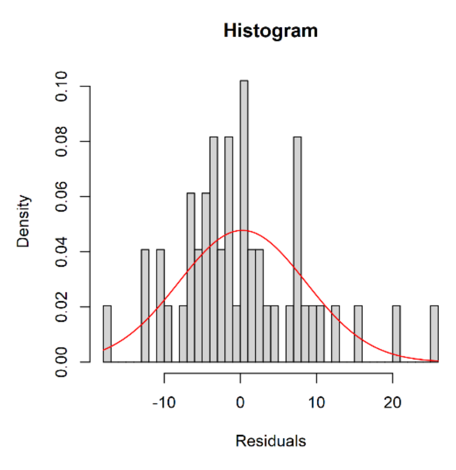


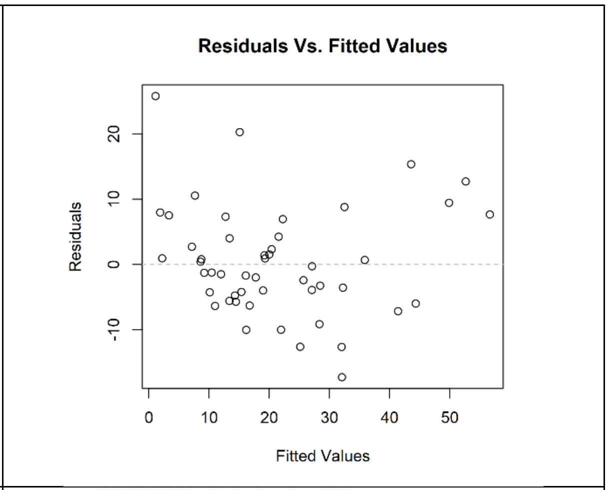


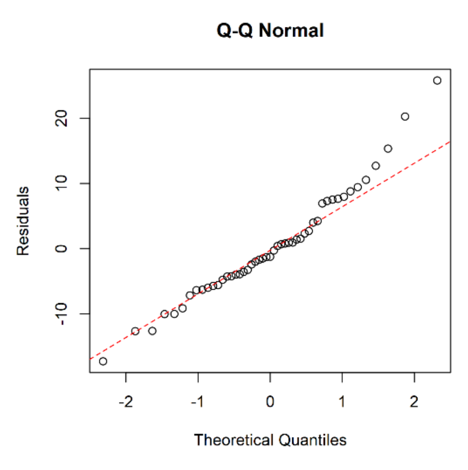
Model 2 (Radius = 5) $CV = 24.08 + 0.01 \cdot d^2h - 143.08 \cdot BA_t + 106.01 \cdot BAL_p - 29.36 \cdot Ratio\ BA_p$

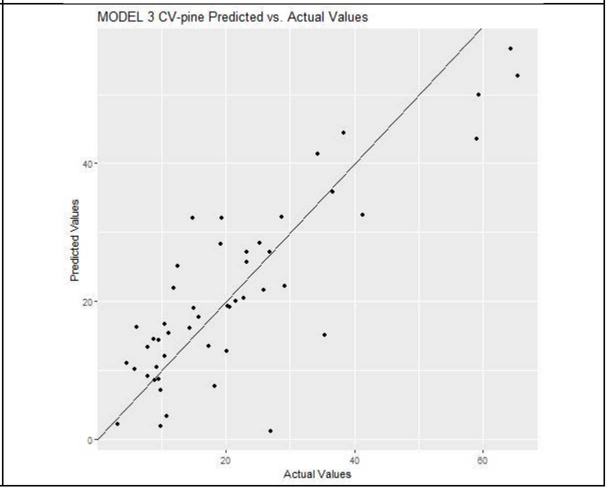


Model 3 (Radius = 5) $CV = 0.01 \cdot d^2h - 131.45 \cdot BA_t + 99.12 \cdot BAL_t - 5.66 \cdot Ratio\ n_p$

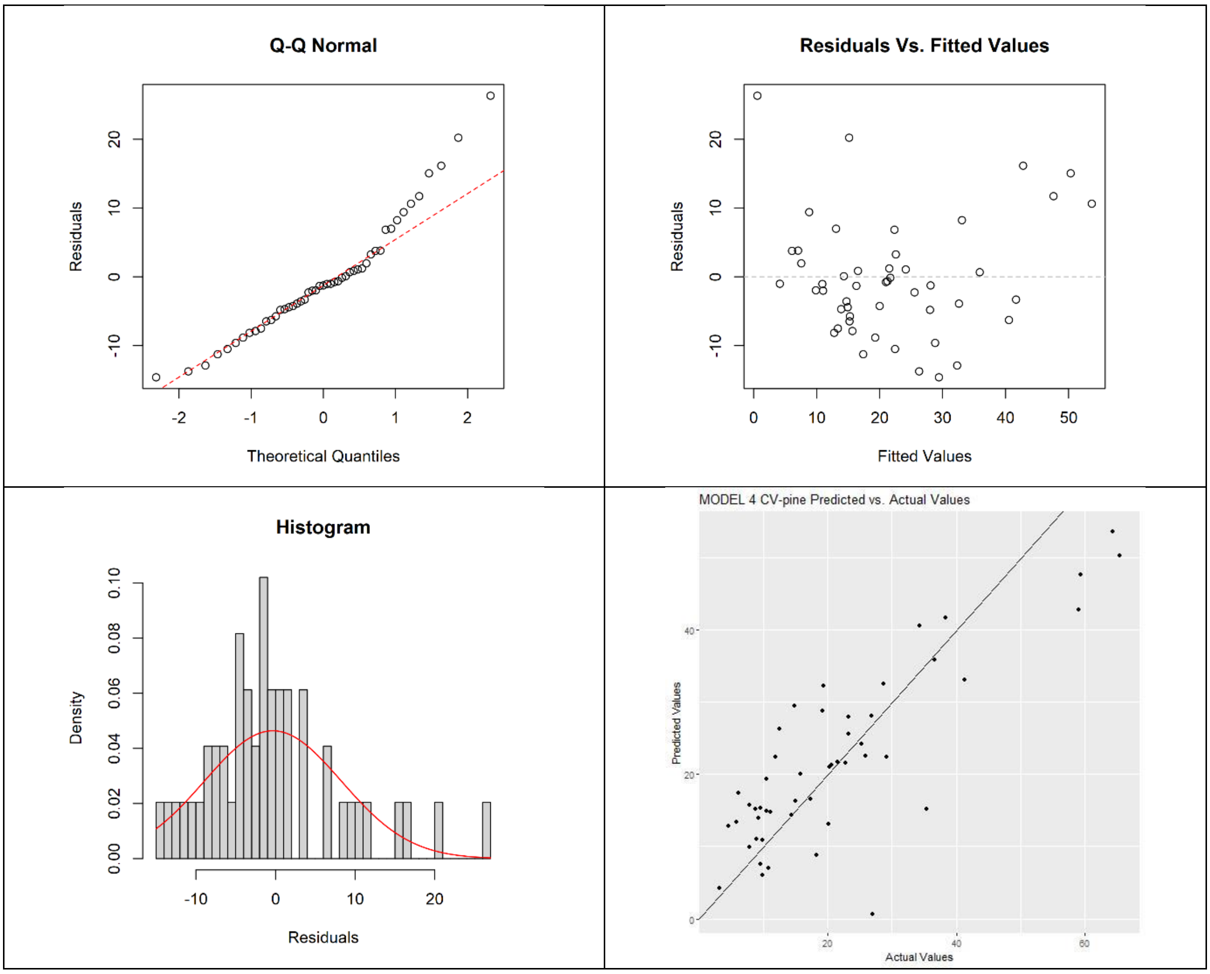




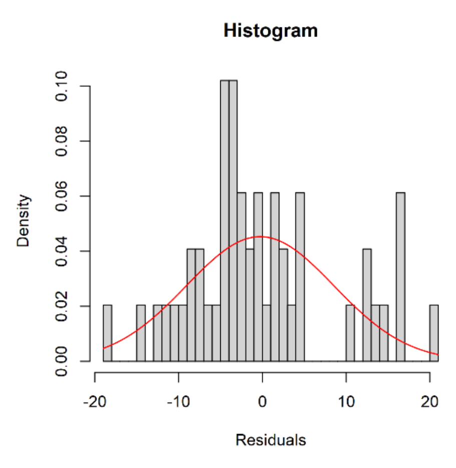


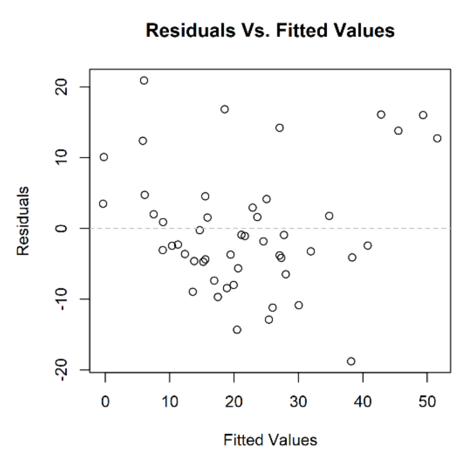


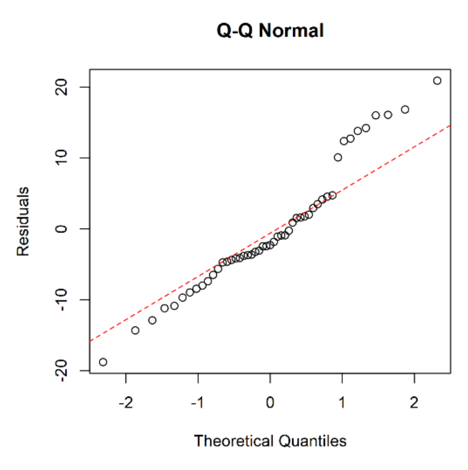
Model 4 (Radius = 5) $CV = 0.01 \cdot d^2 h - 117.28 \cdot BA_t + 79.82 \cdot BAL_t$

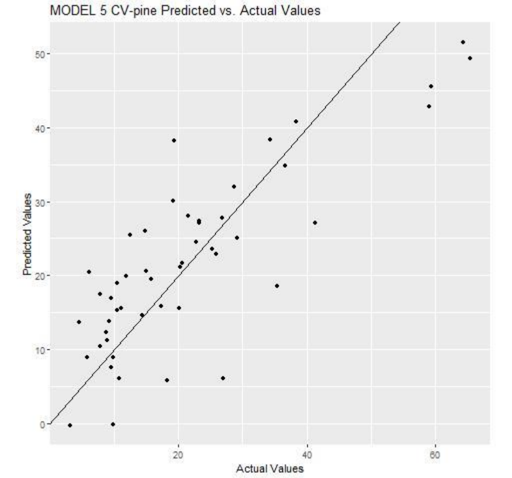


Model 5 (Radius = 10) $CV = 0.01 \cdot d^2h - 30.78 \cdot BA_t + 24.43 \cdot BAL_p$



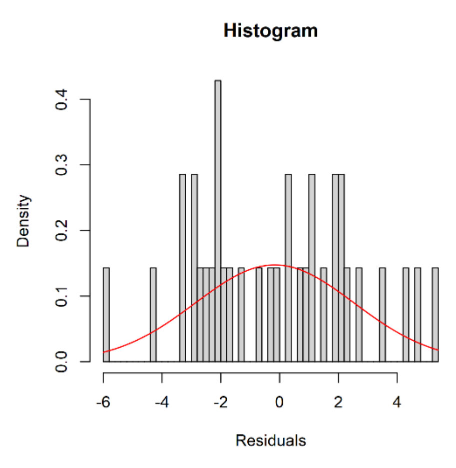


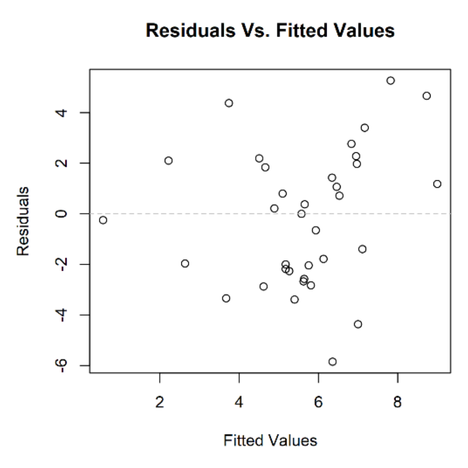


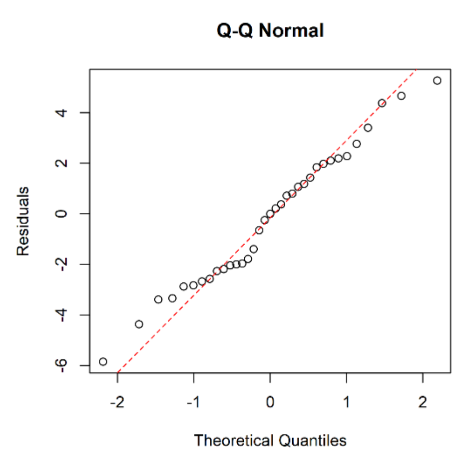


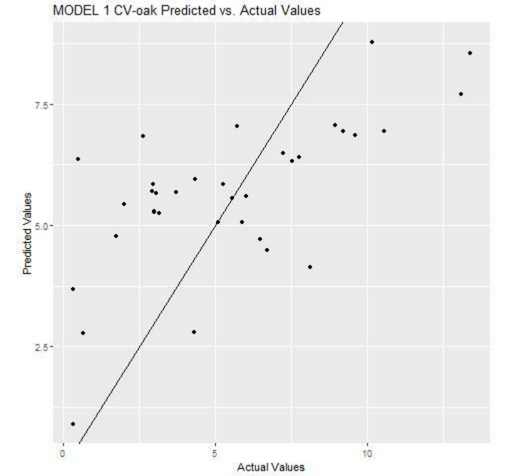
8. OAK: Crown Volume (CV)

Model 1 (Radius = 10) $CV = 1.61 \cdot TH + 10.71 \cdot lnBA_t - 43.49 \cdot BAL_p + 18.01 \cdot \ Ratio\ BA_p$

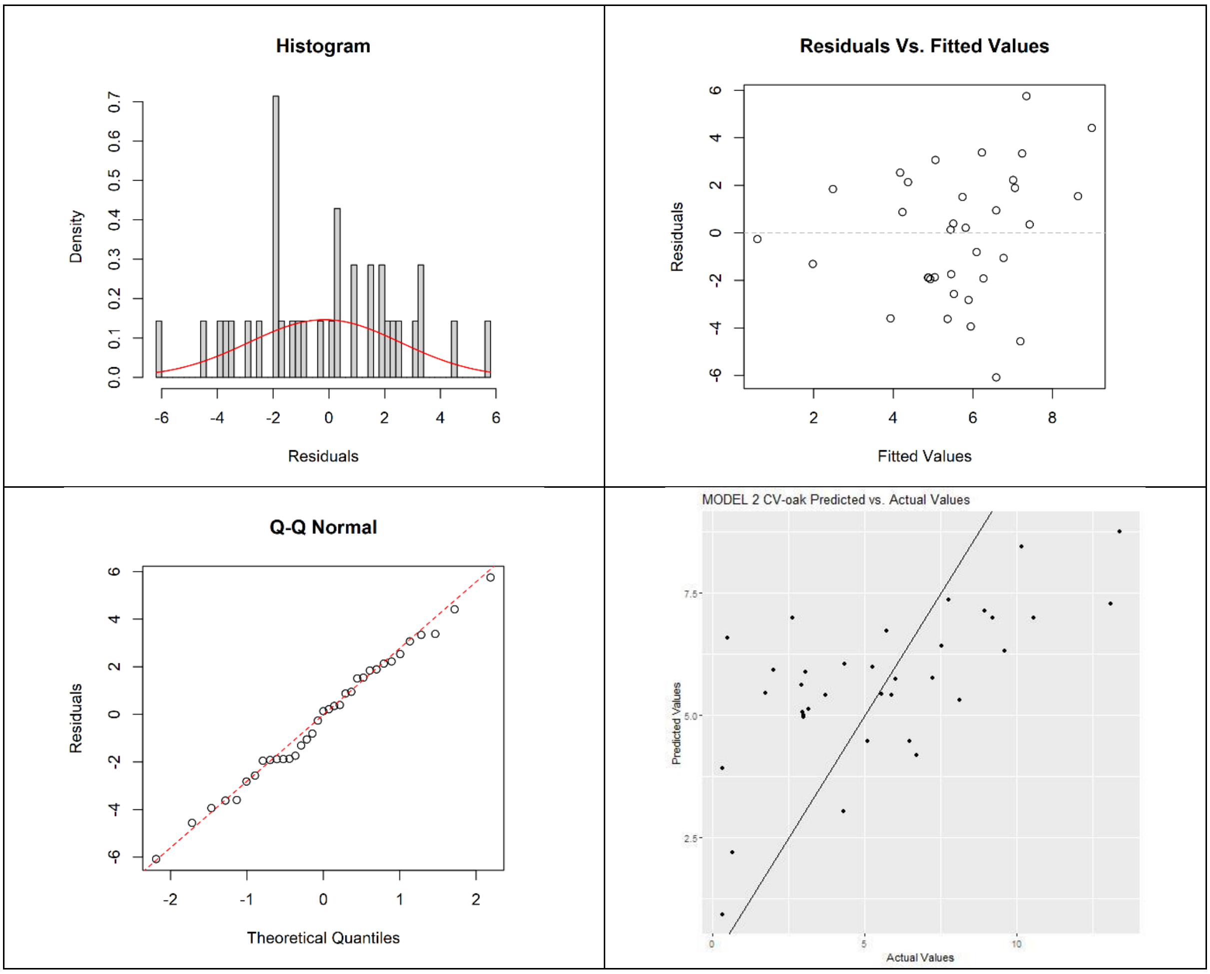




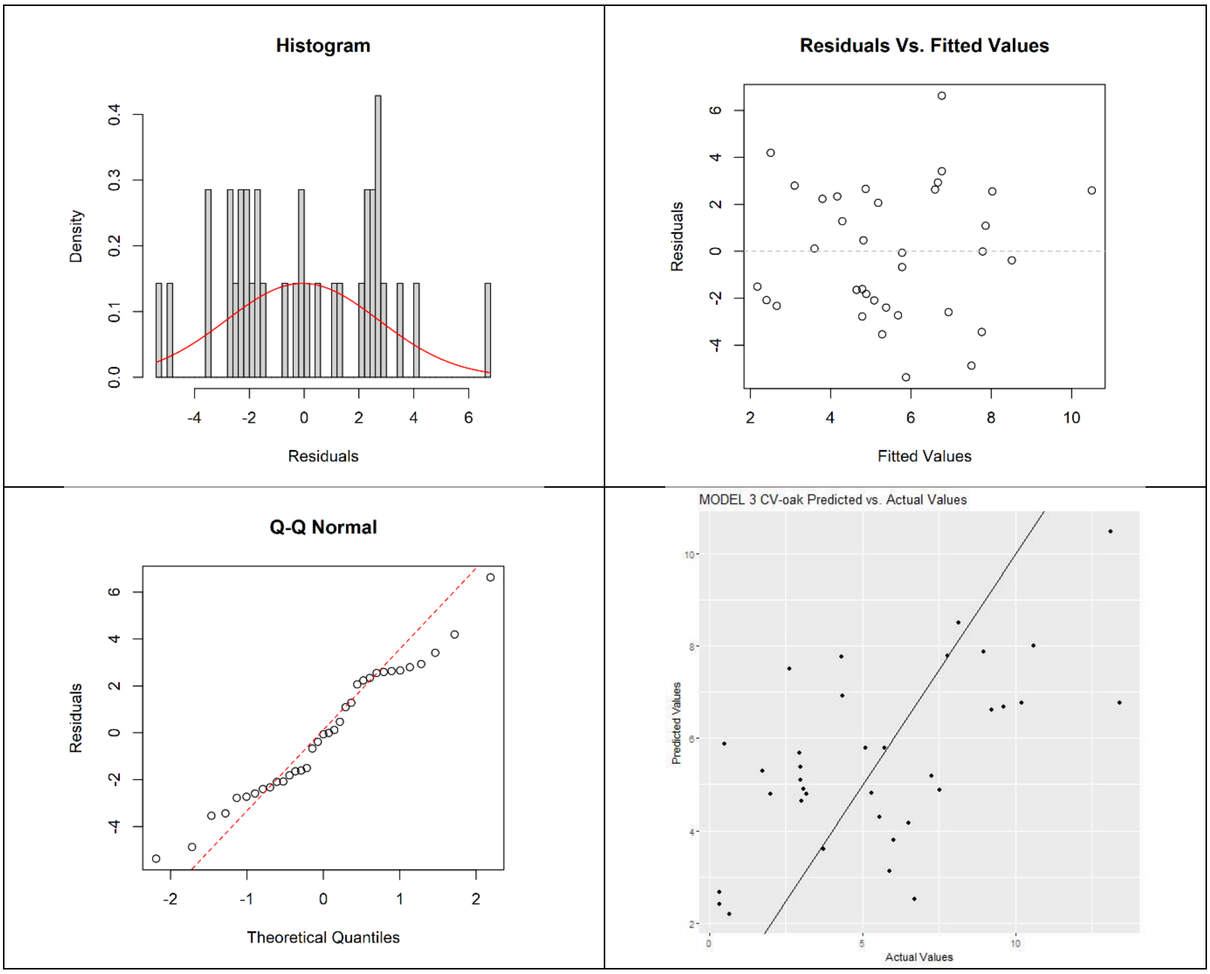




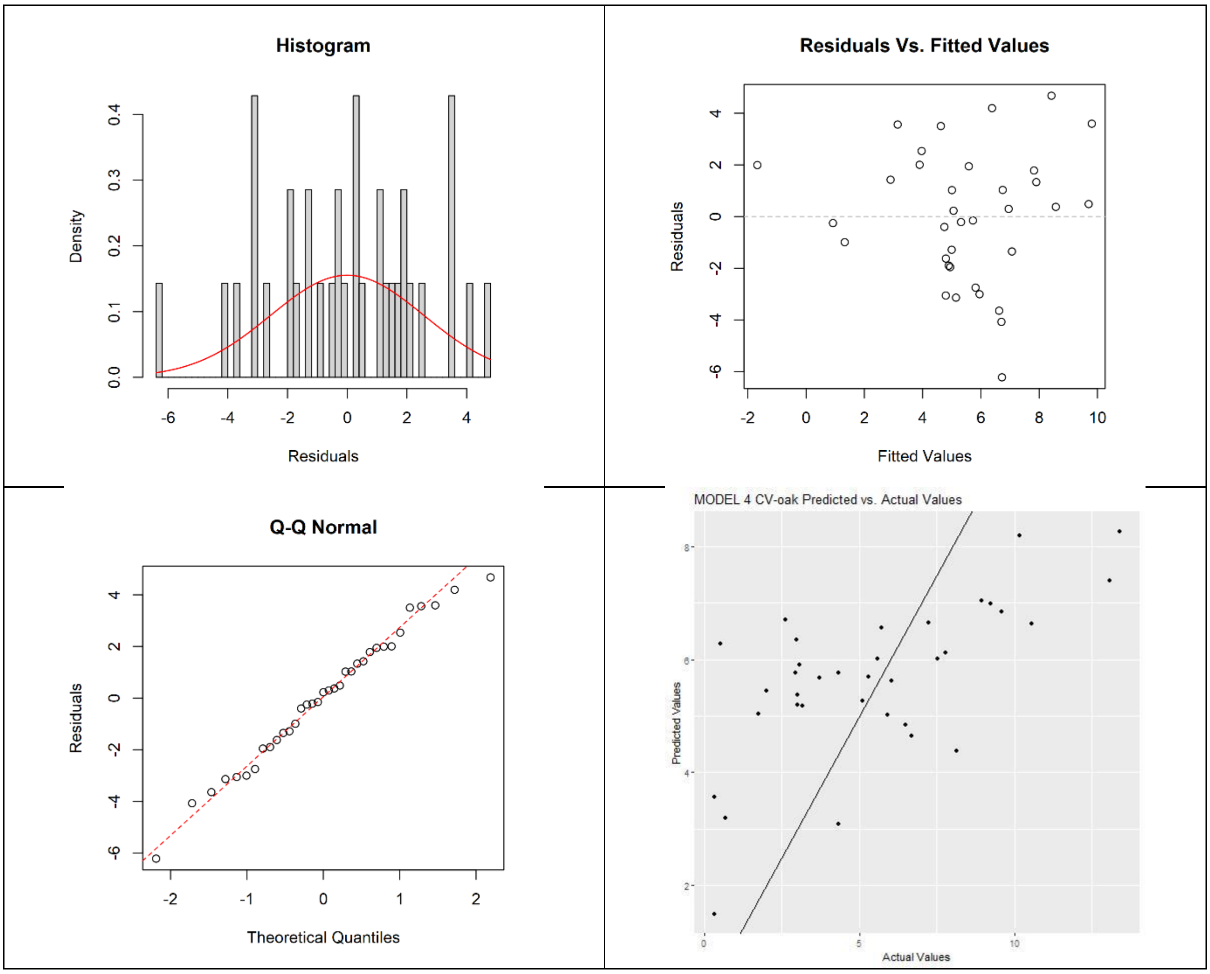
Model 2 (Radius = 10) $CV = 1.90 \cdot TH + 9.68 \cdot lnBA_t - 37.46 \cdot BAL_p + 12.62 \cdot \ Ratio\, n_p$



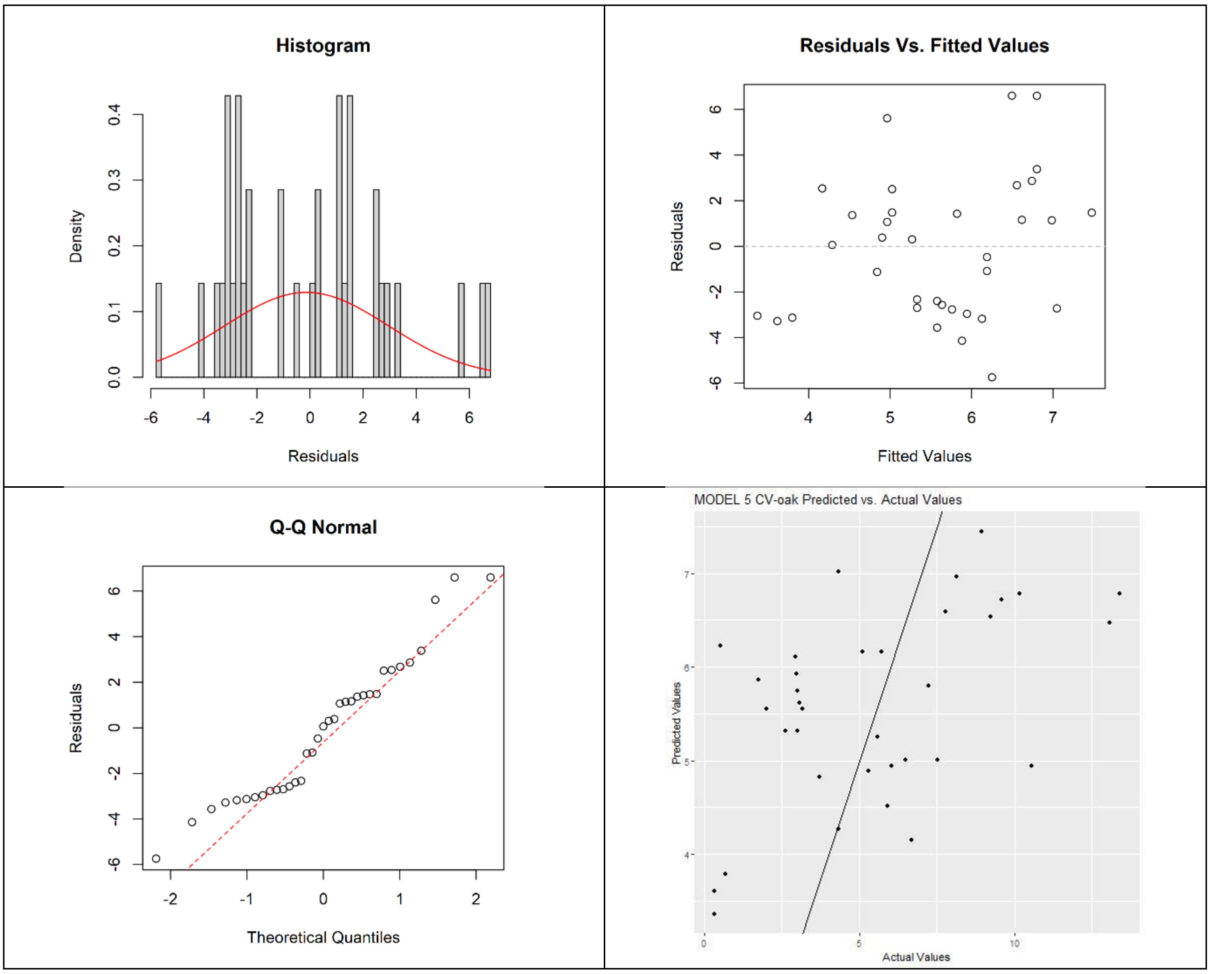
Model 3 (Radius = 5) $CV = 1.89 \cdot TH - 87.21 \cdot BAL_o - 12.23 \cdot \ Ratio\ BAL_p$



Model 4 (Radius 10) $CV = -20.88 + 1.57 \cdot TH + 31.33 \cdot BA_t - 42.86 \cdot BAL_p + 15.97 \cdot \ Ratio\ n_p$



Model 5 (Radius = 5) $CV = 1.65 \cdot TH - 10.58 \cdot \ Ratio\ BAL_p$



ANNEX 4

Residual analyses for Lean and Sweep models

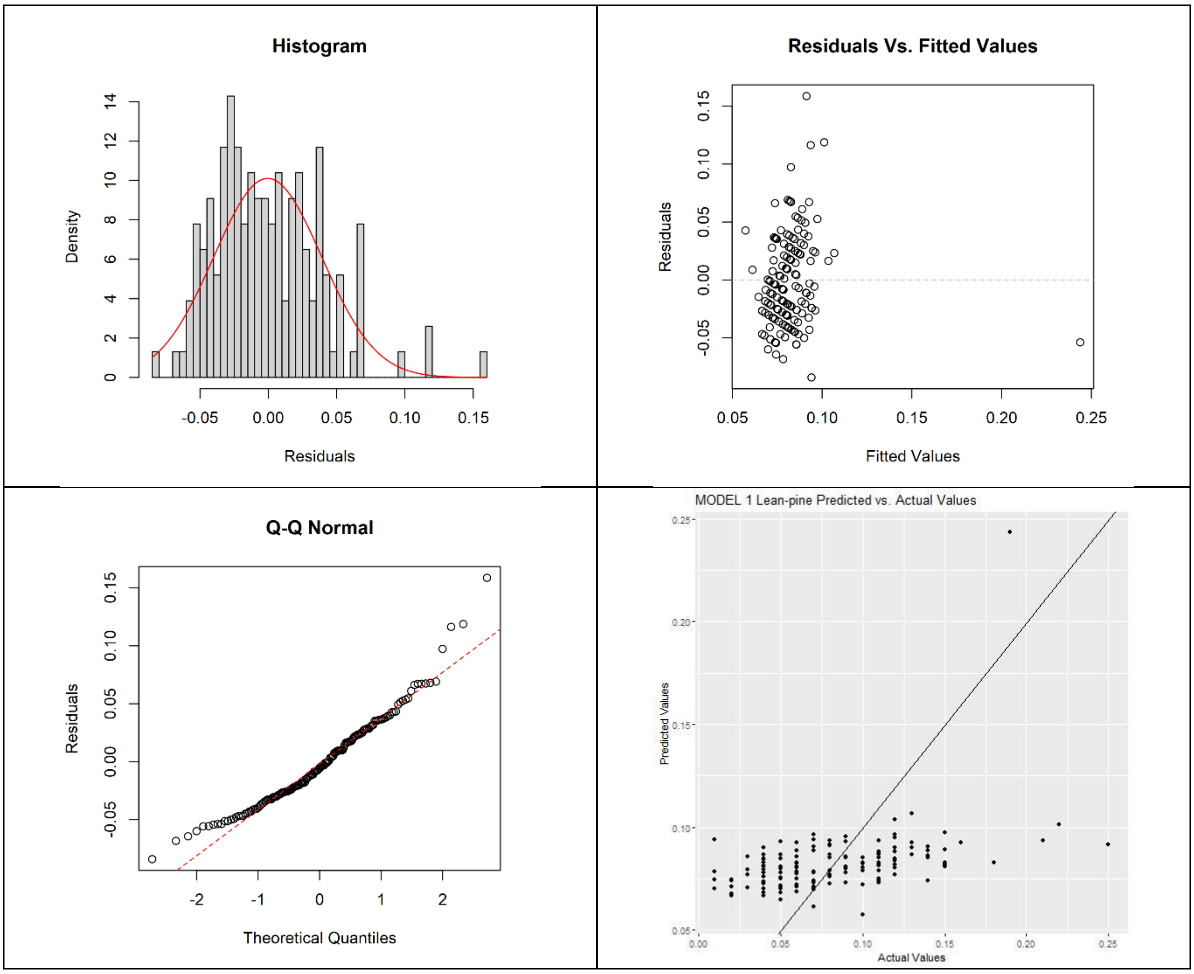
Annex 4

RESIDUAL ANALYSES FOR LEAN AND SWEEP MODELS

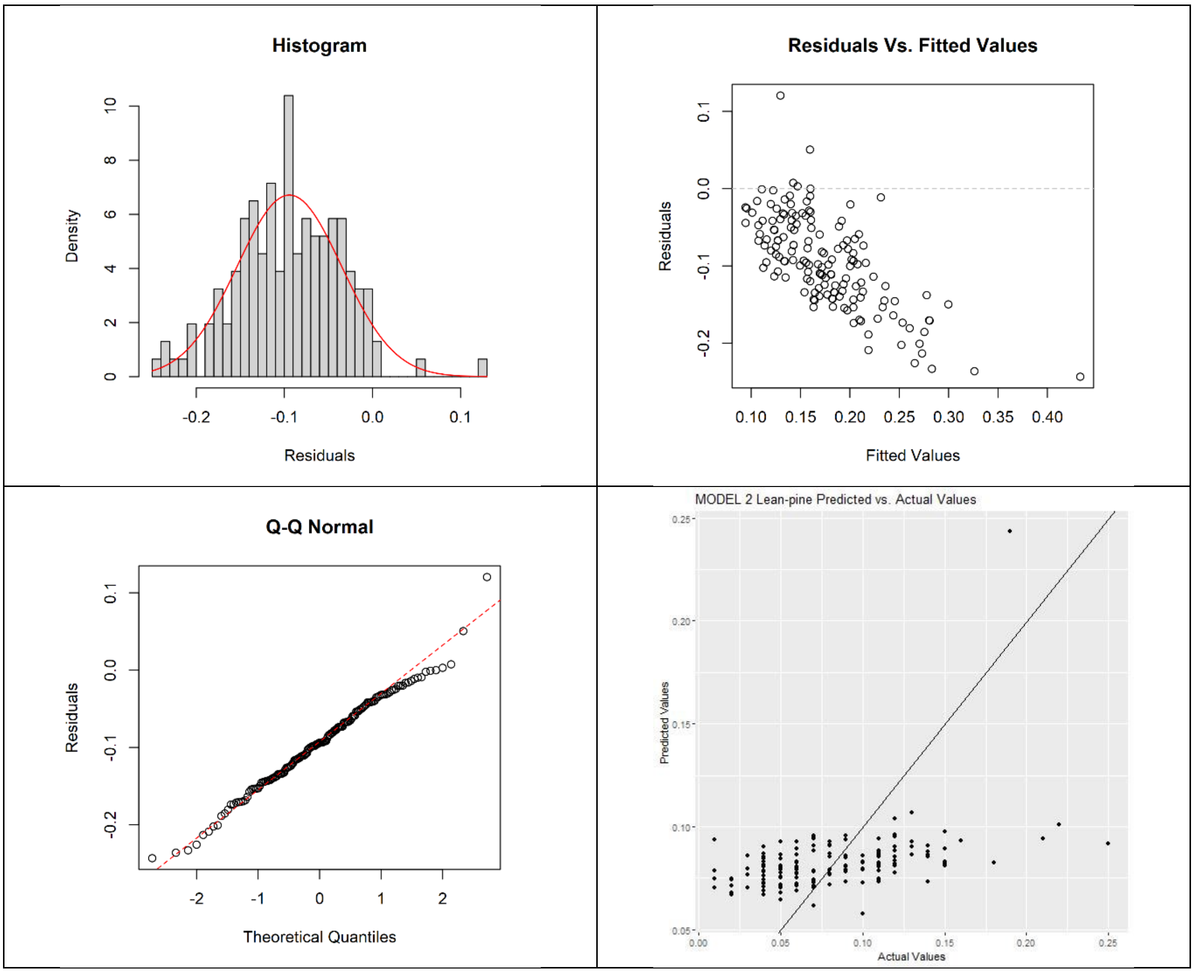
1. PINE: LEAN

Before the analysis outliers were detected and eliminated for our data. The graphs show some extremely large data. We analyzed the influence of those data. We did not find any influence. For this reason, we decided to keep this data to fit our models.

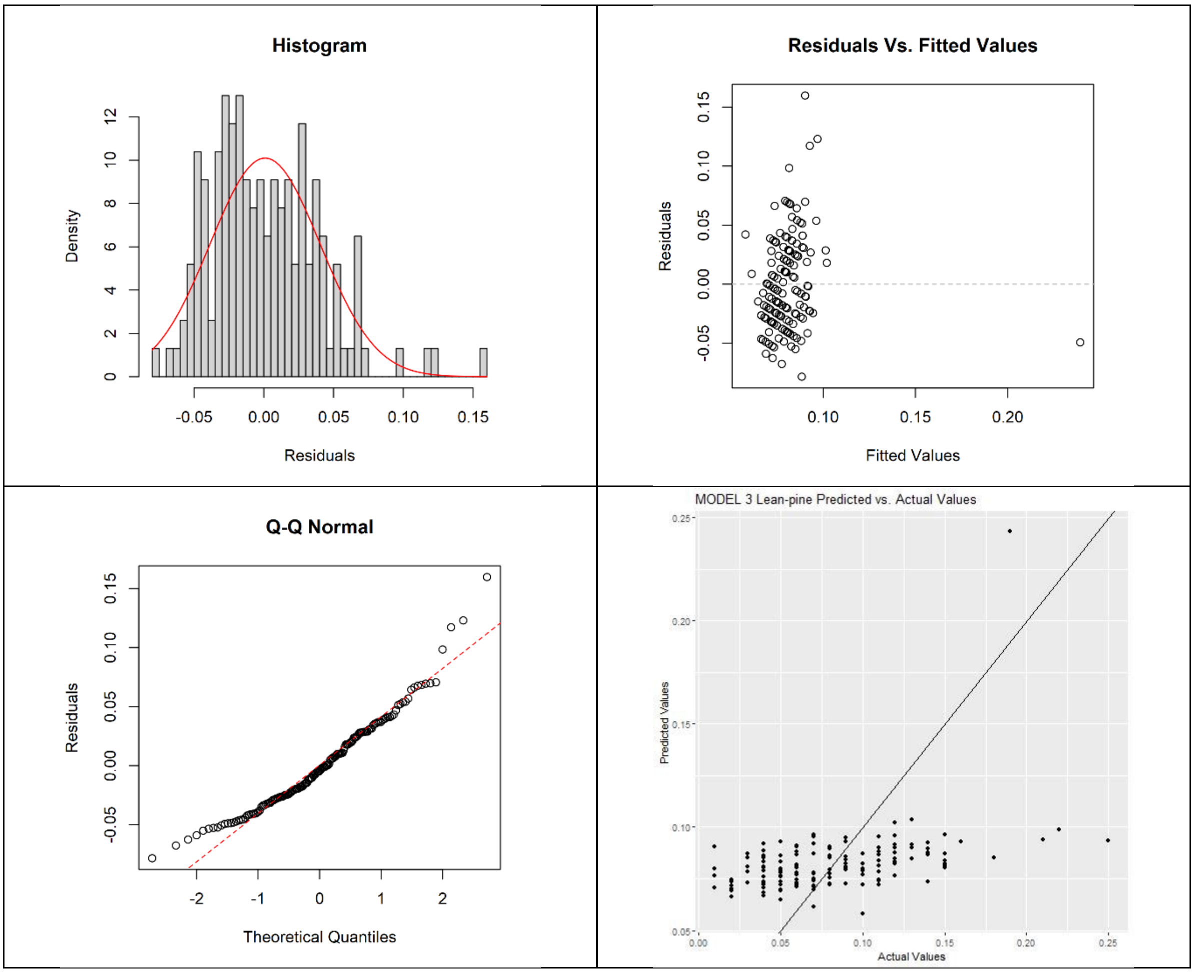
Model 1 (Radius = 10) $Lean = e^{(-1.76-0.04\cdot TH+0.003\cdot BA_t.+0.1\cdot Asym-0.26\cdot Ratio\ BA_p)}$



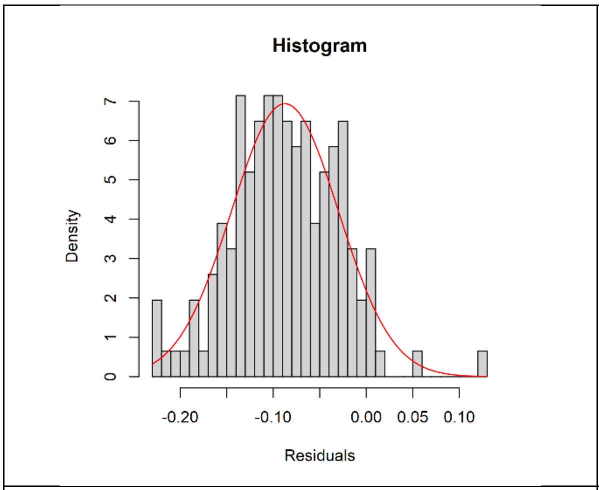
Model 2 (Radius = 10) $Lean = e^{(-1.83-0.04\cdot TH+0.046\cdot lnBA_{t}.+0.1\cdot Asym-0.25\cdot Ratio\ BA_{p})}$

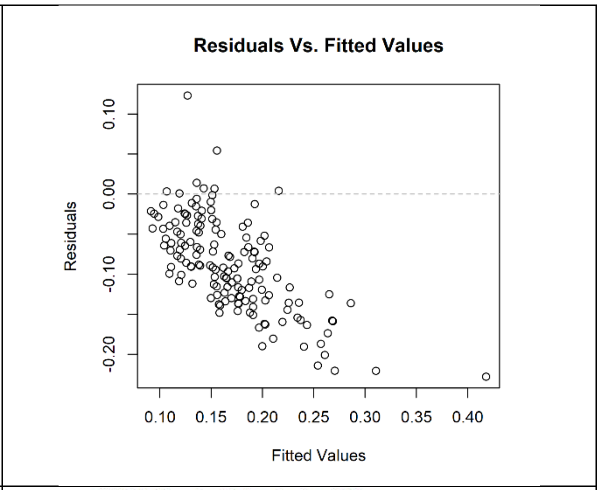


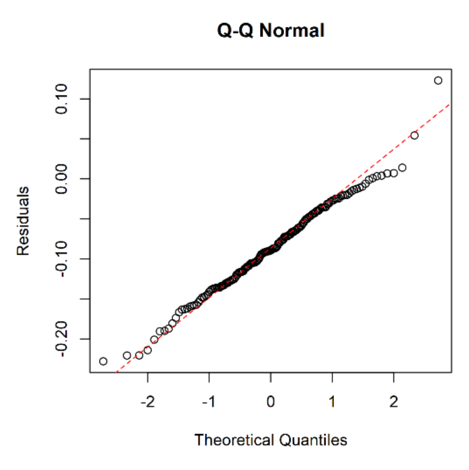
Model 3 (Radius = 10) $Lean = e^{(-1.86-0.04\cdot TH+0.003\cdot BA_t.+0.1\cdot Asym-0.18\cdot Ratio\ n_p)}$

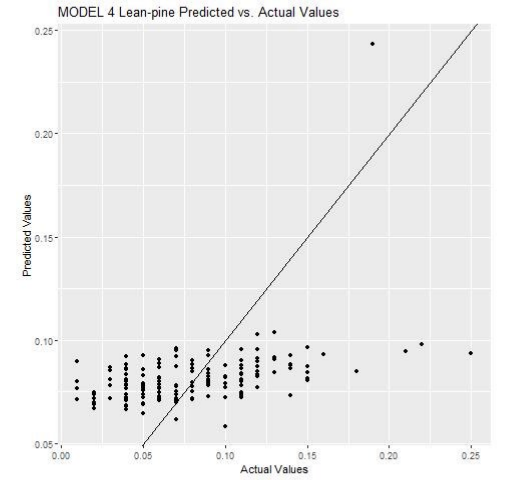


Model 4 (Radius = 10) $Lean = e^{(-1.94-0.04 \cdot TH+0.044 \cdot lnBA_t.+0.1 \cdot Asym-0.17 \cdot Ratio\ n_p)}$

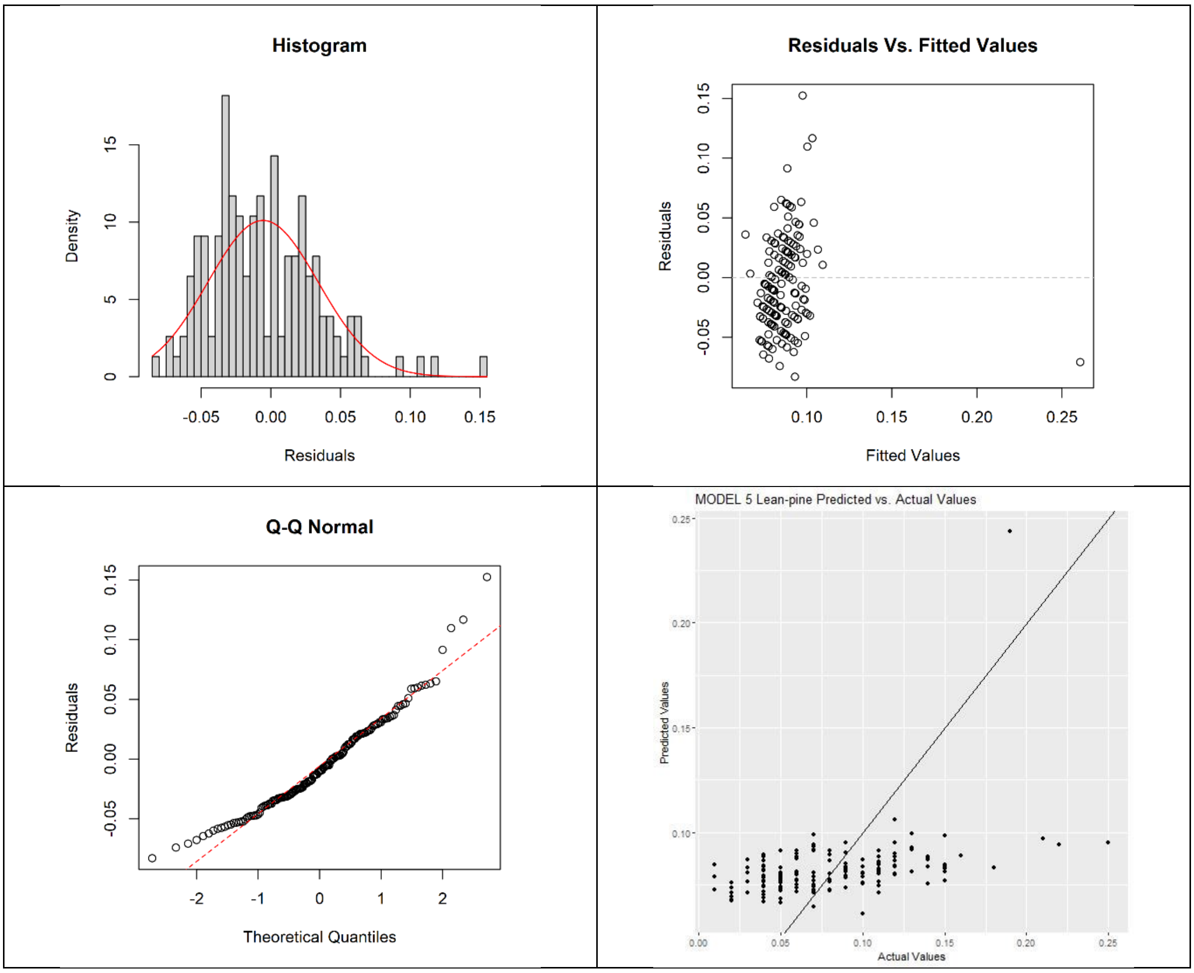






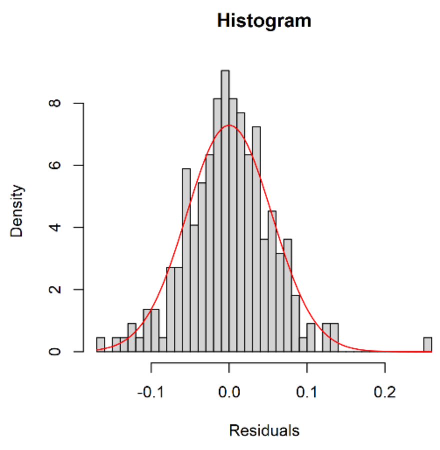


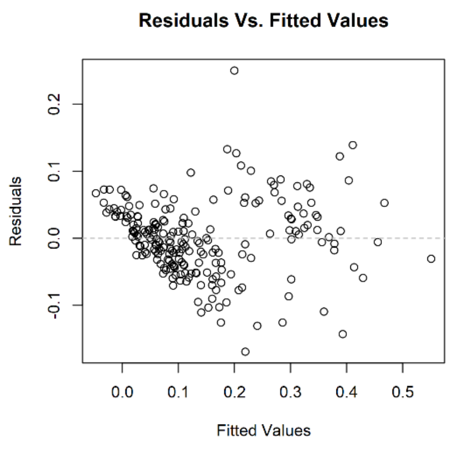
Model 5 (Radius = 5) $Lean = e^{(-1.86-0.04 \cdot TH+0.004 \cdot BA_{t}.+0.1 \cdot Asym-0.14 \cdot Ratio\ BA_{p})}$

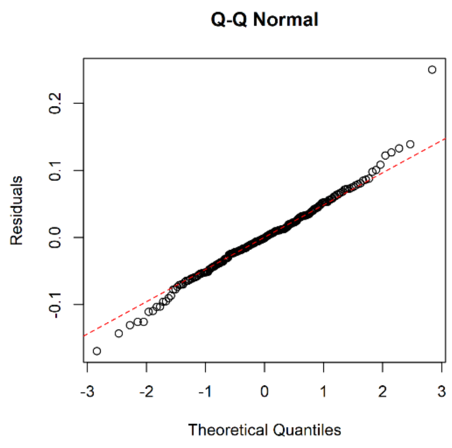


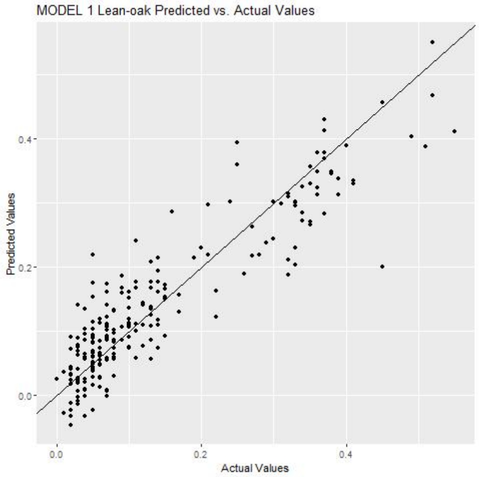
2. OAK: LEAN

Model 1 (Radius = 5, 7.5, 10) $Lean = -1 + e^{(0.23 - 0.01 \cdot TH - 0.004 \cdot lnBA_t. + 0.06 \cdot Asym + 0.02 \cdot Ratio\ BA_p)}$

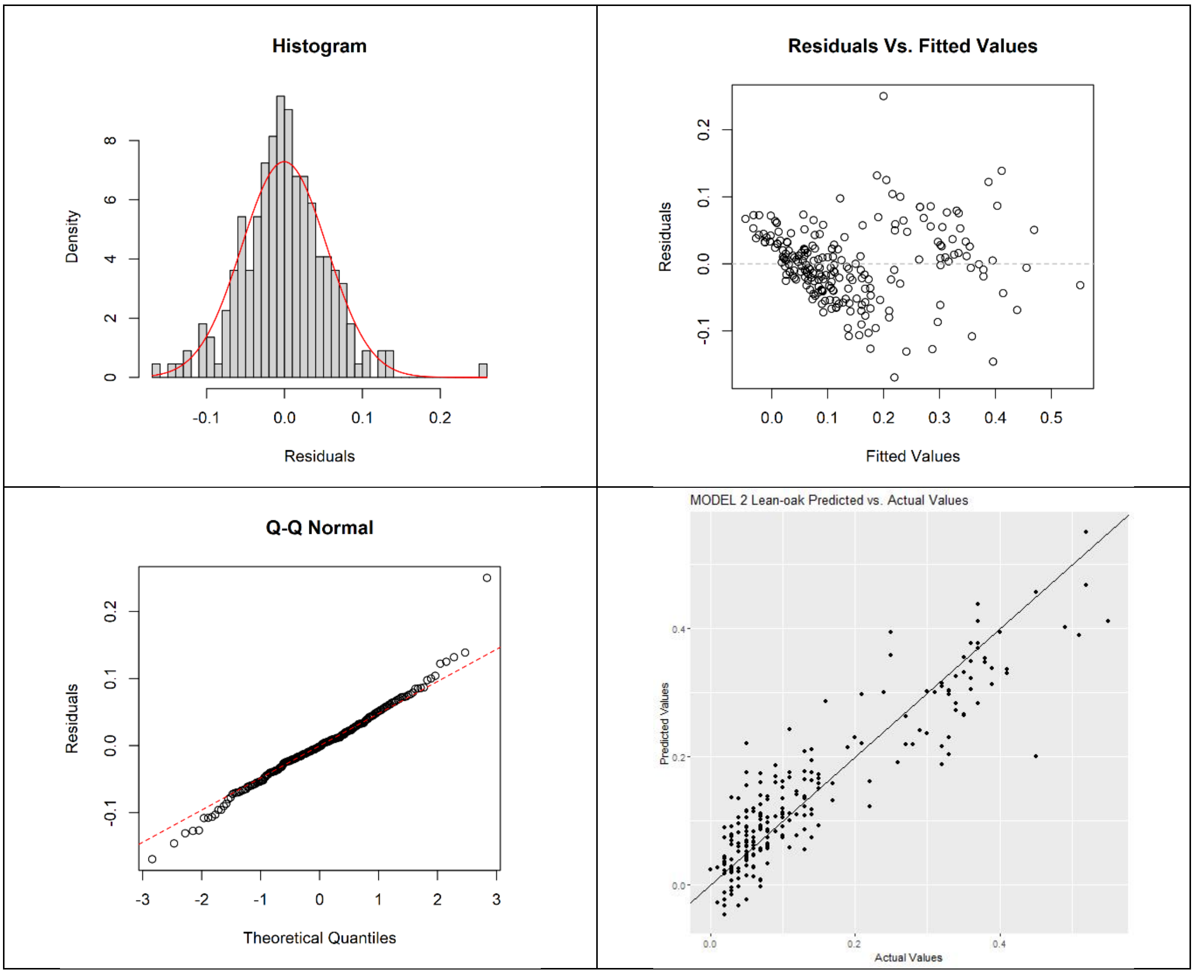

Histogram


Residuals Vs. Fitted Values

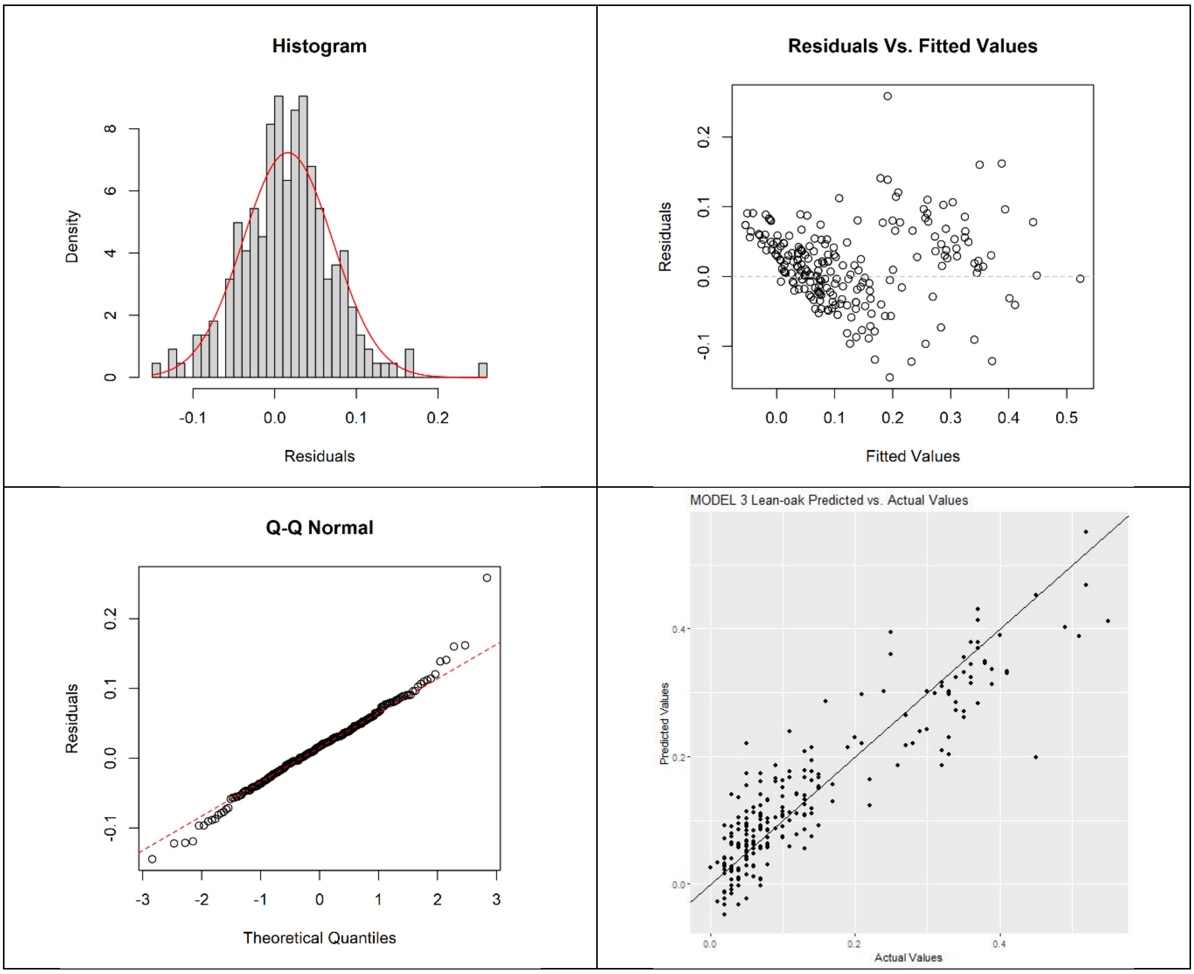

Q-Q Normal


MODEL 1 Lean-oak Predicted vs. Actual Values

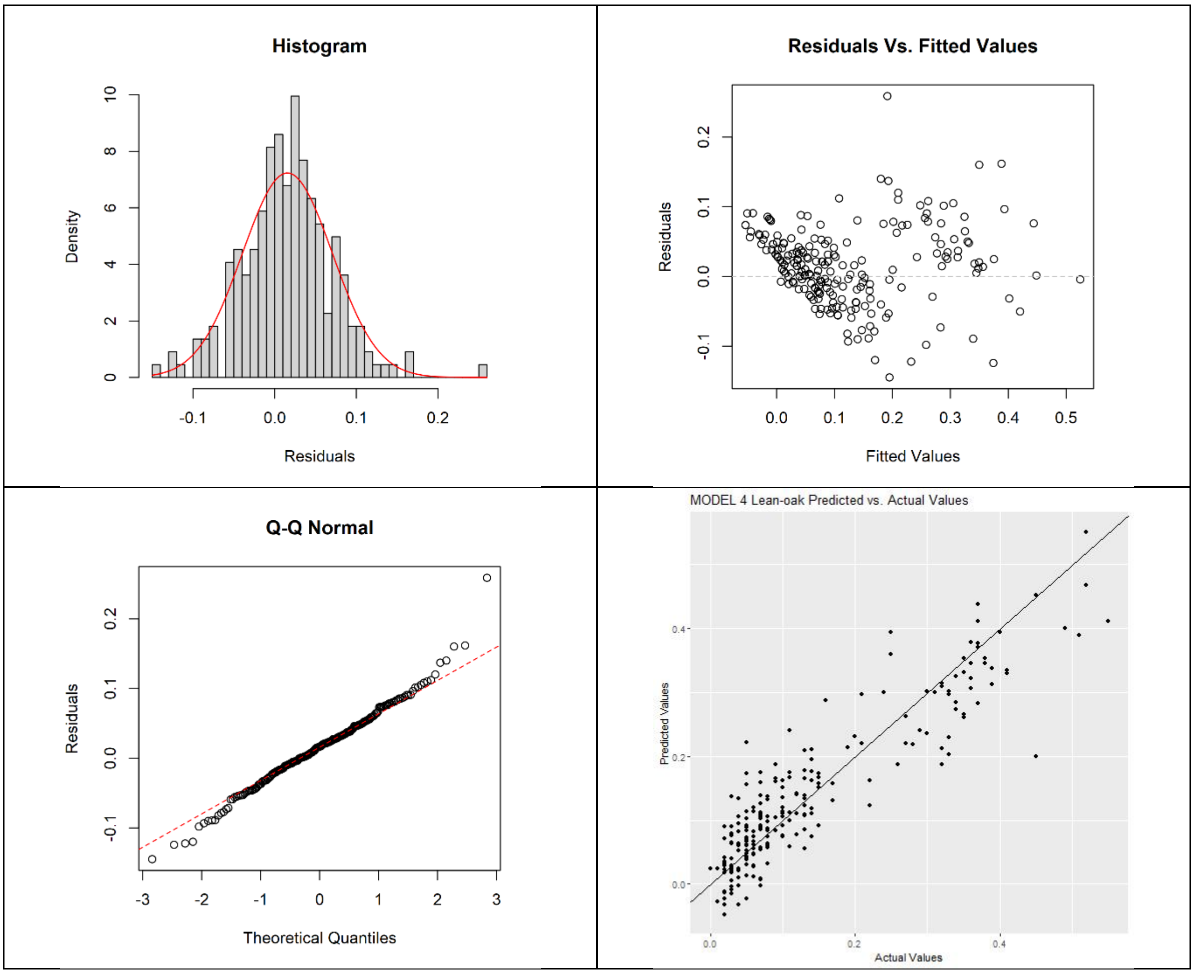
Model 2 (Radius = 10) $Lean = -1 + e^{(0.23 - 0.01 \cdot TH - 0.005 \cdot lnBA_t. + 0.06 \cdot Asym + 0.01 \cdot Ratio\ BAL_p)}$



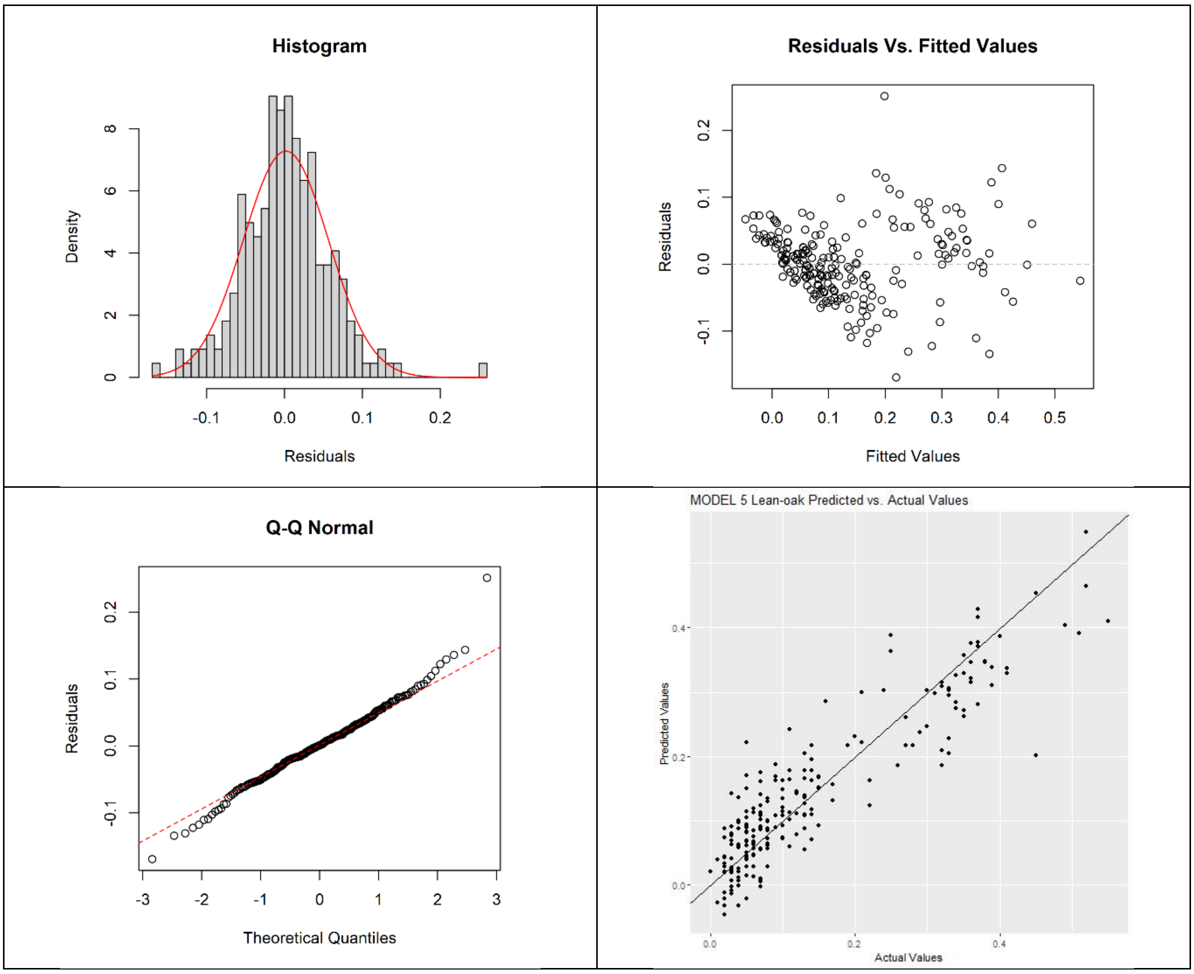
Model 3 (Radius = 10) $Lean = -1 + e^{(0.22 - 0.01 \cdot TH - 0.001 \cdot BA_t. + 0.06 \cdot Asym + 0.02 \cdot Ratio\ BA_p)}$



Model 4 (Radius = 10) $Lean = -1 + e^{(0.23-0.01\cdot TH-0.001\cdot BA_t.+0.06\cdot Asym+0.01\cdot Ratio\ BAL_p)}$

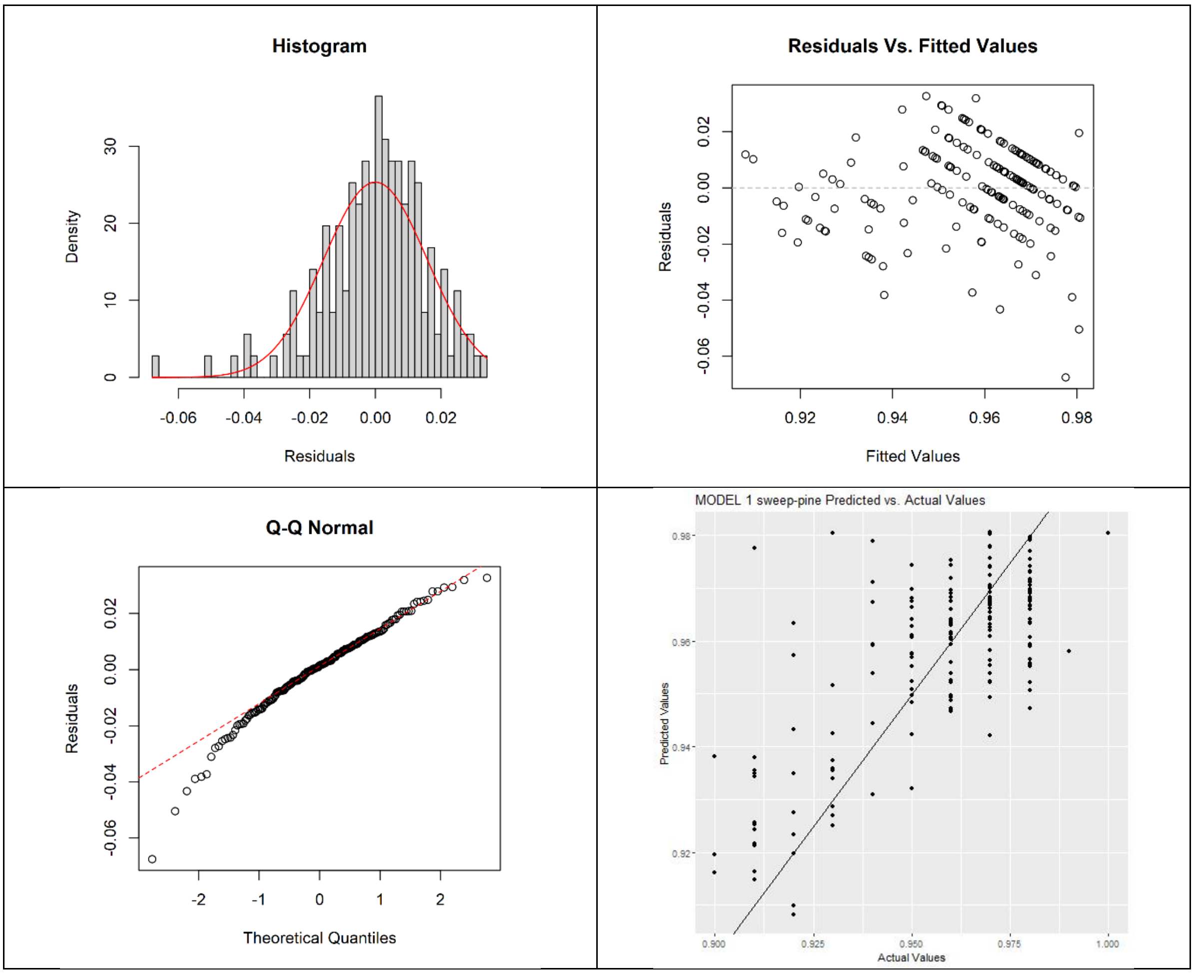


Model 5 (Radius = 5, 7.5) $Lean = -1 + e^{(0.23 - 0.01 \cdot TH - 0.004 \cdot lnBA_{t}. + 0.06 \cdot Asym + 0.02 \cdot Ratio\ n_p)}$

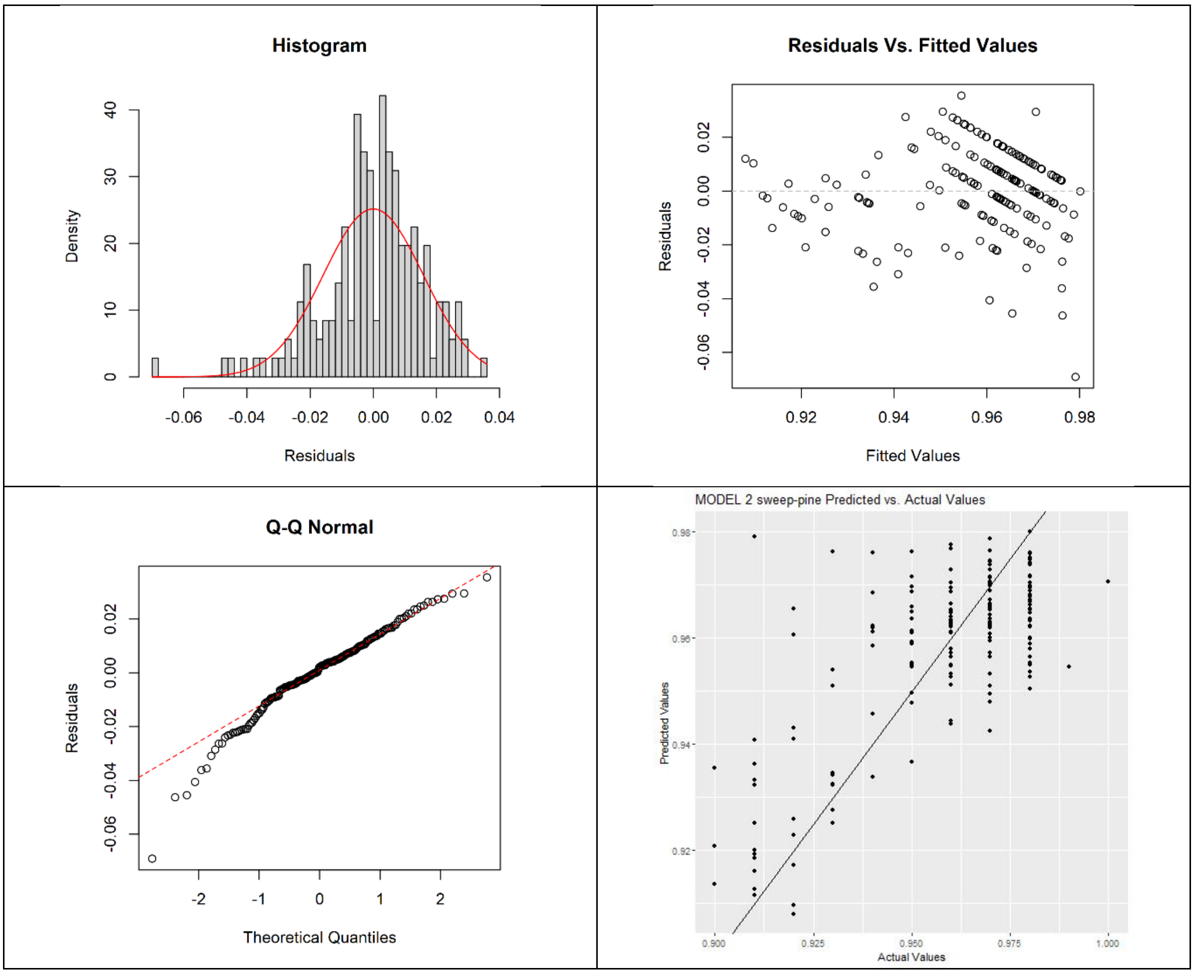


3. PINE: SWEEP

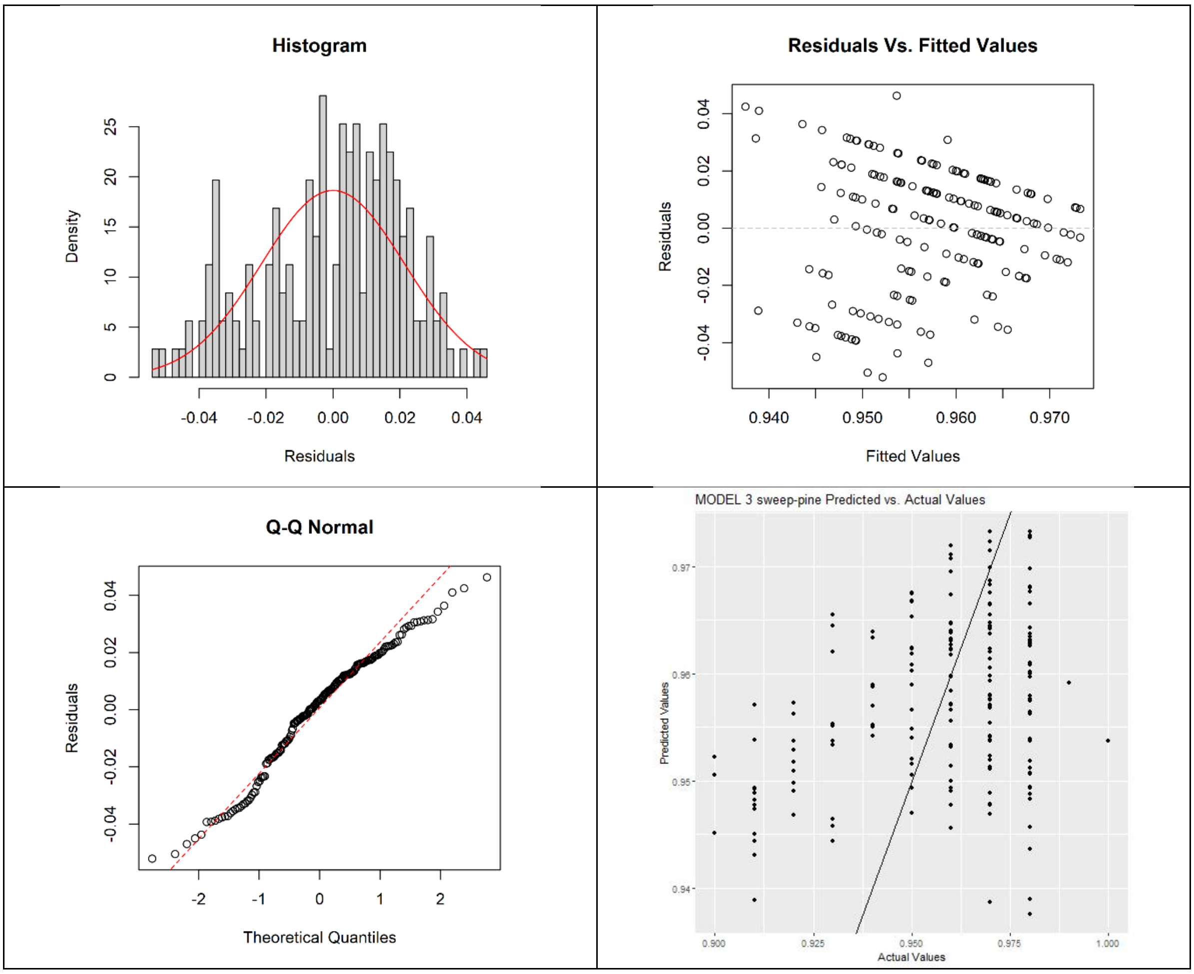
Model 1 (Radius = 5, 7.5, 10) $Sweep = 0.94 + 0.002 \cdot TH - 0.013 \cdot Asym$



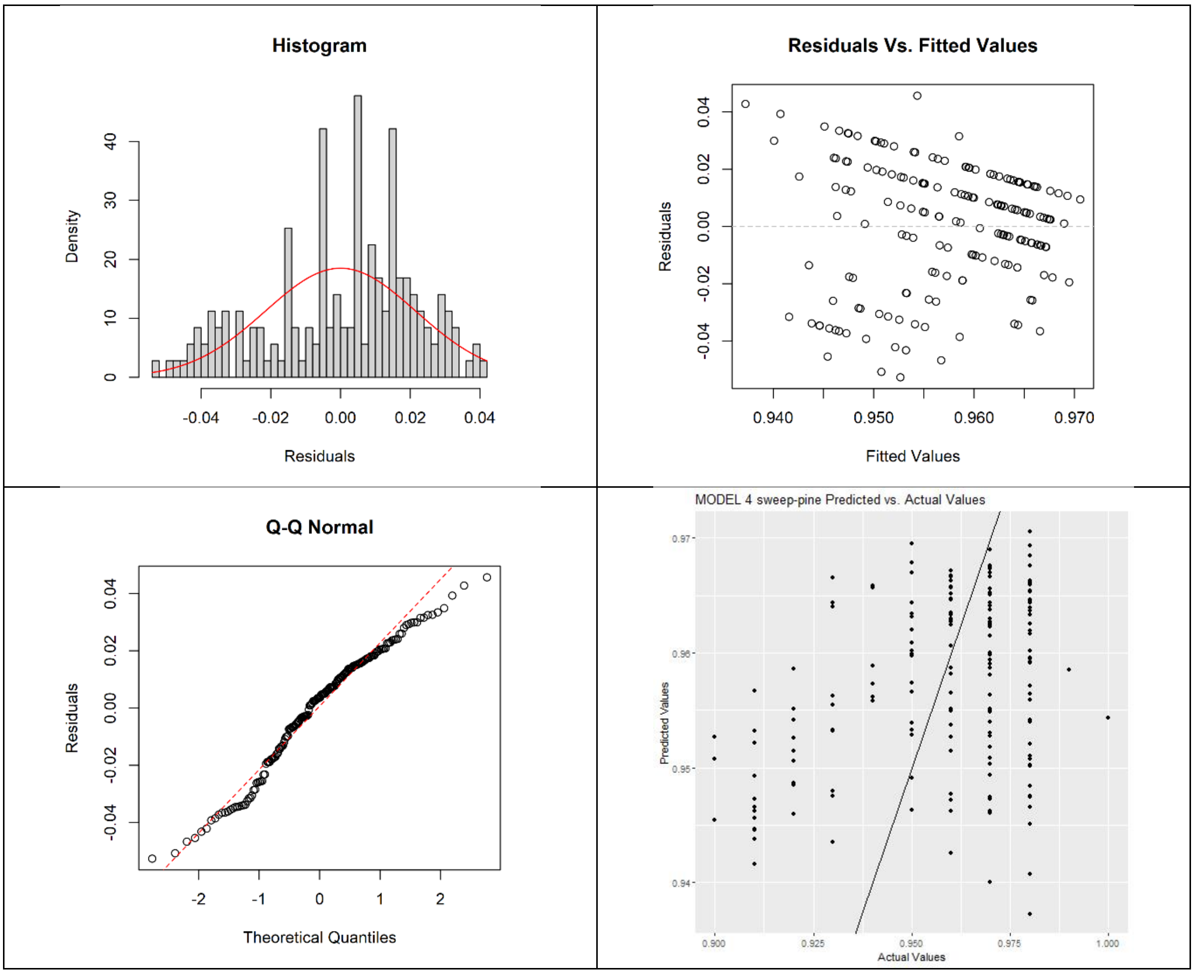
Model 2 (Radius = 5, 7.5, 10) $Sweep = 0.97 + 0.001 \cdot DBH - 0.013 \cdot Asym$



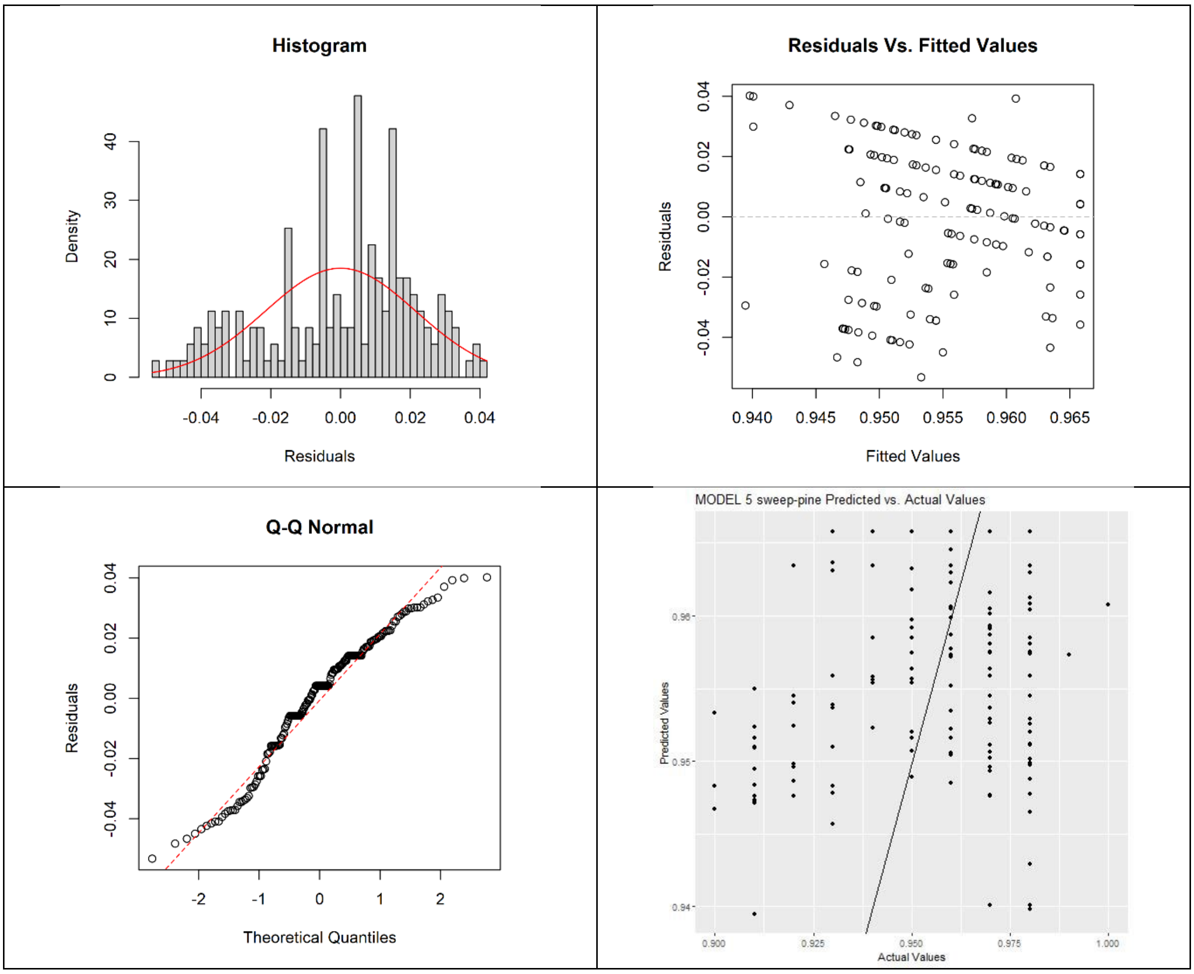
Model 3 (Radius = 10) $Sweep = 0.94 - 0.001 \cdot BAL_p + 0.038 \cdot Ratio\ n_p$



Model 4 (Radius = 10) $Sweep = 0.95 - 0.002 \cdot C.I. + 0.026 \cdot Ratio\ n_p$

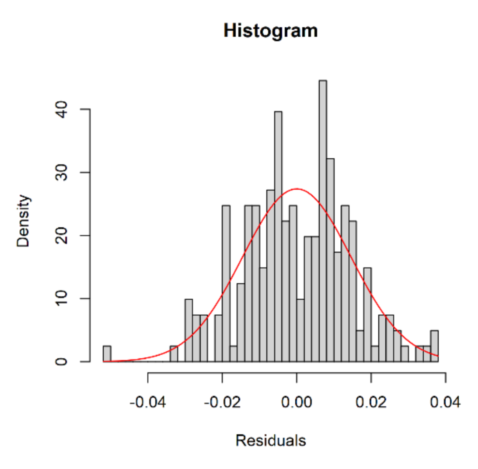


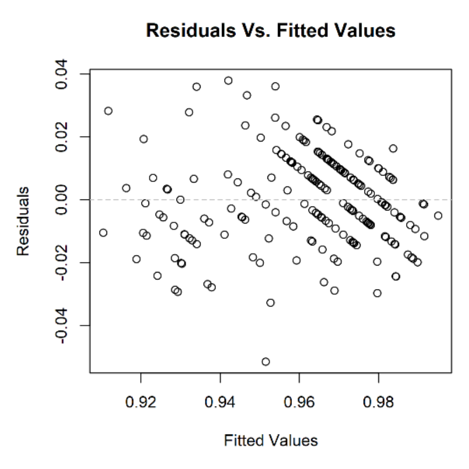
Model 5 (Radius = 10) $Sweep = 0.94 + 0.028 \cdot Ratio\ n_p$

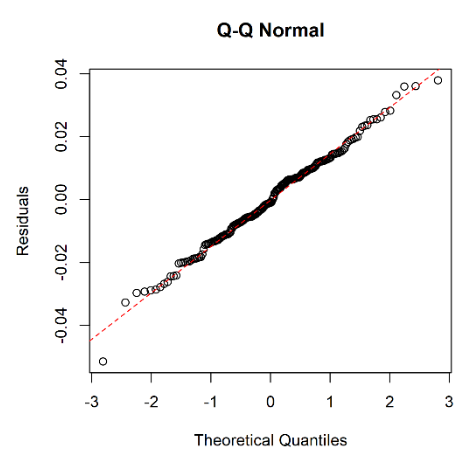


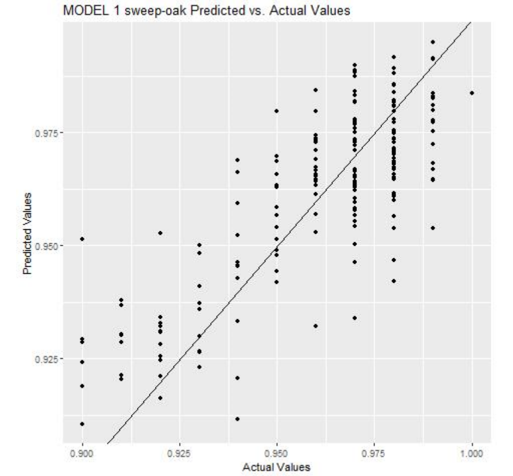
4. OAK: SWEEP

Model 1 (Radius = 5) $Sweep = 0.95 + 0.002 \cdot TH - 0.01 \cdot Asym$

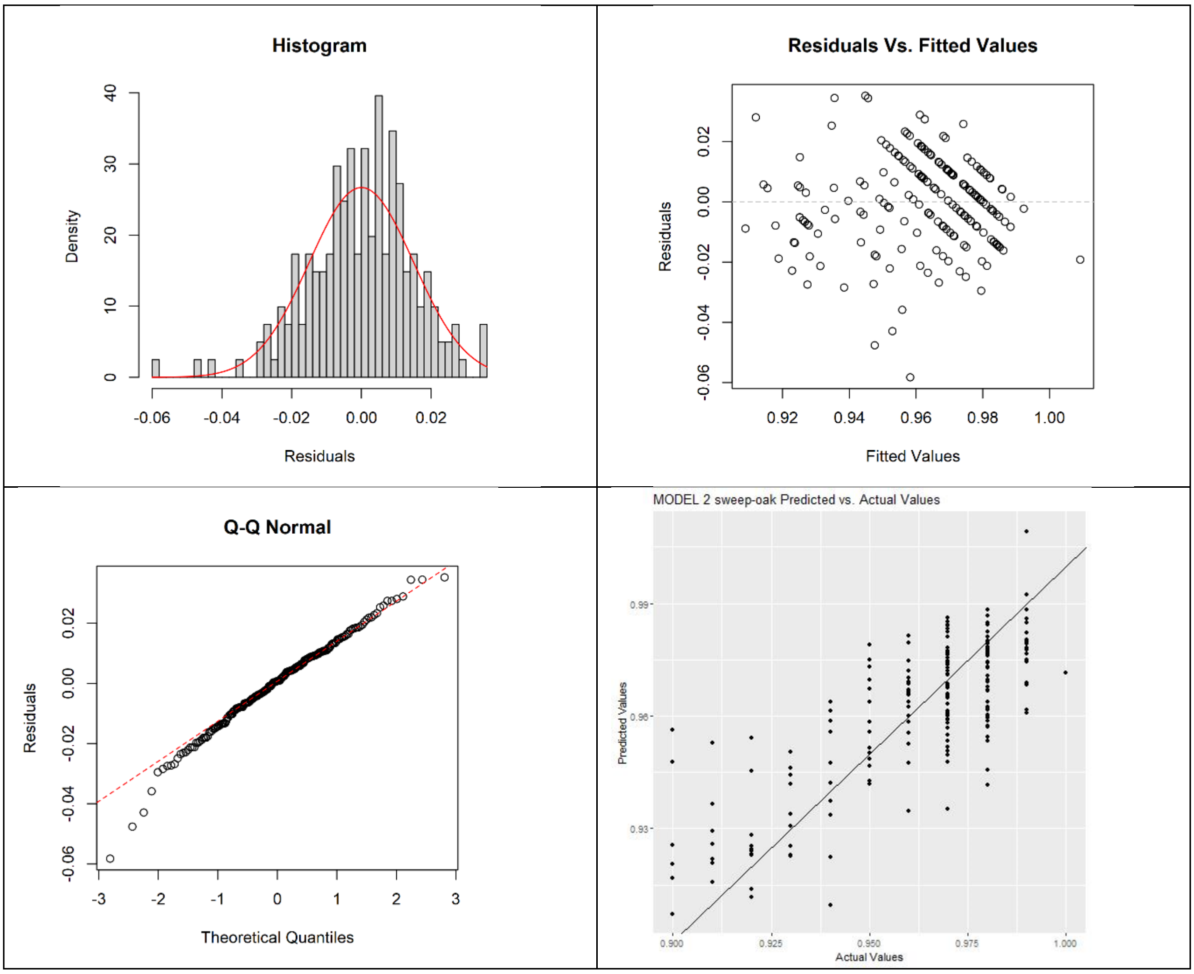




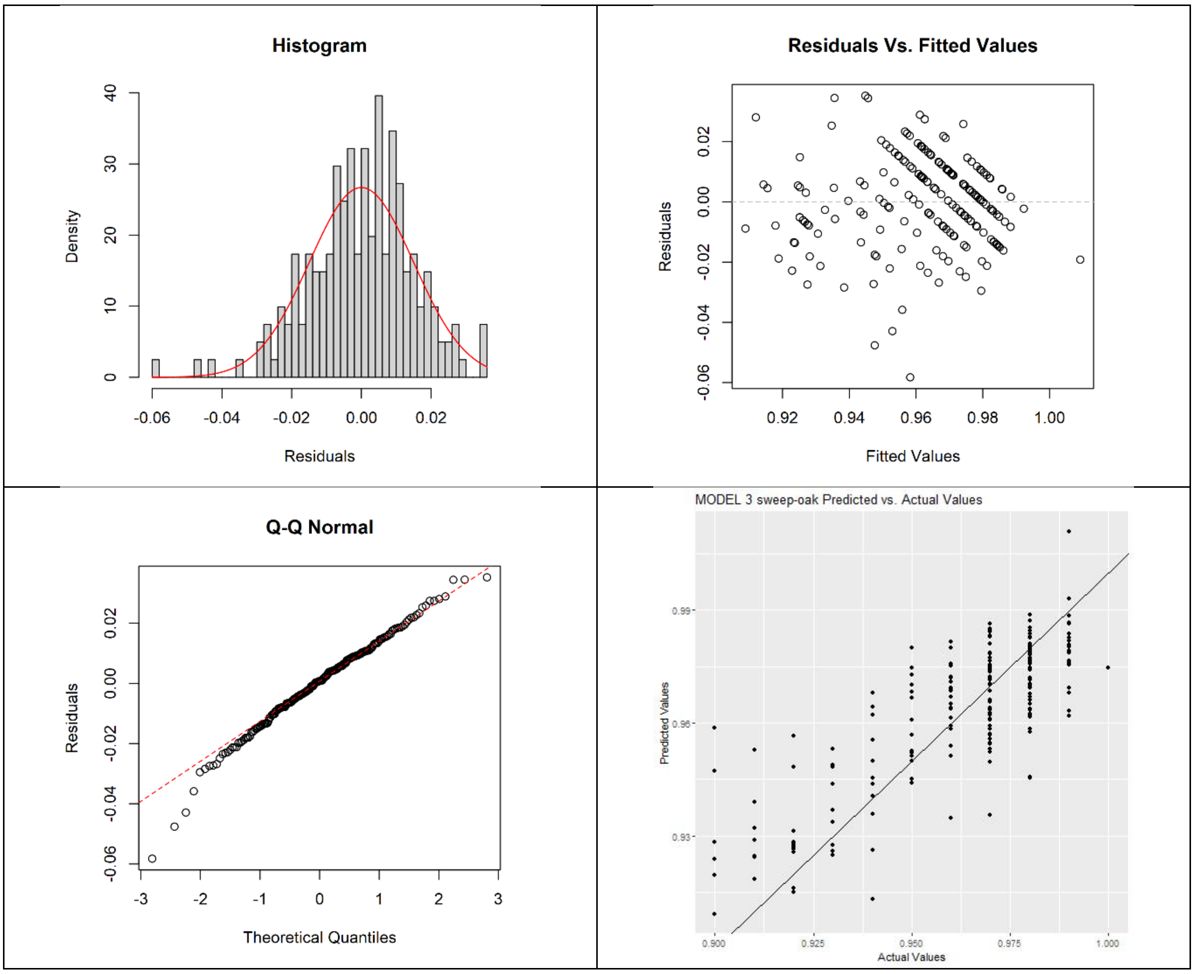




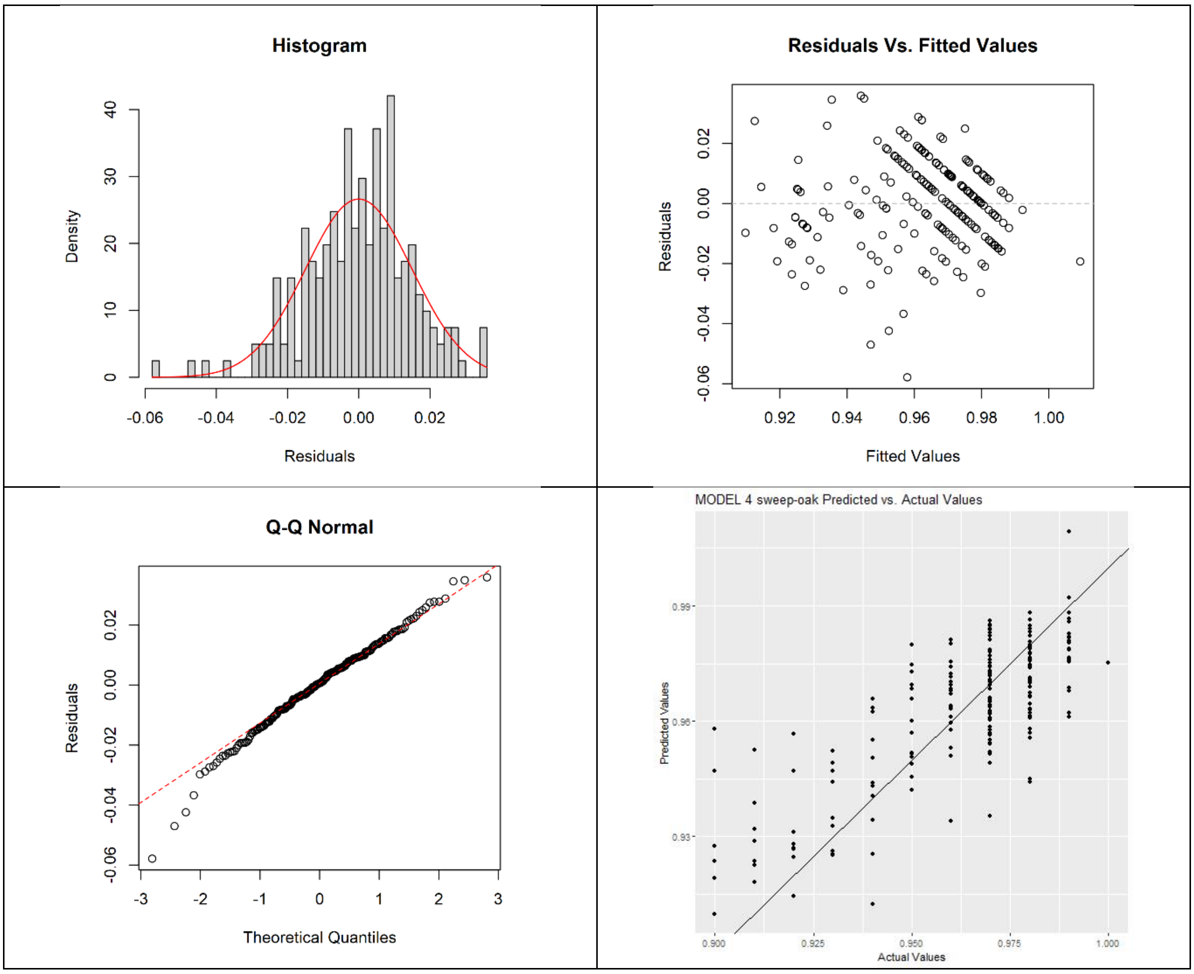
Model 2 (Radius = 5) $Sweep = 0.98 + 0.001 \cdot DBH - 0.01 \cdot Asym - 0.01 \cdot Ratio\ BA_p$



Model 3 (Radius = 5) $Sweep = 0.98 + 0.001 \cdot DBH - 0.01 \cdot Asym - 0.01 \cdot Ratio\ BAL_p$



Model 4 (Radius = 5) $Sweep = 0.98 + 0.001 \cdot DBH - 0.01 \cdot Asym - 0.01 \cdot Ratio\ n_p$



Model 5 (Radius = 5) $Sweep = 0.97 + 0.001 \cdot DBH - 0.01 \cdot Asym$