

Evaluation of management models in a trial of *Castanea sativa* Mill. coppice in Northern Portugal

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Abstract

The sweet chestnut (*Castanea sativa* Mill.) is a valuable species in Portugal, namely in Northeast region, for both fruit and timber. So, a differentiation of management options is needed as an alternative to the traditional practices. The main target of our study was to evaluate three different silvicultural management models that have been tested since 1994 in a trial established in “Serra da Padrela” (41° 30’ 41’’N, 7° 37’ 15’’ W), North of Portugal. This trial is composed by four permanent plots established in a coppice that resulted from the final cut of a sweet chestnut high-forest stand in 1992. These silvicultural management models aim to produce wood of small (P1 = Model 1), medium (P2 = Model 2) and large (P4 = Model 3) dimensions. A control plot was established without any type of silviculture which corresponds to the most of the existing chestnut coppices (P3 = without intervention). At 24 years old, we analyze the growth and yield under different management models as well as the potentiality to produce timber. Height-diameter equations were fitted to improve the existing equations. Dendrometrical measurements were made in all plots in the dormancy of 2016/2017. The evolution of main stand variables over time, under the different silvicultural management models, was analyzed and compared to respective reference models. The results show that Model 1 is in accordance to the expected values in reference models (mean diameter 14-25 cm at 25-30 years). In the plot without intervention the same basal area of plot 1 is obtained ($G\ 30.9\ m^2\ ha^{-1}$) but with an inferior quadratic mean diameter. In this plot there is a natural reduction in the number of shoots almost equivalent to that imposed to P1 by thinnings. Relatively to mortality, a strong reduction of density was observed in plot 3 due to the high competition. In Models 2 and 3 the observed growth follows closely the expected for this growth stage of the coppice. The quality of the individual shoots for wood is clearly superior to that of the plot without intervention although the dominant trees may have similar growth rates. Comparing the mean dendrometric values, higher values were observed in plots with the models application. The results also show that when the wood is to be used for saw-timber, silvicultural intervention is essential.

Keywords: Sweet chestnut, silviculture, height-diameter equations, timber production, sustainable management models.

Resumo

O castanheiro europeu (*Castanea sativa* Mill.) é uma espécie muito valorizada em Portugal, principalmente na região Norte do país, tanto para fruto como para madeira. Assim, é necessário diferenciar as opções de gestão como uma alternativa às práticas tradicionais. O principal objetivo deste estudo foi a avaliação de três diferentes modelos de gestão silvícola que têm vindo a ser testados desde 1994 num ensaio estabelecido na Serra da Padrela (41° 30' 41''N, 7° 37' 15'' W), no Norte de Portugal. Este ensaio consiste em quatro parcelas permanentes instaladas numa talhadia que resultou do corte final de um alto fuste de castanheiro em 1992. Foram considerados 3 novos modelos de gestão silvícola com o objetivo de testar modelos para produção de madeira de pequenas (P1 = Modelo 1), médias (P2 = Modelo 2) e grandes dimensões (P4 = Modelo 3). Foi estabelecida uma parcela de controlo sem qualquer tipo de silvicultura e que corresponde à maioria das áreas de talhadia de castanheiro existentes (P3 = sem intervenção). Aos 24 anos de idade avalia-se o crescimento e produção para os diferentes modelos de gestão aplicados, bem como o seu potencial para produção de madeira, e comparam-se com a não intervenção. Foram ajustadas equações hipsométricas para melhorar as existentes. Foram feitas medições dendrométricas em todas as parcelas no repouso vegetativo de 2016/2017. Analisou-se a evolução das principais variáveis do povoamento para os diferentes modelos de gestão silvícola ao longo do tempo e compararam-se com os respetivos modelos de referência. Os resultados mostraram que o Modelo 1 está dentro dos valores esperados (diâmetro médio 14-25 cm aos 25-30 anos). No modelo sem intervenção consegue-se a mesma área basal $G 30.9 \text{ m}^2 \text{ ha}^{-1}$ mas com um diâmetro da árvore de área basal média inferior. Nesta parcela verifica-se uma redução no número de varas da mesma ordem de grandeza da imposta à P1 pelos desbastes. No que respeita à mortalidade observou-se uma forte redução da densidade na P3 devido à elevada competição. Nos Modelos 2 e 3, o crescimento observado acompanha o esperado para esta fase de crescimento da talhadia. A qualidade das varas individuais para madeira é claramente superior à da parcela sem intervenção (P3) muito embora as árvores dominantes possam apresentar crescimentos semelhantes. Comparando os valores dendrométricos médios observam-se valores superiores nas parcelas intervencionadas. Os resultados também mostram que quando se pretende a valorização do material lenhoso para serração a intervenção silvícola é essencial.

Palavras-Chave: Castanheiro, silvicultura, equações hipsométricas, produção de madeira, modelos de gestão sustentável

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1. Introduction

Sweet Chestnut is considered as one of the most remarkable trees in the world due to its ecological, economic and social importance.

So it is obvious that one of the important issues of chestnut forest management in our days are related to the cultivation and use of Sweet Chestnut and its products for the needs of the modern economy and forest ecosystems. In the countries of Europe the total number of Sweet Chestnut areas reaches 2.53 million hectares (Conedera et al., 2004), where it distributed mostly in countries of Mediterranean basin, mostly in their northern parts (Bragança, 2007).

In Portugal, Sweet Chestnut is located predominantly at north of parallel 39^o from 400 to 1100 meters above sea level and at the sea level in Azores and Madeira (Marques, 1988). Chestnut produces high quality nuts and also high quality timber, with average hardness and good elasticity, being important for the economy of the country (both for local communities and at the country level). The wood of Sweet Chestnut has a good suitability for broadly uses as cooperage, construction and furniture industries. Chestnut fruits (nuts) remain an excellent cultural option in many regions of the country, and the Portuguese varieties are recognized in the international markets for their high quality.

Talking about management of Sweet Chestnut systems we could divide it on three major directions: groves or orchards, coppices and high forest, the last one for quality timber production. In the mountain areas, the coppices and high forest are particularly relevant, especially in deep forest soils. These chestnut areas are natural ecosystems and constitute discontinuities between conifer forests and are important for forest fire prevention, biodiversity and environmental protection. The sustainable management of these areas is crucial and depends on the knowledge of the inputs and outputs of the system (Patrício, Nunes and Pereira, 2012).

Although the chestnut coppice occupy only about 10% of the total area of this species in Portugal, they become of extreme importance for regions, such as the Northeast Region of Portugal (Nordeste Transmontano), where the Sweet chestnut keeps to itself its oldest and most noble traditions (Patrício, 1996). According to the author, proper management of coppices is fully in line with the new concept of multifunctional forest and sustainable revenue, being a system to be promoted in mountain areas where quality timber production is not the priority.

The aim of this study is to evaluate the growth of sustainable management models to produce timber with small, medium and large dimensions. These management models are compared with the situation “without intervention” which is the most frequent situation of the coppices in Northern region. At 24 years old, we analyze the growth and yield under different management models as well as the potentiality to produce timber. Height-diameter equations are fitted to improve the existing equations.

1.1 Framework and general objectives of the trial

In 1994, under the European research project MEDCOP- CT94, a trial was established with 4 permanent study plots in a young chestnut coppice after a final harvest of an old high forest stand. This trial is located in a Communal area of “Serra da Padrela” in a place called "Castanheiro de Cima" in the North of Portugal.

This stand was conducted in high forests for 48 years, having been submitted to a final cut in the year of 1992. The objective of this study was to analyze the long-term growth and to test different models of silviculture applied to Sweet Chestnut in coppice system. The trial has been studied over time by the silviculture team of IPB-ESAB. In this period of time several scientific works and theses were produced (e.g. Aires, 1997; Costa, 1999; Bragado, 2003; Patrício et al., 2005; Geraldes, 2011). This study aims to test 3 models of silvicultural management for production of small, medium and large wood dimensions. This silviculture is based on the management models proposed by Bourgeois (1992). The Silvicultural models for chestnut coppice are presented in table 1 (model for small and medium dimensions) and table 2 (model for large dimensions).

Table 1: Silvicultural management models for wood of small and medium wood dimensions according to Bourgeois (1992)

	Intervention	Dom. Height shoot/ stump (m)	Age (years)	No shoots/ha before thinning	No shoots/ha after thinning	Rotation length (years)
Model 1 Small dimensions	1 st Thinning	6-9	5-9	9000-15000	3000-3500	25-30
	2 nd Thinning	10-12	10-14	3000	1500	
Model 2 Medium dimensions	1 st Thinning	6-9	7-9	9000-13000	2000-2500	30-35
	2 nd Thinning	11-12	11-13	2000-2500	600-800	

Adapted from Bourgeois (1992)

Table 2: Silvicultural management model for wood of large dimensions (Model 3) according to Bourgeois (1992)

Height	Age (years)	Interventions	No stools/ ha
10 - 12 m	10 – 13	<ul style="list-style-type: none"> • Pre-selection of frame-trees • Pruning to 4 or 6 m • 1st strong thinning 	150 - 250 150 - 250
13 - 15 m	13 – 16	<ul style="list-style-type: none"> • 2nd thinning of frame-trees • Possible additional pruning 	
15 - 17 m	18 - 21	• 3 rd Thinning	
17 - 19 m	23 – 26	• 4 rd Thinning	
19 - 20 m	28 - 31	• 5 th Thinning	
22 - 26 m	40 – 50	• Final clear cut	150

Adapted from Bourgeois (1992)

In table 3 we present the previous silvicultural interventions (thinning of shoots) to adapt the density of shoots in the plots to the Bourgeois models. We consider one plot (the No 3) as a control, without intervention. On plot 1 we applied the Model 1; on plot 2 the Model 2 and on plot 4 the Model 3.

Table 3: Comparison of the densities of the plots with theoretical density model over time

Year	Density	Plots			
		1	2	3*	4
1998	Before thinning	8868	8491	8613	8745
1998	After thinning	3473	3778	6305	2523
2003	Before thinning	3422	3685	5788	2510 (selection of 250 shoots/ha)
2003	After thinning	1501**	761**	5788	534
2008	Thinning only in plot 4	1450	761	3455	320
2016	Current Density	1399	761	1866	320

*Plot 3 (control): Natural mortality only; ** last thinning

2. Characteristics of the species *Castanea sativa* Mill.

2.1 Systematic and biology description

According to the scientific classification, Sweet Chestnut has such description:

Kingdom	<i>Plantae</i> (Plants)
Subkingdom	<i>Tracheobionta</i> (Vascular plants)
Superdivision	<i>Spermatophyta</i> (Seed plants)
Division	<i>Magnoliophyta</i> (Flowering plants)
Class	<i>Magnoliopsida</i> (Dicotyledons)
Subclass	<i>Hamamelidae</i>
Order	<i>Fagales</i>
Family	<i>Fagaceae</i> (Beech family)
Genus	<i>Castanea</i> (Chestnut)
Species	<i>Castanea Sativa</i> Mill. (European/Sweet Chestnut)

This tree has a height of 20–35m with a stem, which could reach near 2m in diameter. Sweet chestnut could have a several type of leaves (Cortizo et al., 1996), but there is predominance of the elliptic-lanceolate aspect, elongated-lanceolate and oval-lanceolate. The leaf lamina has a length of 10-25 cm and a width 5-8 cm. The apex is pointed or acuminate, with a fine tip, the base is symmetrical cordiform and non-bite in the adult leaves. The marginal cutting is strongly sawed, with sharp teeth in the prolongation of the minor veins. The leaf coloration changes within the chestnut cultivars. However, there is a clear distinction among the upper surface coloration (green-dark) and the lower surface (clear green) coloration. The petiole color is yellowed or red and the dimensions range from 1.2 cm to 2.5 cm of length (Pinto et al., 2011).

Chestnut is a monoecious plant with separately hollow flowers, which are collected in inflorescences of two types. Flowers with 5-8-membered perianth, collected in groups (3 or more flowers) located on a common axis, in spicate inflorescences 10-35 cm long and up to 1 cm in diameter. In the very base of the inflorescence are female flowers, above the male flower. Many inflorescences consist of only male flowers. In male flowers except for perianth - 8-12 stamens, male flowers are with short, medium, long 5-7mm stamens. Pollination occurs by pollen of flowers with long stamens. Pestilent flowers of greenish color are arranged by glomeruli of 5-7 ovaries in one envelope. Nuts with a leathery pericarp, are enclosed 3 (less often 1-7) in a spherical prickly pluss, which ripens during

maturation to 2-4 segments. The drop of fruits begins at the end of September and lasts until mid-November. The weight of one nut varies from 3 to 12 gram. The bark often has a net-shaped pattern with deep furrows or fissures running spirally in both directions up the trunk. The oblong-lanceolate, boldly toothed leaves are 16–28cm (6–11 in) long and 5–9 cm (2–4 in) broad (Studbooks, 2016).

The Chestnut tree has a root system characterized by robust and deep roots, with the particularity, if the soil conditions are adverse, to shorten the main root and develop the lateral roots, forming a large network that allows the exploration of land (Gomes, 1982)

Leaves blossom in April-May and flowering in June-July. The pollinated is made by bees and other insects, but pollination by wind is also possible. Male and female flowers on one tree are not revealed simultaneously, which ensures cross-pollination. Fruits ripen and drop out of the opened bur in October-November. At the same time, leaves fall. Nuts have good germination. The species would be propagated by seeds and vegetative reproduction by sprouts. Seedlings are rather shade-tolerant (Batat, 2016).

The European chestnut can begin to bear fruit at 3-5 years of age (if the plants are grafted), but mass fruiting begins later, usually 10 years or even later. Such a variety of terms of fruiting is due to the fact that the formation of fruits depends more on the conditions of growth and origin than on age. If the growth of chestnut on the open can bear fruit from the age of 3-5 years, the forest cultures forming a closed canopy begin normal fruiting in 15-20 years, and trees of seed origin, grown in natural plantations of different ages, bear fruit from 25 to 40 years (Studbooks, 2016).

2.2 Distribution

The Sweet Chestnut (*Castanea sativa* Mill.) is the only native species of the genus in Europe. The broad diffusion and active management by man resulted in the establishment of the species at the limits of its potential ecological range, which makes it difficult to trace its original natural area but one think that the species come from northeastern Turkey. The present distribution ranges from North-Western Africa (e.g. Morocco) to North-Western Europe (southern England, Belgium) and from south-western Asia (e.g. Turkey) to Eastern Europe (e.g. Romania), the Caucasus (Georgia, Armenia) and the Caspian Sea. In Europe the main chestnut forests are concentrated in a few countries such as Italy, France and the Iberian Peninsula (Conedera et al., 2016)

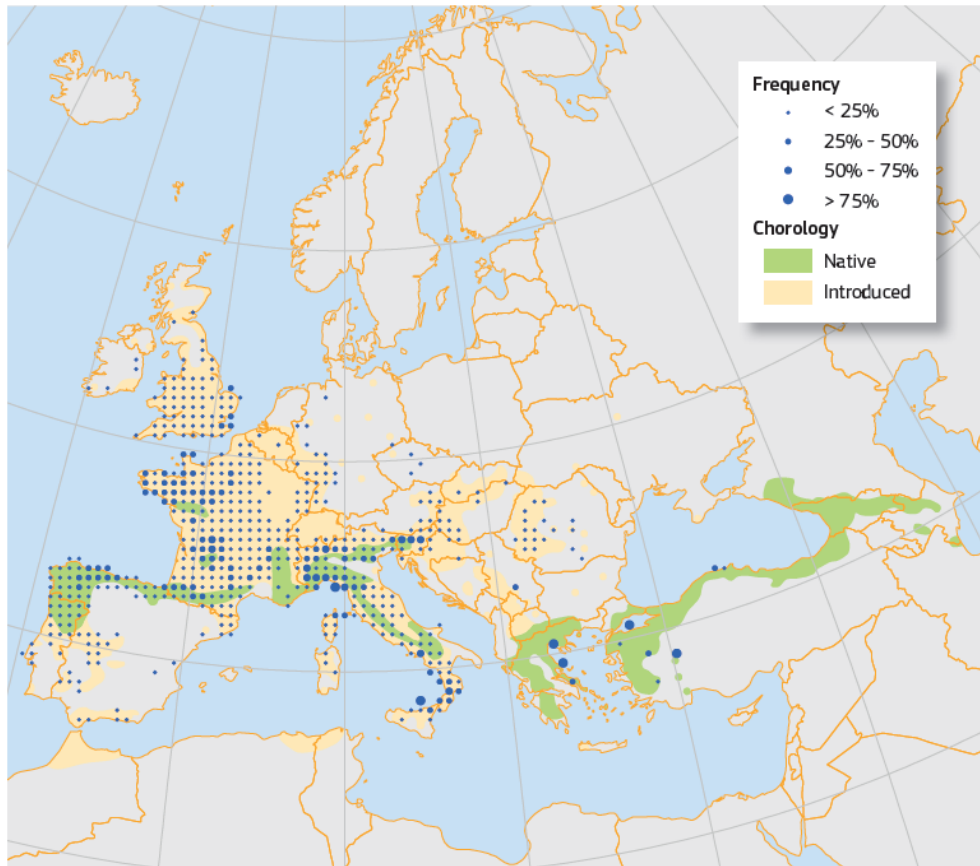


Figure 1: Plot distribution and simplified chorology map for *Castanea sativa*. Frequency of *Castanea sativa* occurrences within the field observations as reported by the National Forest Inventories. The chorology of the native and introduced spatial range for *C. sativa* is derived after several sources (Conedera et al., 2016).

In Portugal, the presence of Sweet Chestnut occurs mainly in the north of the 39th parallel, initially as a companion of the oaks in the respective sub-forest and from the XI-XIII centuries, as a part of high forest stands, mainly high forest groves for the production of fruit, which explains its presence mainly around the mountain settlements, for which were, in those times, a fundamental basis of food (Alves, 1988).

Nowadays its most significant percentage is in the region north of the “Tejo” river (Figure 2).

According to inventory data for the year 2010, the total area of the country is 41,410 ha (ICNF, 2013). The area of Sweet Chestnut has increased from the last forest inventory. This increase in the area of Chestnut wood in recent years has been verified at the expense of community incentives to the afforestation of abandoned agricultural lands.

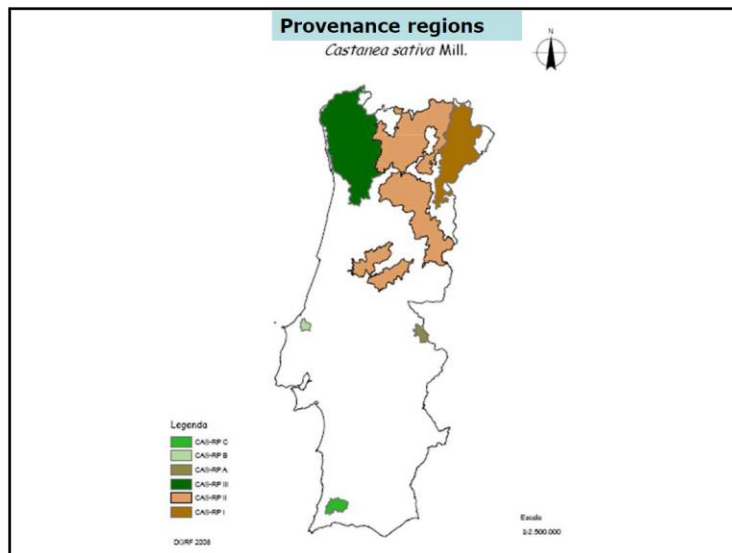


Figure 2: The spread and provenance regions of *Castanea Sativa* Mill. in Portugal.

2.3 Ecology

The chestnut is a mesothermic species that adapts well to places with annual average temperatures between 8 and 15°C, requiring six months of average temperatures over 10°C. It does not withstand temperatures below -15°C and the average temperature of the coldest month cannot be less than -1°C (Alves, 1988). Later young shoots become sensitive to early frost. As all mesophitic species, Sweet Chestnut requires 800 to 1600 mm annually (Alves, 1988). In Portugal, most chestnut trees are located in areas with rainfall above these values.

Alves (1998) states that the species requires as minimum of precipitation, fallen during the April-July period, at least 25% of the annual total. According to the author, low values of rainfall in that period of growth could be a limiting factor for that tree in Portugal. When this happen in first two-three years of life it could be very dangerous because the young plants are very fragile. Too much humidity could also be very dangerous because such problem could lead to roots system diseases (Alves, 1988).

This species has optimal conditions for growth and development at 650-900 m and prefers fresh slopes from north influence (Patrício, 2016) but in Mediterranean climates it can tolerate the 1200 m (“Serra de Bornes”) and the 1600 m (Sierra Nevada).

In terms of aspect, Garcia (2003) indicates that, in the installation of new chestnut trees, the slopes with South exposure should be avoided, especially if the slopes are high (> 8-10%). Fresh slopes with north influence are preferable for the species.

Talking about soils we should know, that sweet chestnut can adapt to many types of soils, but it prefers siliceous acidic soils with pH 5.5-6, well-structured, derived from schist and granite, fresh, deep and well drained soils, with textures from: sandy-loam, silty-loam, loam, sandy-clay-loam (Patricio, 2016).

3. Region characteristics

3.1 Study area

The studied plots are located in a place called "Castanheiro de cima", in "Serra da Padrela" (Figure 3 and 4) Municipality of "Vila Pouca de Aguiar" in "Vila Real" district.



Figure 3: The approximate location of the studied plots on the map of the regions of Portugal (Freeworldsmap, 2017)

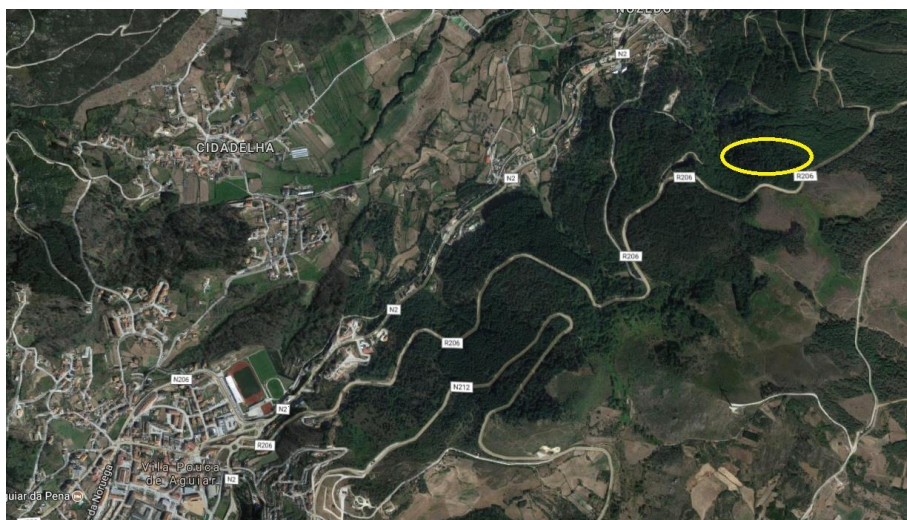


Figure 4: Location of the studied plots (yellow ellipse). The lower left corner of the map is "Vila Pouca de Aguiar"

In the Figure No 5 we present the layout of the coppice trial where the silvicultural models were randomly allocated to the plots (P1- Model 1; P2 – Model 2; P3 – control: P4 – Model 3).

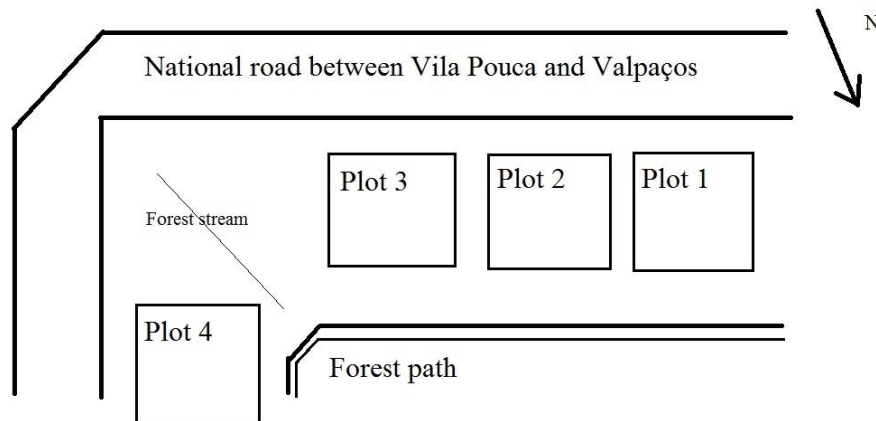


Figure 5: Layout of the studied plots according to Bragado (2003)

Coordinate of this place is 41°30'37.9"N 7°37'03.9"W. Altitude 830 m above the sea level. Exposition: Northeast. Slope: from 26 to 30°, depends from plot. Total number of studied areas from all four plots – 3077 m².

3.2 Climate characteristics

This stand is located in a mountain area characterized by cold and long winters and warm and short summers. The period of frost is felt in this zone between October and May (Agroconsultores and Coba, 1991). The average annual temperature is 12.9°C. The maximum temperature reached higher values in the months of June (315.8°C), July (38.8°C), August (37.5°C) and September (34.2°C). The minimum temperature was in November (-3.3°C), December (-5.1°C), January (-6.0°C) and March (-3°C) (Aires, 1997). The average annual precipitation is around 1073 mm. The dry season corresponds to the months of June, July, August and September. In these months, average month precipitation is lower than 16 mm and the mean monthly temperature is 20°C (Bragado, 2003).

3.3 Soil characteristics

The soils in the study area are dystric-cambisols (represented by A in the Figure 6) from granite (Agroconsultores and Coba, 1991). Cambisols are one of the major soil types of mainland Portugal (Figure 6).

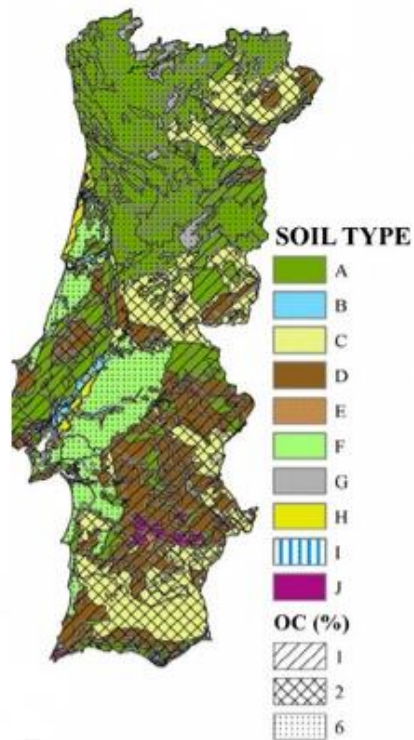


Figure 6: Brief characterization of mainland Portugal soil types.

The soil types are: A —cambisol, B —fluvisol, C —leptosol, D —luvisol, E —planosol, F - podzol, G - ranker, H - regosol, I - solonchak, J - vertisol (Pacheco and Fernandes, 2016).

4. Methodology

4.1 Field survey

In the winter of 2016, we integrated a team from IPB-ESA (Figure 7) that carried out several field trips for collecting field data in the four research plots from the Sweet Chestnut coppice trial. All four plots were in close proximity, which greatly facilitated us in the collection of primary data (height, diameter at breast height, analysis of the state) and the process of updating the diameter at breast height marks (1.30 m from the ground) in the stems as well as the numbering of stools and shoots.



Figure 7: Data collection and numbers renewing operations

The plots themselves were clusters of trees, with the numbering oriented to the north and the area of each of them did not exceed 1000 m². The management models were randomly allocated to the plots. So, in plot 1, we applied the Model 1 for small dimensions; in plot 2, the Model 2 for medium dimensions; plot 3 was the control, without silvicultural intervention and in plot 4, the Model 3 for large dimensions was applied. The number of stools/ha in 2016 ranges from 320-654 and the number of shoots/ha from 320-1866.

One of the main problems was that the stand itself that is located on a slope, whose steepness varied from 26 to 30°, which increased some of the risk. Also it should be noted that the renewal of tree numbers should be carried out at least once in 2-3 years, and a break of eight years (as in our case) makes many numbers almost unreadable.

4.2 Identification and management of plots

The first works of establishing the research plots in chestnut coppice starts in 1994. Plots 1, 2 and 4 were thinned in 1998 and 2003. Only the plot 4 (large dimensions shoots) was thinned again in 2008. After that, in 2016, the plots were measured and repainted. The dendrometrical variables: diameter at breast height, height, live crown height were measured. The natural mortality was observed mainly in plot 3 (without silvicultural intervention). The thinnings that were applied previously aimed to adapt the density of the plots to the ones proposed by Bourgeois (1992). This procedure has as reference the height growth of the dominant shoots in the stools (frame-trees) as prescribed in the respective models.

According to these parameters, when shoots quantity and dominant height growth reach some level, it is recommended to start thinning, helping to maintain the quality of the stand and decrease the competitive pressure.

In case of trees of small and medium size (Table 1) main parameter for starting the thinning in our plots is the level of dominant height growth. Of course, this theoretical model should be adapted for certain conditions, but the main idea will be the same.

When we talk about trees of large dimensions, situation will be little different (Table 2).

In case of large dimensions we use also the growth in dominant height as a reference for the thinning and we select the best 250 shoots/ha for frame trees that will be cut at the end of the rotation. The other shoots that remain in the stand have an important role as the “accompanying shoots” or matrix trees to improve the quality of frame trees and

regulate the competition around them. It means that in case of large dimensions our main purpose is to have shoots with size and quality for valuable saw wood. This is a management type similar to the high forest system because we select the best frame shoot in the stool and we maintain only a shoot per stool as in high forest system. These selected shoots are expected to produce timber of high quality for sawing.

4.3 Diameter measurement

The diameter at breast height was measured in all shoots of the plots. For that we used a diameter tape similar to the figure 8. This tape has two type of scale, one of them is metric, and another one is metric reduced by the value of Pi (Figure 8).



Figure 8: Tape with two scales, for measuring diameter (Tape-measure, 2017)

4.4 Height measurement

Tree height is much harder to measure than tree diameter. The standard practice is to measure tree height with hypsometers (Figure 9). In our work we used hypsometer Vertex IV, which is good for measuring distances, angles, slopes and heights. For measuring, this instrument must be equipped with an external unit the *transponder* (Figure 9)



Figure 9: Hypsometer Vertex IV with transponder (Haglofcg, 2017)

The transponder is placed on a tree, at height of 1.3 m from ground (breast height) and after that we could start our height measurements. When the measurer aims at the transponder the device registers the angle and the distance to the transponder (corresponding to the distance of the observer to the tree), from which the horizontal distance and the height from the transponder to the isohypse are calculated. After that, the device is aimed to the tree top, and calculates the height from the isohypse to the tree top using previously calculated angle and distance. Our ultrasonic hypsometer works on trigonometric principle measure, from eye level, the vertical angles between the baseline and the top and base of the tree, accordingly. Measured height is calculated from measurements of the angle subtended by the top and base of the tree with the horizontal (Figure 10).

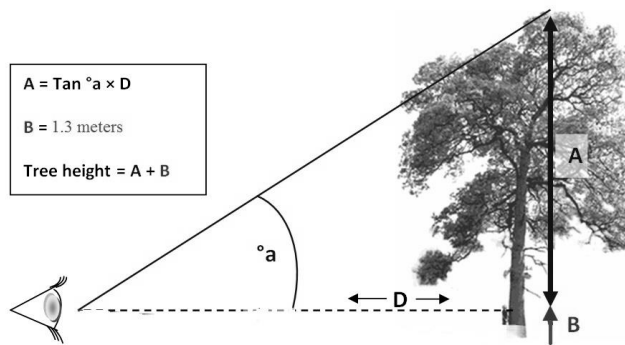


Figure 10: The trigonometric principle of hypsometric devices (Msaouak, 2016)

4.5 Dendrometric characterization of study plots

After recording all field data we proceeded to the calculation of the dendrometric parameters for each plot. In order to calculate the different dendrometric variables in each study plot, we based on the definitions and formulas proposed by Marques (1994).

The calculated parameters were the following: basal area of the stand (G), basal area per shoot (g_v), mean diameter (d_{mean}), mean quadratic diameter (d_g), dominant diameter (d_{dom}), mean height (h_g), dominant height (h_{dom}), mean of stability coefficient (h/d), number of stools per hectare ($N_{st/ha}$), number of shoots per hectare ($N_{sh/ha}$), percent of survived stools ($\%Surv_{st}$), percent of survived shoots ($\%Surv_{sh}$), living crown ratio per plot (CR).

For better understanding the essence of these parameters we present the formulas used in their calculation and a brief description:

Basal area of the stand (G) - is the cross-sectional area of all the trees in a plot expressed in a per hectare base This measurement makes at the level of breast height (1.3m

above ground) and include both the wood and bark of the stem. Because we measure this parameter for each plot, we need to scaled it for 1 hectare of land for comparison. For its calculation we use this formula:

$$G = \sum_{j=1}^n g_i = \sum_{j=1}^n \frac{\pi}{4} d_i^2$$

The basal area of the shoot (g_v) – is the cross-sectional area of the stem at breast height:

$$g_v = \frac{\pi}{4} d^2$$

The mean basal area per shoot (\bar{g}_v) – it is calculated by dividing the basal area of plot by the number of its shoots:

$$\bar{g}_v = \sum g_v / n_{shoots}$$

Mean diameter (d_{mean}) - This parameter is the arithmetic mean of the diameter at breast height of the shoots in the plot. For this we need to summarize all diameters in one plot, after all we divide them by the number of shoots.

$$d_{mean} = \frac{1}{n} \sum_{j=1}^n d_j$$

Mean quadratic diameter (d_g) - it is obtained from quadratic average value of d observed in the stand, it is defined as the diameter of the tree of the mean basal area.

$$d_g = \sqrt{\frac{\sum_{j=1}^n d_j^2}{n}}$$

Dominant diameter (d_{dom}) – Usually corresponds to the mean of the diameters of the thickest 100 trees per hectare. For the plot we consider the respective proportion of trees according to the area of the plot.

Mean height (h_g) – Corresponds to the height of the tree with mean basal area (cross-sectional area) in the plot.

Dominant height (h_{dom}) – Corresponds to the mean of the heights of the thickest 100 trees per hectare. For the plot we consider the respective proportion of trees according to the area of the plot. This parameter is the mean of the heights of the dominant trees used in the calculation of d_{dom} .

Mean stability coefficient (h/d) – This parameter is calculated for understanding the resistance of tree stand to negative impacts, like winds or snows or to analyze the competition.

It's calculated by dividing the height of tree by its diameter in meters. After that we get stability coefficient of one tree. The next step will be in summarizing all h/d coefficients and dividing them by the number of all trees, what give us mean value per plot.

$$h/d = \frac{h_{tree}}{Dbh * 0.01}$$

Where h_{tree} is tree height and Dbh is diameter at breast height.

$$h/d_{mean} = \frac{\sum_{i=1}^n \frac{h}{d}}{n}$$

Number of stools per hectare (N_{st}/ha) – This parameter is a density index that help us to understand the stocking of the stand over time.

It shows the reduction of trees (stools) from one period to another and helps us to compare decreasing rate of density in a stand.

For the conversion to the hectare we use a simple “Rule of Three” or similarly an expansion factor (number of stools multiplied by 10000/plot area in m^2).

Number of shoots per hectare (N_{sh}/ha) – This parameter is very close to previous one and it is calculated in the same way but now we consider the number shoots instead.

It shows the reduction of shoots from one period to another and helps us to compare decreasing rate of shoot density in a stand.

For the conversion to the hectare we use also a simple “Rule of Three” or similarly an expansion factor (number of shoots multiplied by 10000/plot area in m^2).

Percent of surviving stools (%Surv_{st}) - This parameter calculates the number of living stools per hectare. It shows us how changed tree stand from first monitoring period till last one.

Percent of survived shoots (%Surv_{sh}) – This parameter calculates the number of living shoots per hectare in the same manner like previous parameter.

Mean crown ratio (CR) – Corresponds to the mean percentage of live crown.

Analyzing this parameter we can understand in what condition tree growth. If the percentage of live crown, relative to the total height of the tree, is large enough, then we can confidently say that the tree develops in comfortable conditions with moderate or low competition. If the percentage of living crown is less than half of the height of the stem, then this tree is in a state of constant confrontation with its neighbors.

In formula it looks in the next way:

$$\%CR = \frac{h - hcb}{h} \times 100$$

Where

h – total height

hcb –height of crown base.

4.6 Hypsometric curves

In a previous study Bragado (2003) tested 13 mathematical functions to model the relationship between height and diameter at breast height (h-d relationship) of the shoots in the 4 study plots of the coppice experiment. The final selected models are presented in table 4.

Table 4: Final models to estimate h-d relationships (Bragado, 2003)

Plot	Function	R_{adj}^2	RMSE
P 1	$h = 10.784 - 20.004 \frac{1}{d} + 0.084d$	0.624	1.082
P 2	$h = 12.227 - 22.148 \frac{1}{d} + 0.080d$	0.633	1.211
P 3	$h = \left(\frac{1}{0.174 + \frac{0.664}{d}} \right)^{1.591} + 1.3$	0.780	1.188
P 4	$h = 11.708 - 20.830 \frac{1}{d} + 0.127d$	0.435	1.259

These models were validated with the data from 2016 to verify its applicability at present time. For the validation, two simple statistics were used, the mean of prediction residuals (Mpr) and the mean of absolute prediction residuals (MApr):

$$Mpr = \frac{\sum_{i=1}^n (h_i - h_{est})}{n}$$

$$MApr = \frac{\sum_{i=1}^n |h_i - h_{est}|}{n}$$

In the expressions above, h_i are the observed real values of total height of the shoots, h_{est} are the heights estimated by the models and n is the size of the sample (number of observations).

As data from successive measurements in the coppice trial became available (1999, 2003, 2008 and 2016), the range of h and d values for modeling purposes is now broader. For modeling h-d relationship in each plot we joined the available data from all the measurements and we fitted several candidate equations. With the exception of the linear model, we tested all the equations in Bragado (2003) and additionally the Bates and Watts (1980) equation, known in biochemistry as Michaelis-Menten saturation curve. The fitting was done using R software (R Core Team, 2017) using linear or nonlinear least squares (functions *lm* or *nls* from base package *stats*).

To analyze the performance of candidate equations in each plot, its biological behaviour was evaluated, looking the consistency of the signs of the coefficients, value of

the function at the origin, minimum and maximum, inflexion point and asymptote. Statistics evaluating the quality of fit and predictive ability were also calculated.

Quality of fit was evaluated with the adjusted coefficient of determination (R^2_{adj}), the root mean square error (RMSE), the bias (\bar{e}_i), variance of residuals (V_{res}) and the Schwartz-Bayesian Criterion (BIC). Predictive capacity was evaluated by the leave-one-out cross-validation method, using the residuals obtained with one observation deleted, also known as Press residuals. The mean (Mpress), the absolute mean (MApress), the total sum of squares (PRESS) were calculated as follows:

$$R^2_{adj} = 1 - \frac{(n-1) \sum_{i=1}^n (h_i - h_{est})^2}{(n-p) \sum_{i=1}^n (h_i - \bar{h})^2}$$

$$\bar{e} = \frac{1}{n} \sum_{i=1}^n (h_i - h_{est})$$

$$V_{res} = \frac{1}{n-1} \sum_{i=1}^n (h_i - h_{est})^2$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (h_i - h_{est})^2}{n-p}}$$

$$BIC = n \ln(n) \left(\sum_{i=1}^n (h_i - h_{est})^2 / (n-p) \right) + p \ln(n)$$

$$M_{press} = \frac{1}{n} \sum_{i=1}^n (h_i - h_{est}^*)$$

$$MA_{press} = \frac{1}{n} \sum_{i=1}^n |h_i - h_{est}^*|$$

$$PRESS = \sum_{i=1}^n (h_i - h_{est}^*)^2$$

In the above expression, h_i , h_{est} , and n are defined as before, p is the number of coefficients in the equations, and h_{est}^* is a predicted height calculated with the model fitted with the observation i deleted from the original dataset.

In the table 5 we present the summary statistics for h and d in data set with all available data.

Table 5: Summary statistics for h and d used in model fitting

Statistics	Plot1		Plot2		Plot3		Plot4	
	h (m)	d (cm)	h (m)	d (cm)	h (m)	d (cm)	h (m)	d (cm)
Mean	9.2	10.0	9.3	9.5	8.8	7.4	9.7	9.4
SD	3.0	4.7	3.5	5.2	3.6	4.3	2.9	4.8
Maximum	16.4	26.2	19.7	28.5	21.2	24.7	18.1	31.9
Minimum	3.1	2.3	2.9	2.2	2.4	1.5	4.1	2.6
n	614		454		1376		290	

5. Results and Discussion

5.1 Dendrometric characteristics of the plots

The dendrometric parameters were calculated according to the section 4.5. In this study we calculate the dendrometric variables for 2016 data. The same parameters were compiled also for the years 2003, 2008 from previous studies and are summarized in the table 6.

Analyzing the table 6 the plot 1 (Model 1) presents a d_g of about 17 cm and h_g of 13 m as well as d_{dom} 23 cm, h_{dom} 15 m and basal area G 30.4 $m^2 ha^{-1}$ being in accordance to the expected values (mean diameter 14-25 cm at 25-30 years according to Bourgeois (1992); Bourgeois et al. (2004). In the plot without intervention the same basal area is obtained (G 30.9 $m^2 ha^{-1}$) but only with a d_g of 14.5 cm. From the last thinning at 11 years of age, we observed in plot 1, 4% mortality in stools and 7% in shoots while in plot 3, plot without intervention, intense competition led to a reduction of 27% in the number of stools and 68% in the number of shoots in relation to the existing density at 11 years. In this plot there is a reduction in the number of stools almost equivalent to that imposed to plot 1 by thinnings. In plots plot 2 and plot 4, no mortality was observed.

Table 6: Resume of the dendrometric variables for the plot 1 (Model 1), plot 2 (Model 2), plot 3 (control) and plot 4 (Model 3) in 2003, 2008 and 2016

Year	Plot	N _{st} /ha	N _{sh} /ha	hg (m)	h _{dom} (m)	G (m ² /ha)	$\bar{g} \bar{v}$ (m ²)	dg (cm)	d _{dom} (cm)	h/d	d _{mean}	%Surv _{st}	% Surv _{sh}
2003	Plot 1	636	1501	9.6	11.2	12.6	0.008	10.3	14.9	98.6	10.1		
2008	Plot 1	623	1450	12.5	13.4	20.5	0.014	13.4	18.3	93.0	13.1	98.0	96.6
2016	Plot 1	611	1399	13.0	15.4	30.4	0.022	16.6	23.2	80.7	16.2	96.0	93.2

Year	Plot	N _{st} /ha	N _{sh} /ha	hg (m)	h _{dom} (m)	G (m ² /ha)	$\bar{g} \bar{v}$ (m ²)	dg (cm)	d _{dom} (cm)	h/d	d _{mean}	%Surv _{st}	% Surv _{sh}
2003	Plot 2	654	761	10.3	11.1	6.2	0.008	10.2	13.8	109.4	10.0		
2008	Plot 2	654	761	12.7	13.7	13.5	0.018	15.0	19.8	86.3	14.7	100.0	100.0
2016	Plot 2	654	761	15.9	17.2	22.7	0.030	19.5	25.6	85.8	19.0	100.0	100.0

Year	Plot	N _{st} /ha	N _{sh} /ha	hg (m)	h _{dom} (m)	G (m ² /ha)	$\bar{g} \bar{v}$ (m ²)	dg (cm)	d _{dom} (cm)	h/d	d _{mean}	%Surv _{st}	% Surv _{sh}
2003	Plot 3	618	5788	8.9	11.4	24.7	0.004	7.4	15.6	144.7	6.6		
2008	Plot 3	593	3455	9.9	14.6	30.0	0.009	10.5	19.0	117.5	9.7	95.9	59.7
2016	Plot 3	454	1866	13.5	17.8	30.9	0.017	14.5	23.6	114.9	13.7	73.5	32.2

Year	Plot	N _{st} /ha	N _{sh} /ha	hg (m)	h _{dom} (m)	G (m ² /ha)	$\bar{g} \bar{v}$ (m ²)	dg (cm)	d _{dom} (cm)	h/d	d _{mean}	%Surv _{st}	% Surv _{sh}
2003	Plot 4	531	534	10.3	11.7	4.3	0.008	10.1	13.3	110.8	10		
2008	Plot 4	320	320	12.8	13.1	5.9	0.018	15.3	18.1	85.8	15	60.3	60.0
2016	Plot 4	320	320	16.7	16.9	10.8	0.034	20.8	24.3	81.0	20	60.3	60.0

*N_{st}/ha: number of stools per hectare, N_{sh}/ha: number of shoots per hectare, h_g: mean height, h_{dom}: dominant height, G: basal area of the stand, $\bar{g} \bar{v}$: mean basal area per shoot, d_g: mean quadratic diameter, d_{dom}: dominant diameter, h/d: mean of stability coefficient, d_{mean}: mean diameter, %Surv_{st}: percent of survived stools, %Surv_{sh}: percent of survived shoots,

Following is a graphical analysis of the evolution of the main dendrometric variables that characterize the plots.

✓ **Basal area characteristics**

In figure 11 we can observe the evolution of growth in basal area in the period of 2003-2016. As we can see the basal area of the plot 1 (model 1 for small dimensions) is similar to that of plot 3 (without intervention). It is verified that the treatment without intervention naturally tends toward to the results of Model 1. Despite the basal area is similar the quality of the shoots for wood is clearly superior in the plots with silvicultural intervention (Patrício et al., 2009; Geraldes, 2011).

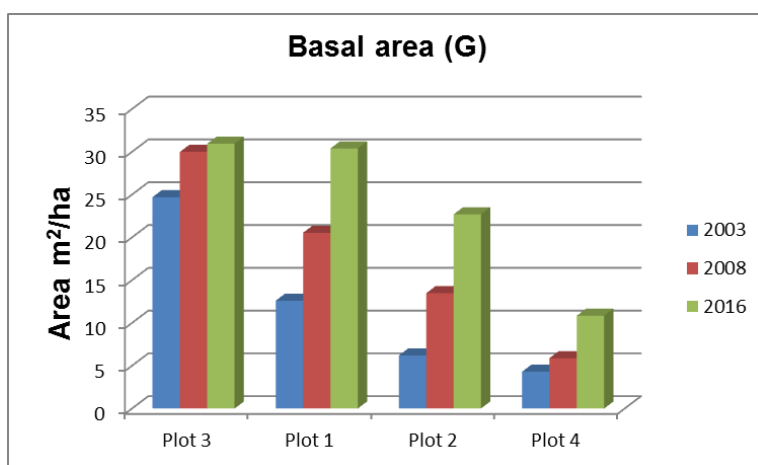


Figure 11: Evolution of basal area over time for the study plots

In the thinned plots the reduction of density has been compensated by the increase of individual growth of the shoots as we can see in figure 12.

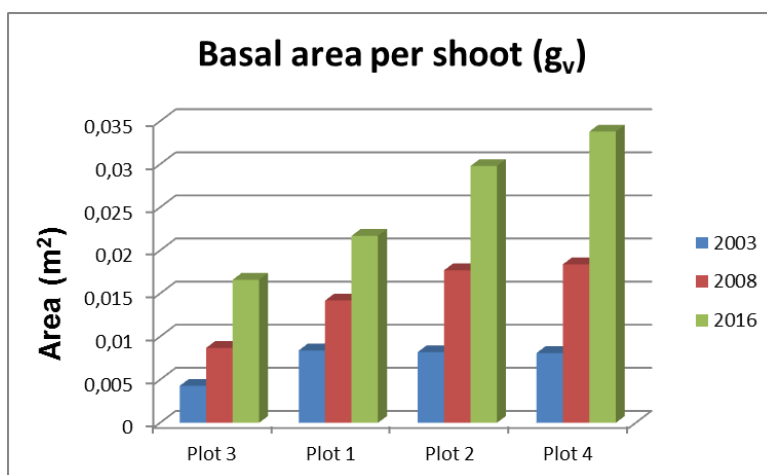


Figure 12: Evolution of basal area per shoot over time

The plot 4 although with much less number of shoots presents larger individual shoots.

✓ Height growth

On average, the evolution of the height of the shoot of mean basal area is superior on the plot 4 but followed closely by plot 2 because (Figure 13), in this stage of development, the number of shoots in the plot 2 is on average 1.2 shoots per stool, and in plot 4 is 1 shoot per stool.

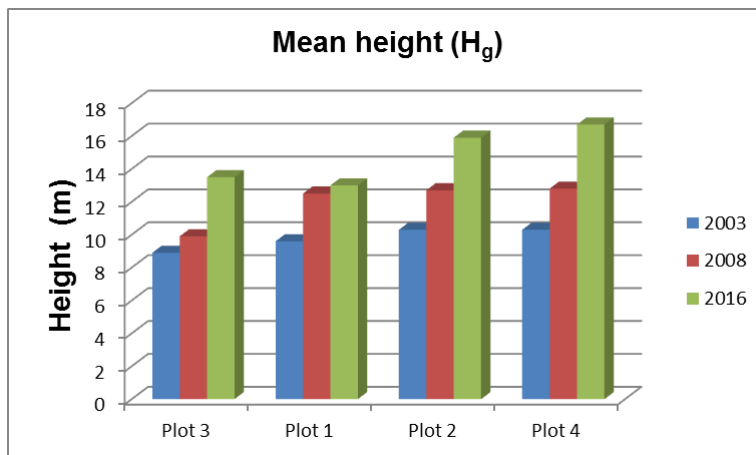


Figure 13: Height evolution of the shoot of mean basal area

As we can see since the year 2008 the gap between plot 3, without intervention, and plots 2 and 4, has been increasing. And we expect that it will continue over time.

Analyzing the dominant height evolution (Figure 14) this difference is not so obvious because in the situation of plot 3, without intervention, it is expected that the bigger trees survive (the dominant shoots in the stools). The natural selection favor the dominant shoots that are the best competitors. That is why the differences are smoother.

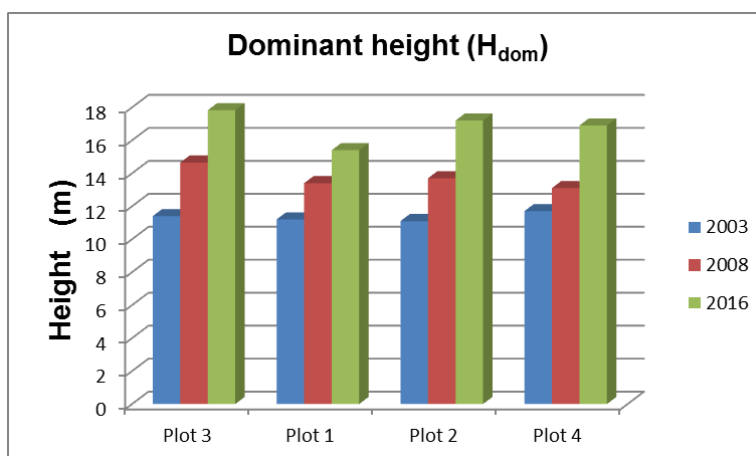


Figure 14: Evolution of the dominant height per plot

✓ Diameter growth

Considering the development of the diameter of dominant shoots in all plots (Figure 15), the tendency is to have slight differences between plots. This can be explained by the fact that we are evaluating the dominant players who are the best competitors and therefore tend to be similar. The difference between plots is on the average values.

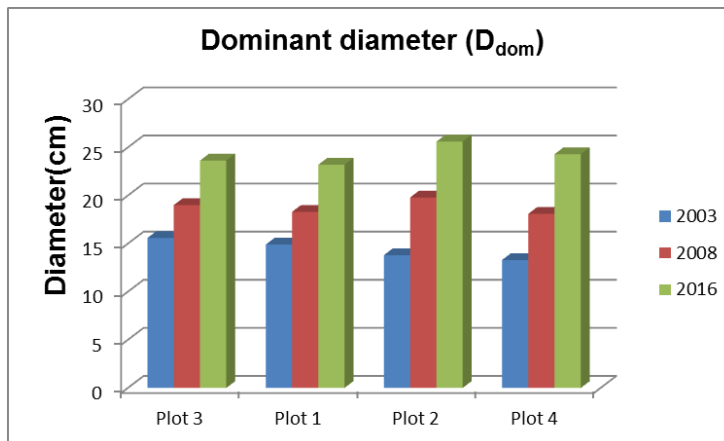


Figure 15: Evolution of the dominant diameter per plot

When we compare the mean parameters we can see that the difference between plots is emphasized on the average values, because these are related to the density levels in the plots (Figure 16).

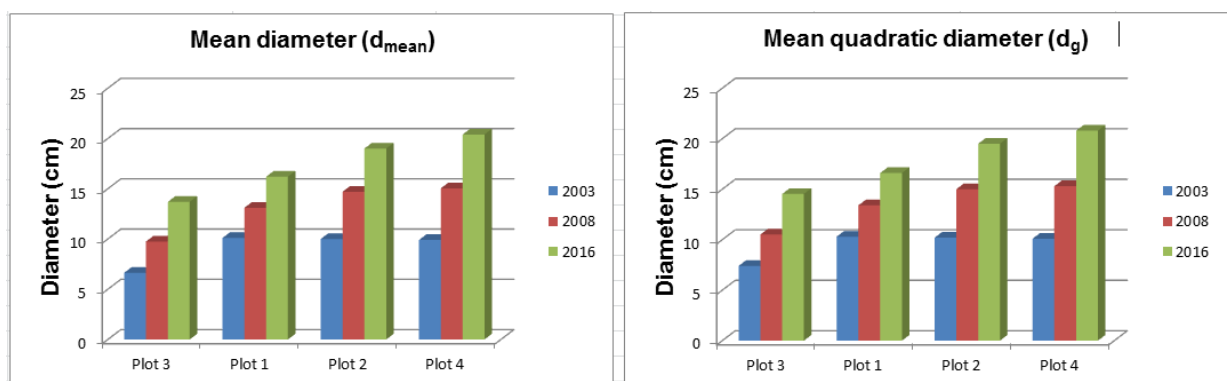


Figure 16: Evolution of mean diameter histogram vs mean quadratic diameter histogram

As expected the averaged parameters of the diameters, regardless of the difference in the manner of calculation, show almost the same result. Plots with medium and large dimension trees shows us an increasing difference in rates compared to other plots. It is possible that with time this gap will only increase.

As we see from the values of diameter, height and basal area, the plots with large tree dimensions have a distinct advantage, which highlight the effectiveness of this management models. But it is not enough to determine the largest and most developed trees, we select the most promising and vigorous trees with a straight and cylindrical stem for wood production. It is still necessary to understand how our choice is correct as to the ability of such trees to resist external conditions and survive in a competitive environment. So we analyze the relation h/d considered an indicator of tree and stand stability.

✓ **Stability coefficient h/d**

The coefficient of stability is calculated from the ratio of height and diameter. This coefficient tells us how much the tree will be resistant to external influences, like strong wind or heavy snow and thinnings. It should be noted that, the lower the value of the coefficient the more stable tree stand is.

As we can see in the figure 17, the best indicators are in plots 1, 2 and 4, where silvicultural models were applied. The control plot (N0 3) has too much difference from the other plots.

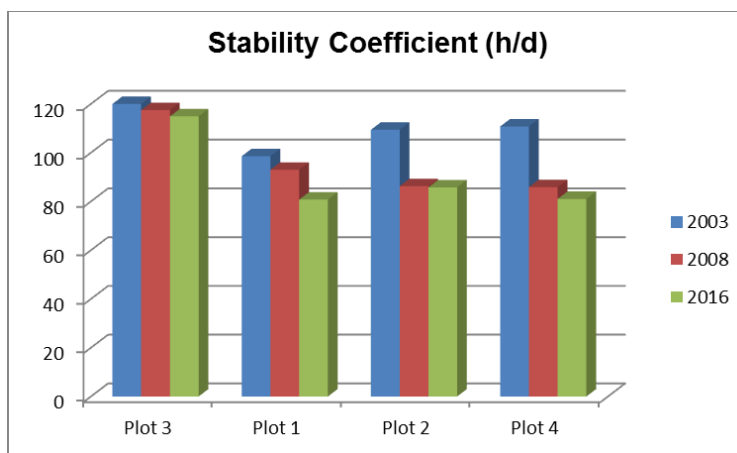


Figure 17: Stability coefficient in the plots

The plots with silvicultural interventions have an increase of stability over time compared to the control plot that maintains high instability with values above 100.

So, good influence of human intervention in this case (comparing with control plot) is obvious.

✓ **Crown ratio (CR)**

The crown ratio is an indicator of the competition by light and, in complementarity with the stability coefficient, gives us important information for silvicultural management, namely to define the opportunity of applying thinnings. Unfortunately, we have this parameter only for the last two periods. Even this, it is enough for us to understand the essence of the changes (Figure 18)

The change in the percentage of a live crown may depend on many factors, both natural and anthropogenic. However, if we take this indicator as a whole, the percentage of the total tree size that is occupied by the crown is important to evaluate the current state of the stand in terms of vigor and competition.

Observing the figure 18, we can see that in parallel with the decrease in the number of trees in the study plots over time (independently of being managed or not), the size of the living crown increases. This is because the natural selection has a similar effect to some thinnings in silvicultural management but usually with poorer quality. This increase means that competitive pressure drops year by year.

Only one exception is the plot 4 which maintain the same number of shoots and the same CR because the competition was well managed by the thinnings.

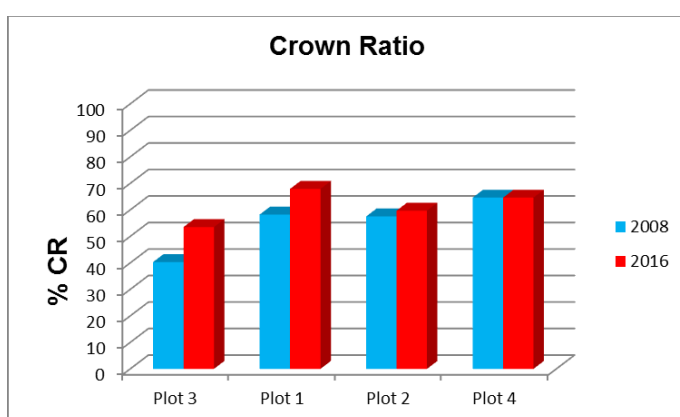


Figure 18: Crown ratio (proportion of living crown) of the plots

Plots 2 and 4, maintain the same ratio of CR because the competition in these plots are well managed. This is especially true for plot 4, where the last thinning was carried out in 2008.

✓ **Number of trees and percentage of survival.**

In addition to the basic parameters of the stand, we need to take into account the proper density for the management objective. We should also pay attention to the survival of the trees themselves, which can be displayed both in numerical and in percentage terms. First of all, we should analyze the number of stools and shoots per hectare.

As can be seen from the figure 19, the natural competition promoted a great reduction of density on plot 3, without intervention. As we can see, progressively the control plot converges toward the density of plot 1 (Model for small dimensions).

On plot 3, from 2003 to 2016, as a result of the most severe competition, the number of stools decreased by almost 30%, and the number of shoots reduced more than in three times. On the remaining plots the density over time was regulated by thinnings (Figure 19).

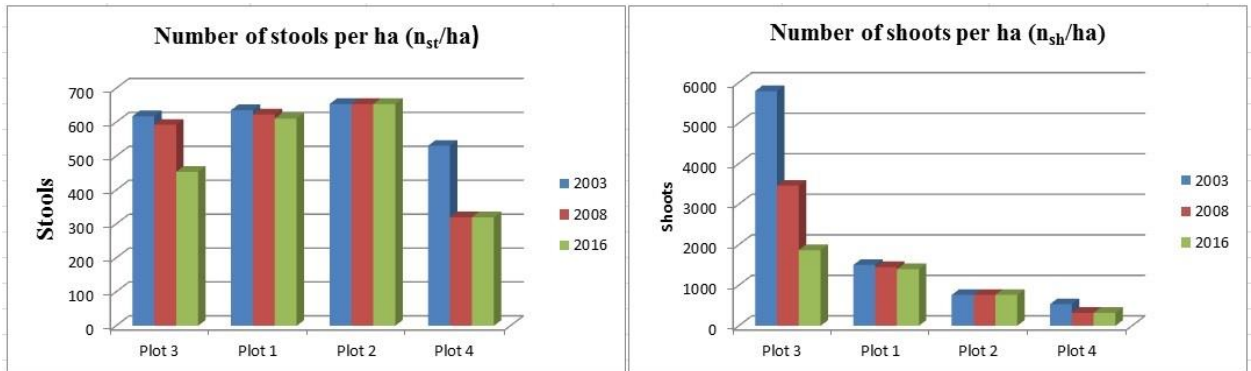


Figure 19: Density of standing stools and shoots in the plots over time.

On figure 20 we present the percentage of survival in the study plots in the dormancy 2016/2017, corresponding to the actual stocking of living stools and shoots in the plots.

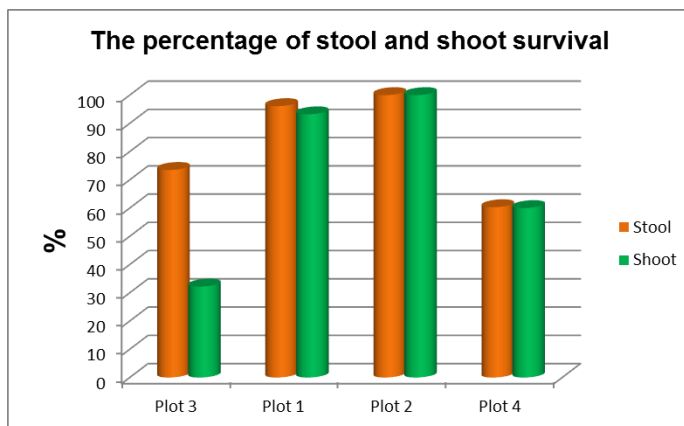


Figure 20: Stocking percentage of stools and shoots in 2016

If we take as the basic hypothesis that in 2003 each tree stand had 100% of the original population, then the reduction of the initial amount becomes more than obvious for plot 3, where no activities were carried out. Other plots remained practically unchanged, except the plot 4 that was submitted to a thinning in 2008.

5.2 Hypsometric curves

Results of validation of Bragado (2003) equations with 2016 data are presented in table 7.

Table 7: Validation of Bragado (2003) equations with data from 2016

Plot	Function	M_{pr}	M_{Apr}
P 1	$h = 10.784 - 20.004\frac{1}{d} + 0.084d$	1.85	2.19
P 2	$h = 12.227 - 22.148\frac{1}{d} + 0.080d$	3.43	3.45
P 3	$h = \left(\frac{1}{0.174 + \frac{0.664}{d}} \right)^{1.591} + 1.3$	2.82	3.35
P 4	$h = 11.708 - 20.830\frac{1}{d} + 0.127d$	2.83	2.83

As can be observed from table 7, when we apply the models from 2003 to data from 2016, predictions are biased underestimating height between 1.85 m and 3.43 m (values of M_{pr}). Also when looking to the M_{Apr} values it is observed that the models commit an error, on average, superior to 2 m.

The models in Table 7 were re-parameterized with data from 2016 measurements. Generally, the models showed worst quality of fit to 2016 data in relation to 2003 data, and presented at least one non-significant parameter (all in the case of model for P3).

Since the existing models did not adapt to the new data of 2016 we decided to prepare a file of data with all h-d available from the measurements of the trial in 1999, 2003, 2008 and 2016. This data file was used to fit again the same equations used by Bragado (2003) plus the equation of Bates and Watts (1980). A total of 13 equations were fitted.

So, from the 13 initial candidates, 6 equations not presenting adequate biological behaviour were automatically excluded. The remaining 7 equations were analyzed in order to select the best model in each plot. The equations are presented in Table 8.

Table 8: The 7 pre-selected equations for modelling h-d relationships

Equations	Reference
[Eq1] $h = b_0 + b_1 \log d$	Henricksen (1950)
[Eq2] $h = \frac{d}{b_0 + b_1 d}$	Prodan (1965)
[Eq3] $h = 1.3 + b_0 d^{b_1}$	Stoffels and Van Soest (1953)
[Eq4] $h = 1.3 + b_0(1 - e^{-b_1 d})$	Meyer (1940)
[Eq5] $h = 1.3 + b_0 d / (b_1 + d)$	Bates and Watts (1980)
[Eq6] $h = b_0 + b_1 d + b_2 d^2$	Trorey (1932)
[Eq7] $h = b_0 + b_1 \frac{1}{d} + b_2 d$	---

Among the 7 equations in Table 8, three of them (Eq1, Eq2 and Eq7) consistently presented the worst performance in all the 4 plots. Thus, results are presented only for the four equations with best performance (Tables 9-12).

Table 9: Performance of the four best equations in plot 1 (P1).

Equation	R_{adj}^2	\bar{e}	V_{res}	QTE	$RMSE$	BIC	M_{press}	MA_{press}	$PRESS$
Eq3	0.807	-0.009	1.703	1.704	1.306	2087.8	-0.009	1.004	1051.5
Eq4	0.811	0.008	1.669	1.669	1.293	2075.4	0.008	0.993	1030.5
Eq5	0.811	0.004	1.671	1.671	1.294	2076.1	0.004	0.994	1031.7
Eq6	0.812	3.4 e-16	1.661	1.661	1.291	2078.6	0.0002	0.991	1027.5

Table 10: Performance of the four best equations in plot 2 (P2).

Equation	R_{adj}^2	\bar{e}	V_{res}	QTE	$RMSE$	BIC	M_{press}	MA_{press}	$PRESS$
Eq3	0.860	-0.004	1.687	1.687	1.300	1543.3	-0.004	0.987	771.9
Eq4	0.858	0.033	1.706	1.707	1.308	1548.5	0.033	0.998	780.6
Eq5	0.859	0.025	1.699	1.700	1.305	1546.6	0.025	0.994	777.3
Eq6	0.861	-2.2 e-16	1.668	1.668	1.294	1544.3	-0.0004	0.981	765.5

Table 11: Performance of the four best equations in plot 3 (P3).

Equation	R_{adj}^2	\bar{e}	V_{res}	QTE	$RMSE$	BIC	M_{press}	MA_{press}	$PRESS$
Eq3	0.793	-0.011	2.620	2.620	1.619	5250.8	-0.011	1.230	3615.1
Eq4	0.793	0.033	2.622	2.623	1.620	5252.6	0.033	1.233	3620.0
Eq5	0.794	0.021	2.613	2.613	1.617	5247.5	0.021	1.230	3606.4
Eq6	0.795	-5.7 e-16	2.599	2.599	1.613	5246.9	-0.000087	1.226	3589.3

Table 12: Performance of the four best equations in plot 4 (P4).

Equation	R_{adj}^2	\bar{e}	V_{res}	QTE	$RMSE$	BIC	M_{press}	MA_{press}	$PRESS$
Eq3	0.841	-0.008	1.293	1.293	1.139	913.5	-0.009	0.892	381.9
Eq4	0.843	0.020	1.278	1.278	1.133	910.2	0.020	0.892	376.1
Eq5	0.844	0.009	1.267	1.267	1.128	907.7	0.009	0.888	373.0
Eq6	0.846	5.8 e-17	1.248	1.248	1.121	908.9	-0.001	0.881	369.3

In figure 21 we can observe the average trend lines from the equations 3-6, plotted over the observed data

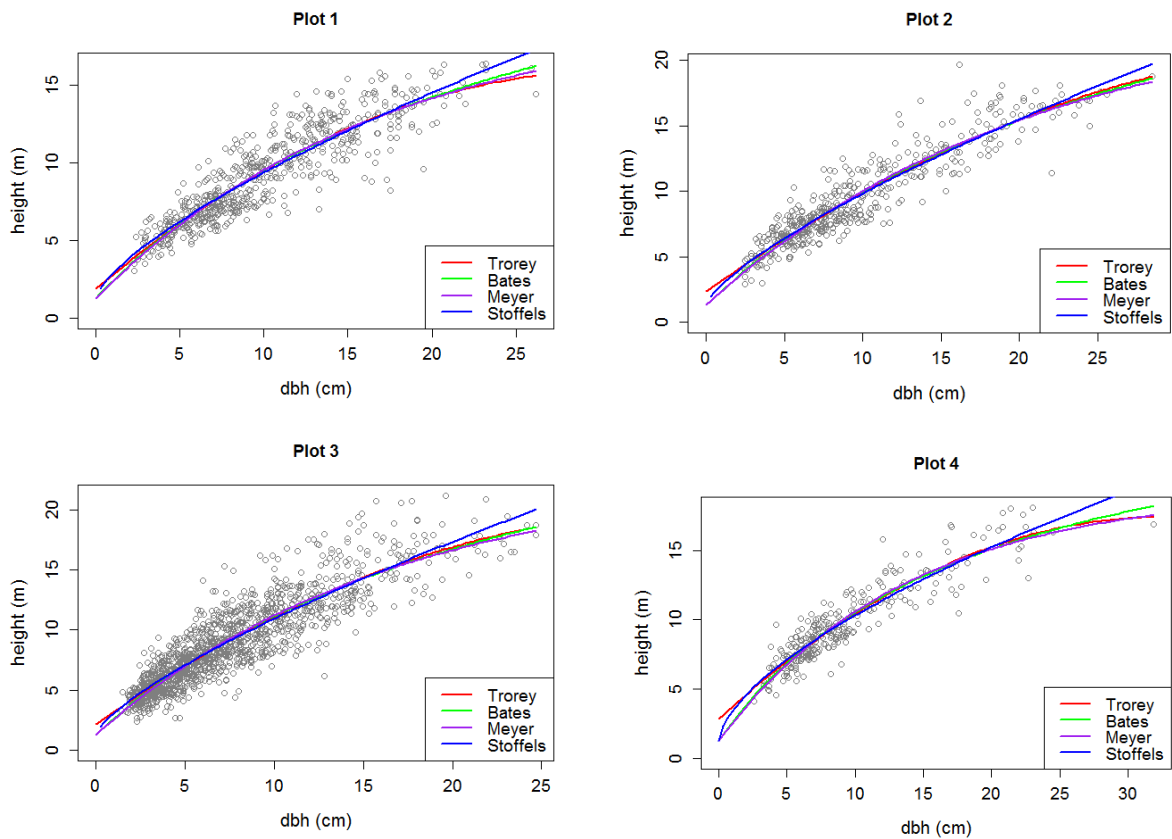


Figure 21: Average trend lines of eqs. 3-6, plotted over the observed data.

Despite the performance was very similar in all the plots, Eq6 corresponding to Trorey (1932) model presented the best statistical performance in all the plots. This equation corresponds to a second degree polynomial. Bates and Watts (1980) equation (Eq5), was almost as good as Trorey's Eq6 in plots P3 and P4 with also adequate performance in P1 and P2, being a two-parameter equation. In plot P4, BIC criterion even gives preference to Eq5, penalizing the 3 parameter equation Eq6. Thus, we decided to present the coefficients of these two equations in Table 13. All the coefficients were significant at 1% level ($p < 0.01$).

Table 13: Coefficients of Trorey (1932) and Bates and Watts (1980) equations resulting from least squares fit.

Coefficients	Trorey (1932)	Bates and Watts (1980)
PLOT 1		
b0	1.9088	30.130
b1	0.9058	26.638
b2	-0.0146	
PLOT 2		
b0	2.3304	37.562
b1	0.8514	33.189
b2	-0.0096	
PLOT 3		
b0	2.1648	35.381
b1	1.0480	25.856
b2	-0.0156	
PLOT 4		
b0	2.8556	27.228
b1	0.8960	19.480
b2	-0.0138	

Analysis of residuals were done using plots of standardized residuals against fitted values, Q-Q plots for checking normality and Lag-plots (residuals against lag of residuals) to detect possible autocorrelation. A low degree of heterocedasticity was detected and also a very slight autocorrelation of residuals was detected (mainly in plots P1 and P2). The assumption of normality was not in question. This can be observed in Figures 22, 23 and 24 for the example of Trorey's equation fit in Plot 1.

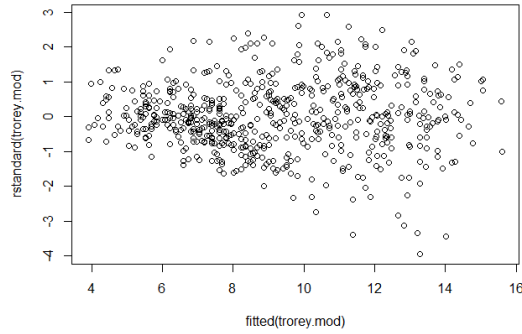


Figure 22: Plot of residuals vs. fitted values (Trorey model in P1)

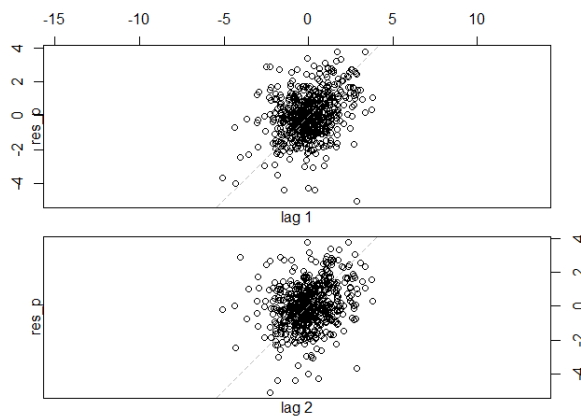


Figure 23: Plot of residuals vs. lag residuals (Trorey model in P1)

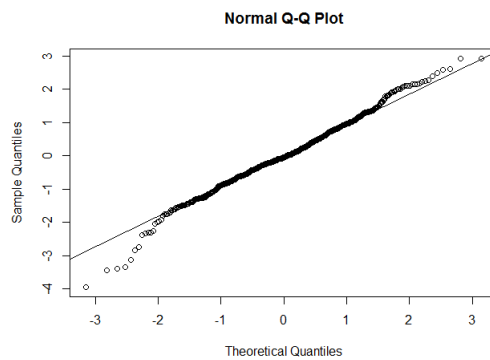


Figure 24: Q-Q plot of residuals (Trorey model in P1)

Remedial measures can be taken to correct for heterocedasticity and autocorrelation. This was done using generalized least squares fitting with the function *gnls* of R package *nlme*, using a power variance function structure (*varPower*) and a continuous autocorrelation structure of order 1 (*corCAR(1)*) as we have measurements irregularly-spaced in time. Residual plots of the

generalized least squares fit showed improvements, as can be seen for the example of Trorey's equation in Plot 1 (Figures 25, 26, 27).

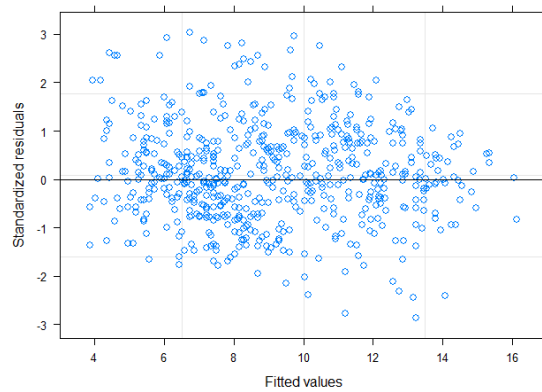


Figure 25: Plot of residuals vs. fitted values after correcting for heteroscedasticity and autocorrelation (Trorey model in P1)

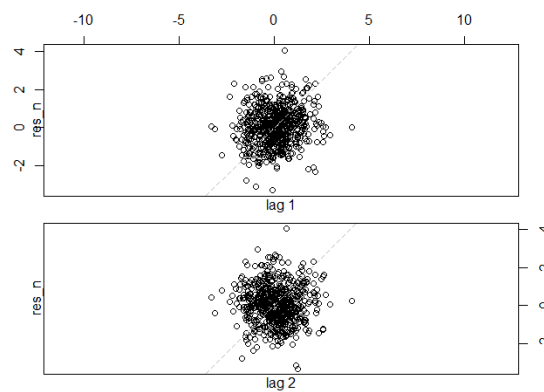


Figure 26: Plot of residuals vs. lag residuals after correcting for heteroscedasticity and autocorrelation (Trorey model in P1)

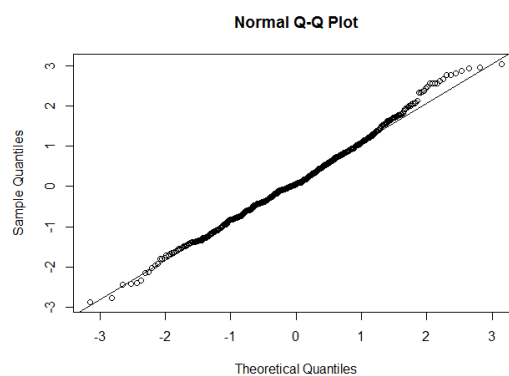


Figure 27: Q-Q plot of residuals after correcting for heteroscedasticity and autocorrelation (Trorey model in P1)

If remedial measures are taken, coefficients of Trorey (1932) and Bates and Watts (1980) equations, resulting from generalized least squares fit after correcting for heterocedasticity and autocorrelation are presented in Table 14. All coefficients are significant at 1% level ($p < 0.01$).

Table 14. Coefficients of Trorey (1932) and Bates and Watts (1980) equations resulting from generalized least squares fit with correction for heterocedasticity and autocorrelation.

Coefficients	Trorey (1932)	Bates and Watts (1980)
PLOT 1		
b0	1.9766	32.674
b1	0.8524	30.452
b2	-0.0119	
ρ	0.67	0.67
PLOT 2		
b0	2.5822	36.8639
b1	0.7709	32.5732
b2	-0.0060	
ρ	0.70	0.69
PLOT 3		
b0	2.0883	43.8063
b1	1.0073	33.8663
b2	-0.0103	
ρ	0.52	0.52
PLOT 4		
b0	2.9880	28.5030
b1	0.8490	20.8406
b2	-0.0112	
ρ	0.54	0.57

6. Conclusions

Despite the fact that the study plots in question are still under observation, and the collection of material on them will also continue, we can already draw some conclusions.

- 1) The plots submitted to forest management (application of silvicultural models 1, 2 and 3) give undoubtedly a better result than those that do not imply interference.
- 2) Model 1 presents a d_g of about 17 cm and h_g of 13 m as well as d_{dom} 23 cm, h_{dom} 15 m and basal area G $30.4 \text{ m}^2 \text{ ha}^{-1}$, being in accordance to the expected values in reference models (mean diameter 14-25 cm at 25-30 years).
- 3) In the plot without intervention the same basal area of plot 1 is obtained (G $30.9 \text{ m}^2 \text{ ha}^{-1}$) but only with a d_g of 14.5 cm. In this plot there is a natural reduction in the number of shoots almost equivalent to that imposed to P1 by thinnings.
- 4) Relatively to mortality, from the last thinning at 11 years of age, we observed in P1 4% mortality in stools and 7% in shoots. In plots P2 and P4, no mortality was observed. A strong reduction of density was observed in plot 3 due to the high competition.
- 5) In Models 2 and 3 the observed growth follows closely the expected for this growth stage of the coppice. The quality of the individual shoots for wood is clearly superior to that of the plot without intervention although the dominant trees may have similar growth rates.
- 6) Comparing the mean dendrometric values, higher values were observed in plots with the models application.
- 7) The results also show that when the wood is to be used for saw-timber, silvicultural intervention is essential.
- 8) Among all three models, at this stage, the model 3 for large shoot dimensions is clearly in the lead. This model has both the best average values for height and diameter, and excellent indicators for stability and crown ratio.
- 9) Finally, local h-d equations were obtained for the plots in the coppice experiment using data measurements from 1999 to 2016. These equations will be available for the similar Sweet Chestnut coppices in the area where the data was collected. Future work could be done to develop generalized h-d equations for a broader application.

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Appendix

Layout adapted from Bragado (2003)

Plot 1 (Objective: Small dimension)

1 DESCRIPTION

Administration: Forest place of Vila Pouca de Aguiar

Altitude: 830 m

Area of the plot: 786 m²

Slope: 26°

2 STAND

Composition: Pure

Type of Soils: Cambisol

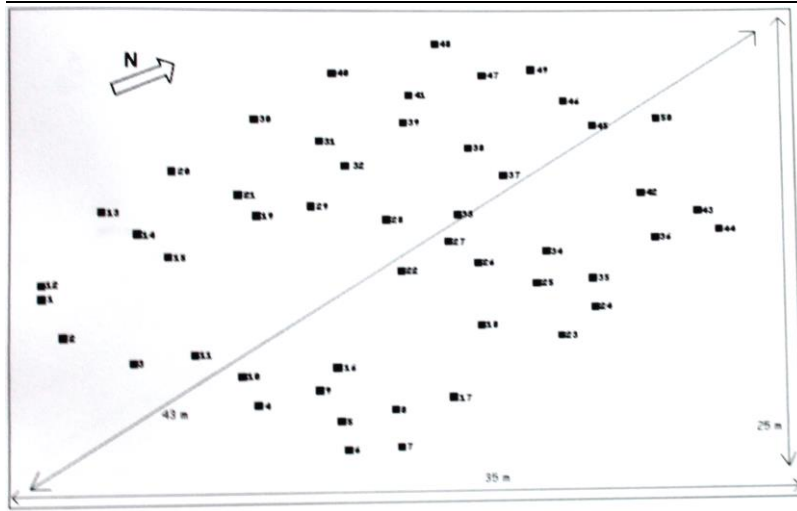
Species: *Castanea sativa* Mill.

Ecologic zone: SA (Sub Atlantic)

System: Coppice

Age: 24 years

3 DISTRIBUTION OF THE STOOLS IN THE PLOT AND SITE



4 PICTURE OF THE PLOT AT 11 YEARS OLD



Plot 2 (Objective: Medium dimension)

1 DESCRIPTION

Administration: Forest place of Vila Pouca de Aguiar

Altitude: 830 m

Area of the plot: 749 m²

Slope: 30°

2 STAND

Composition: Pure

Type of Soils: Cambisol

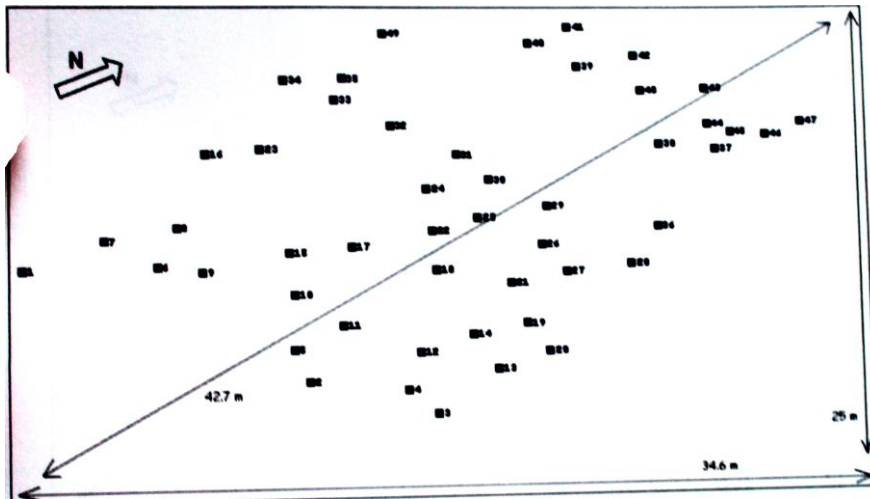
Species: *Castanea sativa* Mill.

Ecologic zone: SA (Sub Atlantic)

System: Coppice

Age: 24 years

3 DISTRIBUTION OF THE STOOLS IN THE PLOT AND SITE



4 PICTURE OF THE PLOT AT 11 YEARS OLD



Plot 3 (Control)

1 DESCRIPTION

Administration: Forest place of Vila Pouca de Aguiar

Altitude: 830 m

Area of the plot: 793 m²

Slope: 27°

2 STAND

Composition: Pure

Type of Soils: Cambisol

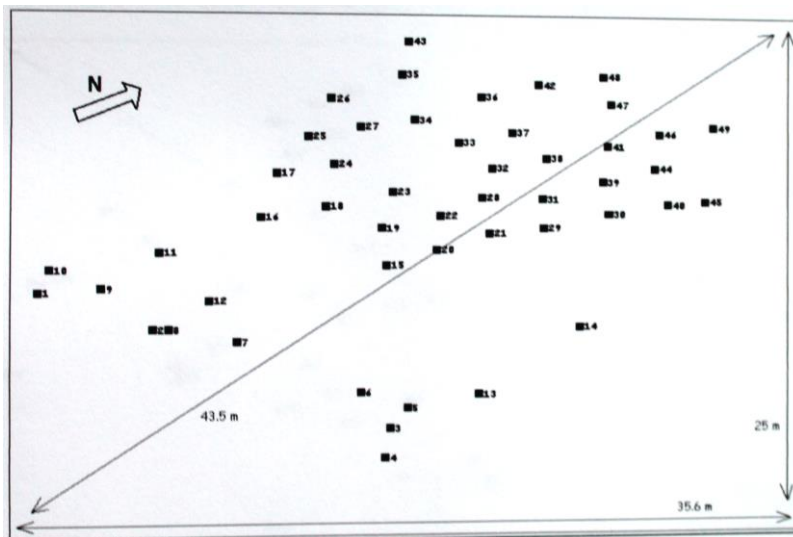
Species: *Castanea sativa* Mill.

Ecologic zone: SA (Sub Atlantic)

System: Coppice

Age: 24 years

3 DISTRIBUTION OF THE STOOLS IN THE PLOT AND SITE



4 PICTURE OF THE PLOT AT 11 YEARS OLD



Plot 4 (Objective: Large dimension)

1 DESCRIPTION

Administration: Forest place of Vila Pouca de Aguiar

Altitude: 830 m

Area of the plot: 749 m²

Slope: 30°

2 STAND

Composition: Pure

Type of Soils: Cambisol

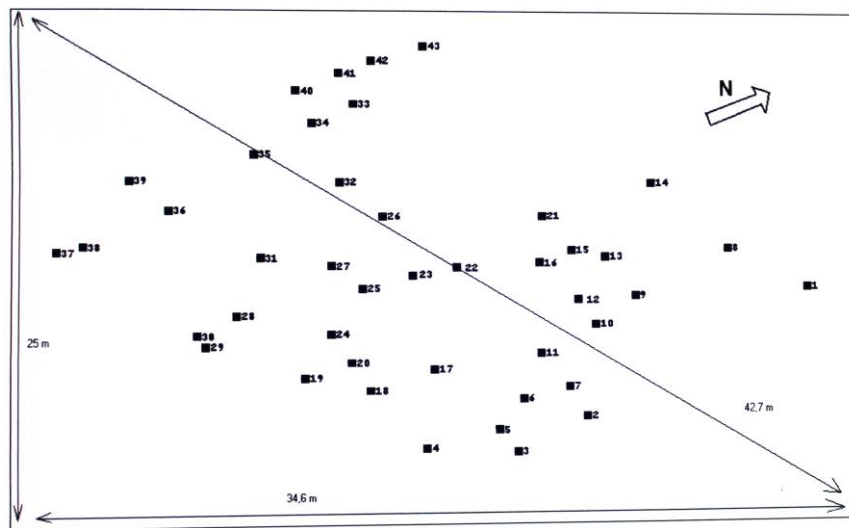
Species: *Castanea sativa* Mill.

Ecologic zone: SA (Sub Atlantic)

System: Coppice

Age: 24 years

3 DISTRIBUTION OF THE STOOLS IN THE PLOT AND SITE



4 PICTURE OF THE PLOT AT 11 YEARS OLD

