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A Stand Density Management Diagram for mixed stands of *Pinus sylvestris* and *Pinus pinaster* in the *Sierra de la Demanda* (Spain)

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RESUMEN

Los diagramas de manejo de la densidad son herramientas de decisión robustas disponibles para los gestores forestales que disponen de información limitada. Los diagramas son modelos empíricos a nivel de masa, gráficamente representan las relaciones temporales entre la densidad de masa y diferentes variables como el diámetro medio cuadrático, la altura dominante o el volumen. Son usados para definir espaciamiento inicial de una plantación o para organizar las claras. En la actualidad hay un interés creciente en los bosques mixtos como una opción de la gestión forestal adaptativa ya que se consideran cada vez más como una garantía para salvaguardar una amplia variedad de servicios ecosistémicos dentro de la sostenibilidad. Pero hay todavía una falta de conocimiento, herramientas eficientes y modelos para las masas mixtas, como pueden ser los diagramas de densidad.

El objetivo de este estudio es desarrollar un diagrama de densidad para las masas mixtas de *Pinus sylvestris* y *Pinus pinaster* en la Sierra de la Demanda usando los datos del tercer Inventario Forestal Nacional ya que son dos de las coníferas más importantes en Europa y en la cuenca mediterránea, sobre todo en España.

Se pueden usar diferentes variables para desarrollar un diagrama de densidad. En este caso se usaron el diámetro medio cuadrático, la altura dominante, el volumen de la masa, la densidad y el índice de Reineke. Además se realizó un ajuste simultáneo de dos ecuaciones. Estas ecuaciones se ajustaron incluyendo una nueva variable representando la proporción de ambas especies para tener en cuenta la mezcla de la masa. Todos los análisis estadísticos y la construcción del diagrama se realizaron usando el software estadístico R.

Los resultados del ajuste simultáneo mostraron que la nueva variable representando la proporción de ambas especies no fue significativo. Basado en esto se construyó un diagrama sin el grado de mezcla de las especies. Este diagrama podrá ser usado por los gestores forestales como una eficiente herramienta para la gestión de la selvicultura de estas masas.

Palabras clave: Índice de Reineke, altura dominante, selvicultura, clara, grado de mezcla

ABSTRACT

Stand density management diagrams (SDMDs) are robust decision-support tools available to forest managers under limited information. SDMDs which are empirical models at stand level, graphically represent the temporal relationships among stand density, and different stand variables such as quadratic mean diameter, dominant height and mean tree volume. They are used to define initial planting spacing or thinning interventions, in order to meet various management objectives. Nowadays, there is a growing interest in mixed-species forests as an option of adaptive forest management, where they are considered a guarantor to safeguarding a wide variety of ecosystem services within the framework of sustainability. But there is still a lack of knowledge and efficient tools and models for mixed stands such as SDMDs.

The aim of this study is to develop an SDMD for *Pinus sylvestris* and *Pinus pinaster* mixed stands in the *Sierra de la Demanda* using data from the third Spanish National Forest Inventory, as they are two of the important coniferous species in Europe and in the Mediterranean basin zone especially in Spain.

Different variables can be used to develop an SDMD. In this case quadratic mean diameter, dominant height, total stand volume, number of trees per hectare and stand density index (Reineke index) were estimated. Moreover a simultaneous fitting was developed. These equations were fit including a new variable representing the proportion of both species to take into account the mixed stand. All statistical analysis and the construction of the SDMD were developed using the software R.

The results of the simultaneous fitting showed the new variable representing the proportion of both species was not significant. Based on that, the SDMD was constructed without including mixture degree. This SDMD can be used by forest managers as an efficient tool to plan thinning practices.

Key words: Reineke index, dominant height, silviculture, thinning, mixture degree.

1.- INTRODUCTION

Stand density has a considerable effect on both tree size and stand yield (Drew and Flewelling 1979), thus it impacts how a stand develops over a rotation period, Long et al (2004) defined a stand development as the increase of mean tree size with decreasing number of trees per unit area. In silviculture, forest density regulation or in other words, density management, can be seen as one of the most robust and effective tools available to foresters, in order to achieve desired conditions of the managed stands, consequently a wide range of stand management objectives can be acquired. Hence it may help in overcoming some of the harmful effects of climate change and site degradation.

From a conceptual point of view, stand density management is defined as a procedure to control tree competition through density manipulation to meet various management objectives (Newton, 1997; Newton et al. , 2005). At the operational level, this manipulation of density can be achieved by controlling the level of growing stock through initial spacing and/or a sequence of thinning interventions (Barrio-Anta and Álvarez-González 2005). Hence the responses to such practices, are the results of their influence on the availability of resources necessary for growth, the ability of trees to utilize available resources and finally the distribution of those resources within the site (Long et al., 2004).

Determining proper levels of growing stock is critical for planning a stand density regime and should be done precisely. This determination of levels is a complicated process as it involves biological, technological, economic and operational factors fixed to a specific management case (Castedo-Dorado et al. 2009). The process needs selecting the upper and lower limits of growing stock, considering that the upper limit of growing stock is selected to ensure acceptable stand-level growth and tree vitality, while the lower limit of growing stock is selected to ensure maintaining adequate site-occupancy (Dean and Baldwin, 1996). Thus the optimal exploitation of site resources by individual trees and ensuring a sound stand growth are a matter of the proper timing and intensity of thinning treatments, which are strongly dictated by both limits of the growing stock (Kimsey et at., 2019).

The implication of thinning treatments at stand level have a major favorable impact on its productivity and yield. This is due to two main reasons, on one hand, making profits from the removed trees (commercial thinning) that would die as a result of stand self-thinning, while on the other hand, these treatments decrease competition among trees, consequently accelerating and improving individual tree growth (Dean and Baldwin, 1993).

As mentioned before, thinning interventions have to be scheduled precisely as much as possible, if we are aiming to fulfill maximum benefits out of a given stand. Dean and Baldwin (1993) stated that by overly soon thinning, a stand will negatively be affected in terms of its growing stock and gross yield, as a result of slow tree response.

In spite of the fact that thinning experiment plots are the best and most competent method to set the proper timing of thinning and to define density targets (Valbuena et al., 2008; Schnell et al., 2012). They have some critical restrictions, they are time-consuming as they need too many years to get the results, which cannot be accurately applied on sites have different conditions (site quality and management objectives) from those experienced in field trials (Dean and Baldwin, 1993; Schnell et al., 2012). Moreover, stand densities can occur in an almost infinite array of combinations, consequently, it is unreasonable to expect that all possible combinations could be tested in field trial before applying it in operational forestry (Valbuena et al., 2008).

In this regards, stand density management diagrams (SDMDs), also known as 'stand density control diagrams' and 'yield-density diagrams' have emerged as a time-saving and cost-effective approach, Jack and Long (1996) concluded that SDMDs have a robust conceptual principle in describing even-aged stand dynamics.

On the contrary to thinning trials, SDMDs are simple decision-support tools found to help forest managers in the decision-making process under limited information, they are flexible and adaptable to different site conditions and management goals (Schnell et al., 2012). They are efficient in quantitative silviculture as they help forest managers to design, display and evaluate various density management regimes (Jack and Long, 1996; Newton, 2003), in order to predict what stand post-thinning density would be. In terms of operating costs, SDMDs are an inexpensive tool especially for certain areas like the Mediterranean region where the silvicultural practice has to be enacted under critical budget constraints (Valbuena et al., 2008).

The main principle of any SDMD based on the stand self-thinning rule, SDMDs are defined as empirical models at stand level which graphically represent the temporal relationships among stand density, and different stand variables such as quadratic mean diameter, dominant height and mean tree volume (Farnden, 1996; Newton, 1997).

This size-density relationship is a cornerstone for the establishment of those diagrams by characterizing the growing stock, using indices that relate the average tree size (e.g. diameter, volume, or height) to the number of trees per hectare(Barrio-Anta & Alvarez-González 2005). Among these density indices which based on size-density relationships, Reineke’s stand density index (SDI) (Reineke, 1933) was used the most (e.g. Shaw and Long, 2007; Valbuena et al., 2008; Vanderschaaf and Burkhart, 2012; Quiñonez-barraza et al., 2018). Moreover Reineke index is more accurate in Mediterranean pine forests than Hart index (Rodríguez et al. 2008). SDI can be computed based on number of trees per unit area and one of the following stand attributes: quadratic mean diameter, mean stem volume, mean stand height or stand basal area. However, Burkhart (2013) reported that SDI calculated using quadratic mean diameter performed best in comparison with the other stand attributes.

Practically, SDMDs are used to defined initial planting spacing or thinning interventions, consequently to meet various management objectives, which include but not be limited to, increasing stand stability and decreasing crown fire risk (López-Sánchez and Rodríguez-Soalleiro, 2009), creating and conserving habitat for wildlife endangered species (Shaw and Long 2007). reducing vulnerability to beetles attacks (Anhold et al. 1996; Long and Shaw, 2005), optimizing stand density for timber production purposes at rotation age (Cabrera-Pérez et al., 2019).

SDMDs have been developed worldwide for a broad set of species, which varied between broad-leaved and conifer species. However most of them were focused monoculture stands: *Quercus robur* (Barrio Anta and Álvarez González, 2005), *Pinus banksiana* (Sharma and Zhang, 2007), *Pinus palustris* (Shaw and Long 2007), *Pinus halepensis* and *Pinus pinaster* (Valbuena et al., 2008), *Pinus radiata* (Castedo-Dorado et al., 2009), *Picea abies* (Vacchiano et al., 2013), *Cunninghamia lanceolata* (Tang et al., 2015), *Eucalyptus grandis* (Marangon et al., 2017), *Castanea sativa* (Patrício and Nunes 2017). While there are very few SDMDs for mixed-species forests: *Abies balsamea*, *Picea rubens*, *Picea mariana* and *Picea glauca* forests in northeastern North America (Swift et al., 2007), *Juniperus procera* and *Podocarpus falcatus* natural mixed forest in Ethiopia (Tesfaye et al., 2016) or *Pinus-Quercus* natural mixed forests in Mexico (Cabrera-Pérez et al., 2018).

According to the State of Europe's Forests 2015 Report, the forested lands with a single tree species dropped over the last 15 years at a rate of about 0.6% annually, while mixed stands cover is estimated to be about 19% of European forest area. In Spain about 19% of the forested areas are mixed forests which are around 3.5 million hectares, in the form of broadleaf-broadleaf or broadleaf-conifer species, which is mostly composed of *Pinus-Fagus sylvatica* or *Pinus-Quercus* species (MAGRAMA, 2012).

For the time being, forest management is paying more attention to have measures and strategies aimed at increasing the resistance, resilience, and adaptability against disturbances to forest ecosystems (Puettmann et al., 2015). This new tendency gives priority to safeguarding a wide variety of ecosystem services within the framework of sustainability by adopting the species mixing principle as an option of adaptive forest management (Ammer, 2016). In this context, it is becoming increasingly worthwhile for mixed-species forests to play a significant role in reinforcing ecosystem functions and services, consequently enhancing the contribution to climate change mitigation and adaptation, and the conservation of biodiversity.

Mixed forests in comparison with monoculture forests have favorable effects on various ecosystem services at higher levels, including production (Gamfeldt et al., 2013). Moreover, they have more resistance to natural disturbance factors (Jactel et al., 2017), and species mixing can positively influence the stability of productivity (del Río et al 2017). All these demonstrate the widely-known multifunctionality of the mixed forests (Van Der Plas et al., 2016).

While there is a growing interest in mixed-species forests, there is still a lot of room for research in this area. Specifically, studies which focus on comparing mixed stands and monoculture stands in similar stands, making these discussions mostly theoretical (Pretzsch 2009a).

In the Mediterranean basin, it is known that forests are characterized by low productivity. While there are studies that analyse intra- and inter- specific interactions from a productivity stance (Piotto et. al 2004; Kuehne et al. 2013; Vanclay et al. 2013), there is a dearth of information about different ecosystems like Mediterranean forests or species in terms of a low productivity standpoint.

This gives rise to the important endeavour of producing additional data and information for forest managers using evidence-based silivicultural procedures (Coll et al., 2018).

Scots pine(*Pinus sylvestris* L.) and Maritime pine (*Pinus pinaster* Ait.) are two of the important coniferous species in Europe and in the Mediterranean basin. Where *P. sylvestris* is widely distributed over the Eurasian continent (Mátyás and Samuel 2004), while *P. pinaster* occurs in the western Mediterranean Basin, and the Atlantic coast in Spain, Portugal, and France, and currently it is used for forestation even outside its natural distributions (EUFORGEN 2011).

The wood of *P. sylvestris*, with its good mechanical properties, is commercially significant due to its industrial use as timber for construction and pulpwood (Mátyás and Samuel 2004). On the other hand *P. pinaster* has a traditional use in resin tapping in addition to its uses in afforestation programs for wood production or soil protection, due to its high drought tolerance for long periods and its capability to grow in poor soil (EUFORGEN 2011).

In Spain, *P. sylvestris* has an area of 1.20 million hectares, and it grows mostly in montane climates: 800-2000 m.a.s.l., 600-1200 mm mean annual precipitation and summer precipitation above 100 mm. While *P. pinaster* has 0.68 million hectares and it grows in sub-humid and continental Mediterranean climates: 600-1300 m.a.s.l., 400-800 mm mean annual precipitation and 20-125 mm summer precipitation. *P. sylvestris* and *P. pinaster* occur in natural and afforested stands, either mixed or pure stands (Serrada et al., 2008). Co-existing pine species occur as well in Spain, with a forest cover of 0.5 million ha (Montero and Serrada, 2013), where both of these species are co-existing in mixed stands, distributed in an area of around 120000 hectares of moderate slopes, mainly in the Iberian and Central Mountain Range (Riofrío et al., 2018). These mixed stands occur at different altitude levels ranging from less than 400 m up to 2000 m, where the largest areas are at 1000-1200 m, 800-1000 m, and 200-1400 m, representing 44.3%, 22.6%, and 16.3% respectively of the total area of *P.sylvestris-P.pinaster* mixed stands (Cañellas et al. 2000). In terms of productivity, *Pinus pinaster* comes first exceeding 500000 m^3 of stock, while *P.sylvestris* and *P.pinea* have the second highest production with 300000 m^3 (Alberdi et al., 2017).

The silvicultural treatments for *Pinus pinaster* in mountain pine forests of the Iberian system include the seed-tree method as a regeneration cut type as it increases timber production possibilities, consequently increasing the profitability of the mountains (Serrada, 2004). The pre-commercial thinning treatments are applied at a maximum of two times, the first one at the age of 6-10 years while the second one at 10-15 years old, to get in the end a density of 1500-2000 trees per hectare and not higher than 2500 trees per hectare. In Spanish regions which have a significant presence of *Pinus sylvestris* these pre-commercial thinnings are applied later, until 15-20 years old (Rodríguez et al. 2008). Commercial thinning depends on different factors like initial density, site quality, and management objectives and it usually starts at 20 years old. For timber production objective at the end of the rotation period, 4 low thinning with 10-years intervals are applied to reach target densities of 250 to 300 trees per hectare, where 25 to 35 % of the basal area can be removed (Rodríguez et al. 2008), in some cases, the first commercial thinning can be postponed to 30 or 40 years (JCYL, 2003).

For *Pinus sylvestris*, the pre-commercial thinning treatments are usually applied when stands are at the age of 15-25 years old. Either low thinning or mixed thinning by felling the subdominant and co-dominant trees can be used for commercial thinning treatment, which should be carried out between 20 and 40 years old with around 10-years intervals, by removing 40% of the basal area at maximum in stands of lower altitudes, while in other sites a moderate intensity is recommended to avoid wind and snow damages (Cañellas et al. 2000).

The rotation period for *Pinus sylvestris-Pinus pinaster* mixed stands is about 100 years, particularly in mountain pine forests of Soria and Burgos (Rodríguez et al. 2008).

2.-OBJECTIVES

From the perspective of the current highly valuable and recognized role of mixed-species forests in ecosystem functions and services, and out of a lack of efficient tools and models in quantitative silviculture for mixed stands such as SDMDs. Thus, the main objective of this study is to develop SDMDs for *Pinus sylvestris* and *Pinus pinaster* mixed-stands in The *Sierra de la Demanda*. A secondary objective is to study the behavior of *Pinus sylvestris* and *Pinus pinaster* in mixed stands.

This SDMD would be an efficient and cost-effective tool in the hands of forest managers in order to schedule thinnings interventions, improve tree growth, and consequently maximize stands productivity.

3.- MATERIAL AND METHODS

3.1. Study site

The *Sierra de la Demanda* is an elongated mountainous massif bounded by three provinces. Rising in the extreme northwest of the Iberian system, it’s west is bordered by the province of Burgos, to its south is Soria and to its east is La Rioja. Its terrain is also surrounded by three mountain ranges: The Sierra de San Millán, Mencilla and Neila (Figure 1).

Since the area is mountainous, the average elevation of the area is around 2000 meters above sea level. The mountain range covers 2000 km^2 of land. Its highest peak is the summit of San Millán (2131m). The distance from its northernmost point (Villafranca Montes de Oca) to its southern tip (La Gallega) is 75km while from its westernmost tip (Covarrubias) to its easternmost (Monterrubio de la Demanda) is 64km.

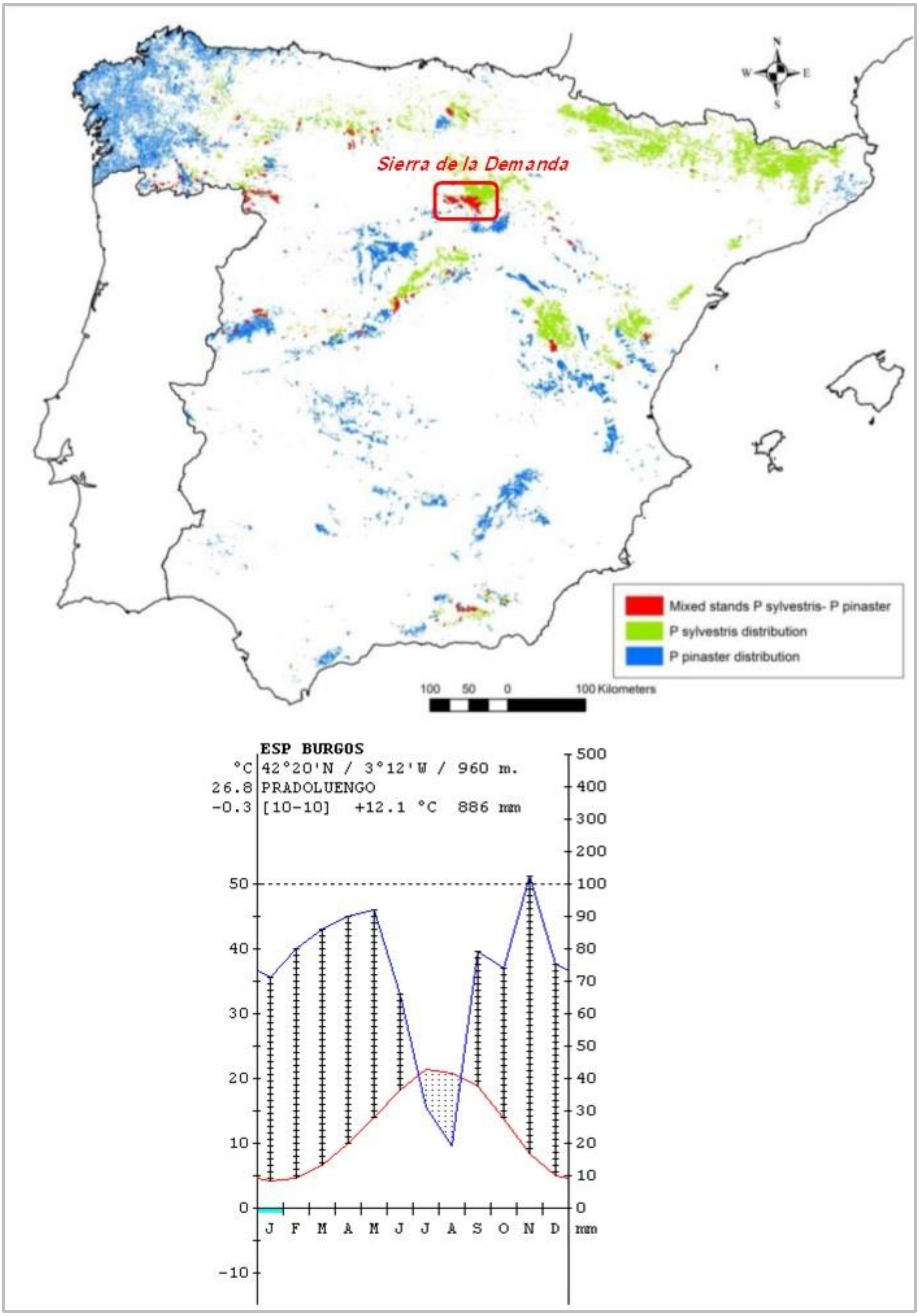


Figure 1: Study area (*Sierra de la Demanda)* (Adopted from Riofrío et al., 2018), Climodiagram from Rivas-Martínez and Rivas-Sáenz (1996–2009)

The potential vegetation is very degraded, mostly as a result of anthropic action. Despite this, the beech in the high zones and the oak in the lowlands, with ash, rowan, holly and yew trees found across them, stand out in the mountain range. Reforestation efforts have introduced several species of pine, namely Scots pine (*Pinus sylvestris*), Maritime pine (*Pinus pinaster*), Black pine (*Pinus nigra*) and Mountain pine (*Pinus uncinata*).

Scots pine (*Pinus sylvestris*) forests cover 296.02 km^2 of land (about 19.19% of the total forest cover) while Maritime pine (*Pinus pinaster*) cover only 20.57 km^2 of land (about 1.06% of the total forest cover) (Agalsa 2006).

Its climate is characterized as Continental Mediterranean but owing to its elevation, it experiences long, cold winters and short, cool summers. Average total annual precipitation, according to data from the Meteorological Station in Pradoluengo from 1990-2006, is at 746.9 mm with a high of 87.19 mm in November and a low of 36.16 mm of rainfall in February. Temperatures range from annual isotherms of 3.48 °C to 18.78 °C (Agalsa 2006).

3.2. Data

Data from the third Spanish National Forest Inventory (SNFI3) (1997– 2007) was extracted as a primary input for the purpose of developing an SDMD for *Pinus sylvestris* and *Pinus pinaster* mixed stands in the *Sierra de la Demanda*, all mixed and pure plots of both species in Spain from NFI are shown in (Figure 2). Mixed plots where defined based on the criterion of the combined proportion of basal area for both species accounted for at least 90% of the total, while the proportion of each species in the mixed plots was higher than 15% (Riofrío et al., 2016). A total of 210 mixed plots were analyzed, main plots characteristics are summarized in Table 1.

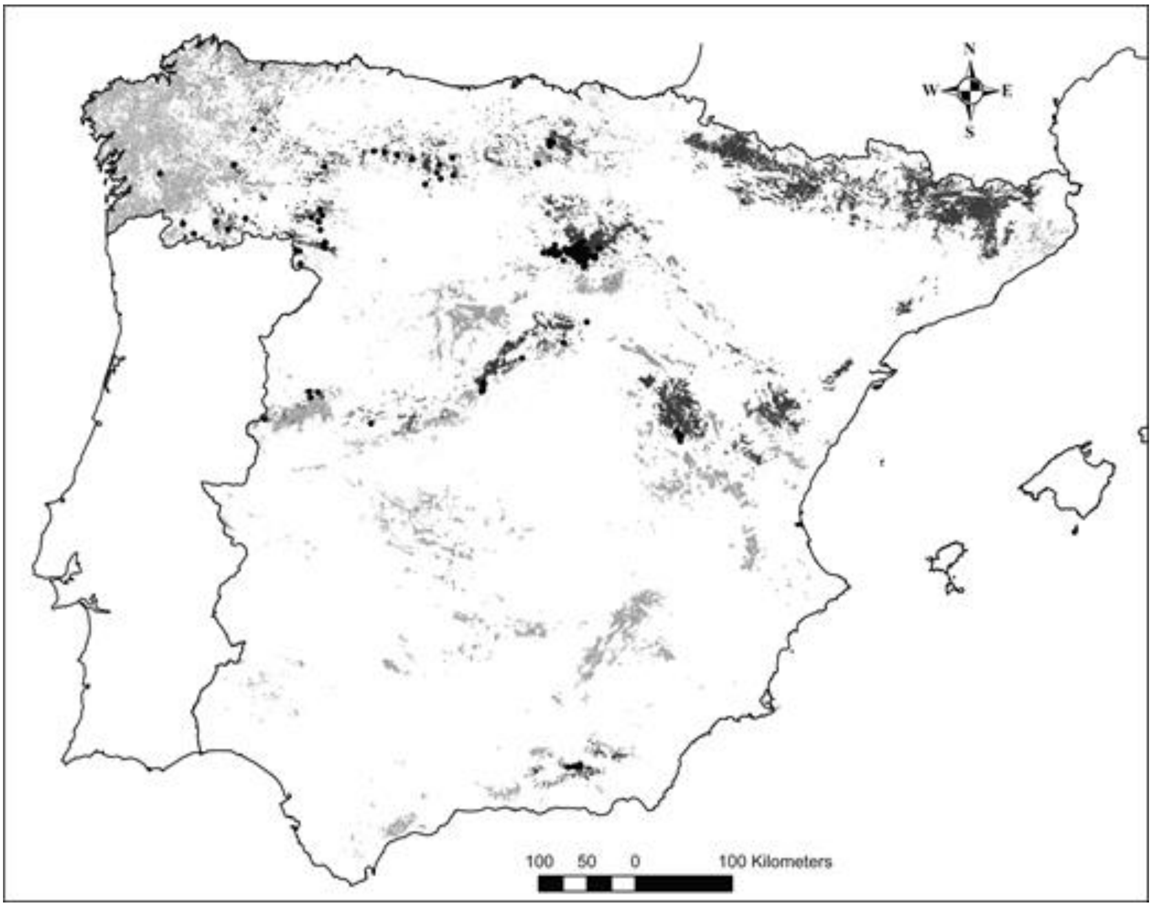


Figure 2: Location of mixed and pure plots from NFI (black dots) (Adopted from Riofrío et al., 2016).

The Spanish national forest inventory (SNFI) is the main open and large-scale data source for national assessments at the Spanish level, as it provides robust and objective statistics and information on the state and evolution of forests, making it a highly reliable and solid foundation in order to conduct a various set of leading studies at national and regional levels, thereby enabling more efficient and effective decision making. The plots of (SNFI) are permanent plots systematically distributed on UTM square grids with a resolution of 1km by 1km each. The plots are re-measured in approximately 10-year intervals. Each plot is composed of four circular concentric subplots with radii of 5, 10, 15, and 25 meters. For trees in the 5m circle, trees with a diameter (DBH) that exceed 7.5cm are taken into account; in the 10m subplot, those that exceed 12.5cm; for trees in the 15m circle, those greater than 22.5cm; and lastly, in the 25m subplot, those that exceed than 42.5cm. Variables that are taken into account include height (h), species, and distance and azimuth of trees measured from plot center. Forest type, erosion factors, anthropogenic activity, tree damage, shrub species, cover (in the 10m subplot), and plot identification are other data recorded from the concentric subplots (Figure 3). The caliper was used to measure tree diameter, by taking two diameter measurements at right angles to each other.

Different variables are necessary to develop an SDMD: quadratic mean diameter (QMD), dominant height (Ho), total stand volume (V), number of trees per hectare (tree density) (N), and stand density index (SDI).

The total stand volume, quadratic mean diameter (QMD), and tree density (N) were estimated using three different functions from the Package 'basifoR' (Lara et al., 2019).

The function "nfiMetrics" helps to derive tree-level metrics required to compute over bark volumes, according to parameters of (SNFI), the output metric units of this function are the mean diameter (DBH) in mm, the tree height (H) in dm, basal area (G) in m^2 $tree^{-1}$, and the expansion factor (exp.fact) in order to convert later the data into hectare. The second function "metrics2Vol" computes over bark volumes in dm^3 at tree-level.

While the function "dendroMetrics" transforms the tree-level dendrometrics derived by the first two functions to stand units, consequently this function summarizes the following variables: tree basal area (G) in m^2 ha^{-1}, average diameter (DBH) in cm, quadratic mean diameter (QMD) in cm, average tree height (H) in m, the number of trees per hectare (tree density) (N), and the over bark volume (V) in m^3 ha^{-1}.

The dominant height was calculated according to the criterion of Assmann, which is the definition most widely used in Spain (Mandojana, 1999), where it considers the dominant height as the height corresponding to the tree that presents the average height of the 100 thickest trees per hectare (Assmann, 1970). The following formula was used:

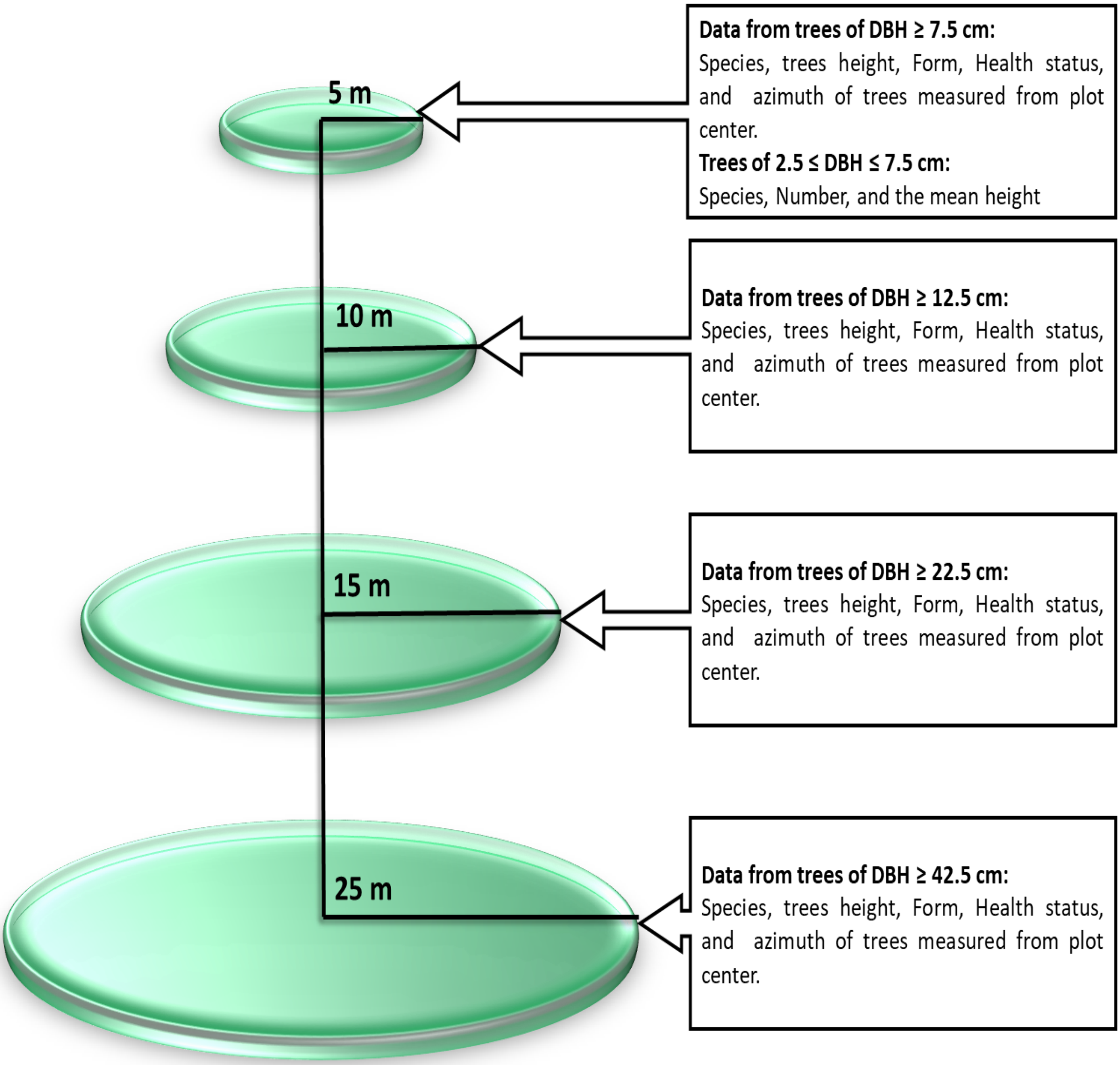
$$Ho = \frac{\sum_{i=1}^{n} H_i}{100}$$

where:

Ho: dominant height (m)

H: tree total height (m)

i: from 1 to 100 of thickest trees



Data from trees of DBH ≥ 7.5 cm: Species, trees height, Form, Health status, and azimuth of trees measured from plot center.
Trees of 2.5 ≤ DBH ≤ 7.5 cm: Species, Number, and the mean height

Data from trees of DBH ≥ 12.5 cm: Species, trees height, Form, Health status, and azimuth of trees measured from plot center.

Data from trees of DBH ≥ 22.5 cm: Species, trees height, Form, Health status, and azimuth of trees measured from plot center.

Data from trees of DBH ≥ 42.5 cm: Species, trees height, Form, Health status, and azimuth of trees measured from plot center.

Figure 3: Spanish National Forest Inventory plot design and main data measured in each subplot of sampling plot.

Due to the NFI design, trees are considered in different subplots depending on their DBH so the 100 thickest trees should be defined using the expansion factors. At the first time the thickest 20 trees can be considered because the biggest subplot is 25 meters' radius but it is not correct. Each tree means a different number of trees per hectare, accordingly to each subplots, it means, the expansion factor. Moreover, exactly 100 trees should be considered so the number of trees per NFI plot varies for each estimation. For this reason, the following formula derived from Assmann formula was used to calculate the dominant height:

$$Ho = \frac{\sum_{i=1}^{n} H_i \times \mathrm{exp}fact}{100}$$

where:

expfact: expansion factor

n: number of thickest considered trees, this value can vary depending on each NFI plot

Detailed explanation about the process of calculating dominant height in one example plot is shown in (Figure 4).

Reineke's index (SDI) was used as a stand density index equation [1]. The optimal density-growth interval was determined by upper and lower growing stock limits, where the upper limit intended to avoid trees mortality caused by competition due to high trees density, and it was defined by 60% of maximum SDI found for both species (Dean and Baldwin, 1993), while the lower limit was defined by 35% of maximum SDI aiming to ensure adequate site occupancy (Long, 1985).

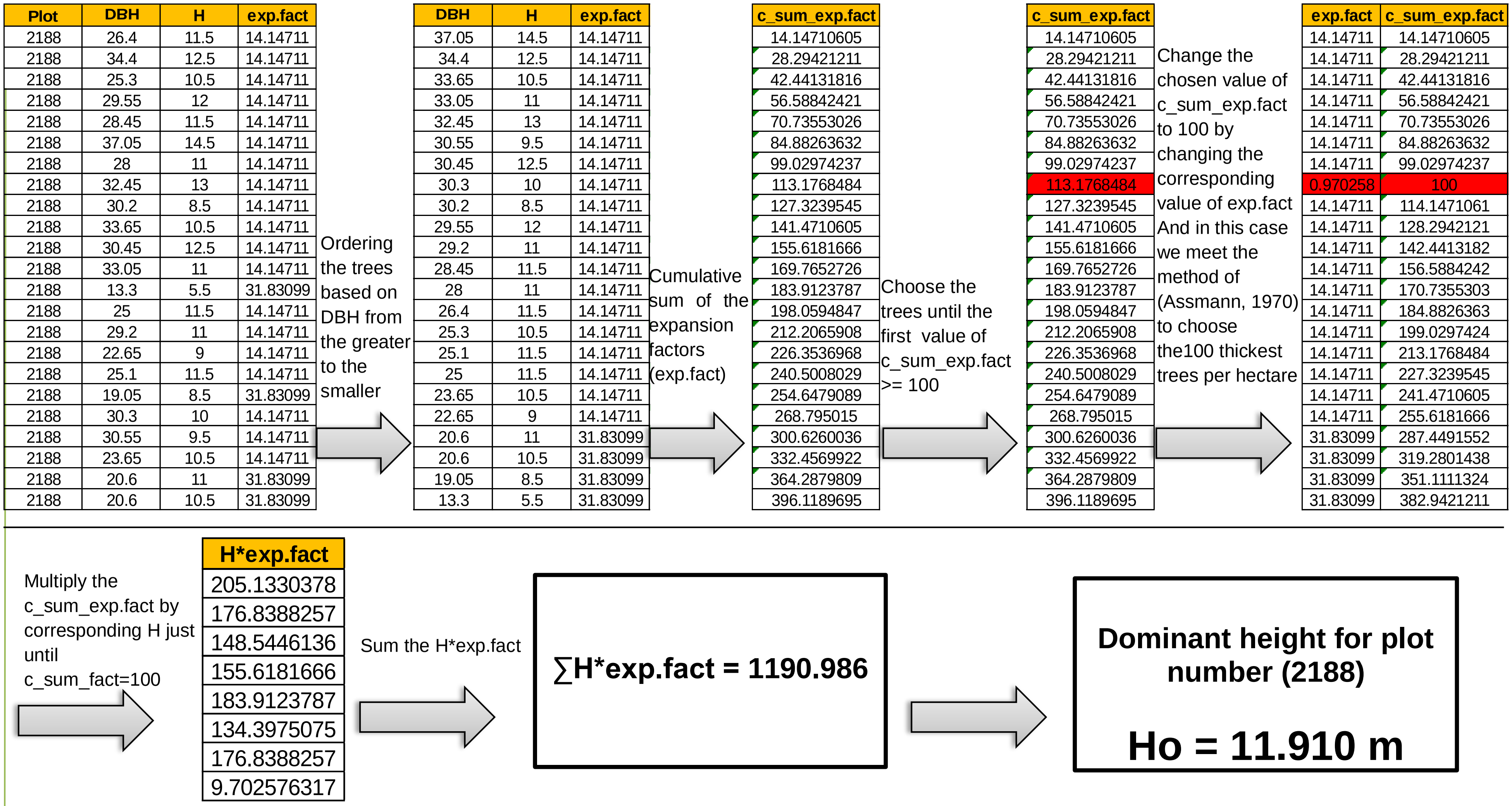
$$SDI = N\left(\frac{QMD}{25.4}\right)^{1.605}$$

where:

SDI: Reineke's stand density index

N: the number of trees per hectare

QMD: quadratic mean diameter (cm)



Plot	DBH	H	exp.fact
2188	26.4	11.5	14.14711
2188	34.4	12.5	14.14711
2188	25.3	10.5	14.14711
2188	29.55	12	14.14711
2188	28.45	11.5	14.14711
2188	37.05	14.5	14.14711
2188	28	11	14.14711
2188	32.45	13	14.14711
2188	30.2	8.5	14.14711
2188	33.65	10.5	14.14711
2188	30.45	12.5	14.14711
2188	33.05	11	14.14711
2188	13.3	5.5	31.83099
2188	25	11.5	14.14711
2188	29.2	11	14.14711
2188	22.65	9	14.14711
2188	25.1	11.5	14.14711
2188	19.05	8.5	31.83099
2188	30.3	10	14.14711
2188	30.55	9.5	14.14711
2188	23.65	10.5	14.14711
2188	20.6	11	31.83099
2188	20.6	10.5	31.83099

Ordering the trees based on DBH from the greater to the smaller

DBH	H	exp.fact
37.05	14.5	14.14711
34.4	12.5	14.14711
33.65	10.5	14.14711
33.05	11	14.14711
32.45	13	14.14711
30.55	9.5	14.14711
30.45	12.5	14.14711
30.3	10	14.14711
30.2	8.5	14.14711
29.55	12	14.14711
29.2	11	14.14711
28.45	11.5	14.14711
28	11	14.14711
26.4	11.5	14.14711
25.3	10.5	14.14711
25.1	11.5	14.14711
25	11.5	14.14711
23.65	10.5	14.14711
22.65	9	14.14711
20.6	11	31.83099
20.6	10.5	31.83099
19.05	8.5	31.83099
13.3	5.5	31.83099

Cumulative sum of the expansion factors (exp.fact)

c_sum_exp.fact
14.14710605
28.29421211
42.44131816
56.58842421
70.73553026
84.88263632
99.02974237
113.1768484
127.3239545
141.4710605
155.6181666
169.7652726
183.9123787
198.0594847
212.2065908
226.3536968
240.5008029
254.6479089
268.795015
300.6260036
332.4569922
364.2879809
396.1189695

Choose the trees until the first value of c_sum_exp.fact >= 100

c_sum_exp.fact
14.14710605
28.29421211
42.44131816
56.58842421
70.73553026
84.88263632
99.02974237
113.1768484
127.3239545
141.4710605
155.6181666
169.7652726
183.9123787
198.0594847
212.2065908
226.3536968
240.5008029
254.6479089
268.795015
300.6260036
332.4569922
364.2879809
396.1189695

Change the chosen value of c_sum_exp.fact to 100 by changing the corresponding value of exp.fact And in this case we meet the method of (Assmann, 1970) to choose the100 thickest trees per hectare

exp.fact	c_sum_exp.fact
14.14711	14.14710605
14.14711	28.29421211
14.14711	42.44131816
14.14711	56.58842421
14.14711	70.73553026
14.14711	84.88263632
14.14711	99.02974237
0.970258	100
14.14711	114.1471061
14.14711	128.2942121
14.14711	142.4413182
14.14711	156.5884242
14.14711	170.7355303
14.14711	184.8826363
14.14711	199.0297424
14.14711	213.1768484
14.14711	227.3239545
14.14711	241.4710605
14.14711	255.6181666
31.83099	287.4491552
31.83099	319.2801438
31.83099	351.1111324
31.83099	382.9421211

Multiply the c_sum_exp.fact by corresponding H just until c_sum_fact=100

H*exp.fact
205.1330378
176.8388257
148.5446136
155.6181666
183.9123787
134.3975075
176.8388257
9.702576317

Sum the H*exp.fact

∑H*exp.fact = 1190.986

Dominant height for plot number (2188)

Ho = 11.910 m

exp.fac: Expansion factor represents the number of trees per hectare, and as trees are considered in different subplots depending on their DBH we have the following expansion factors:

exp.fac = 5.092958: subplot of 25 m radius, trees with a DBH ≥ 42.5 cm are measured
exp.fac = 14.14711: subplot of 15 m radius, trees with a DBH ≥ 22.5 cm are measured
exp.fac = 31.83099: subplot of 10 m radius, trees with a DBH ≥ 12.5 cm are measured
exp.fac = 127.324: subplot of 5 m radius, trees with a DBH ≥ 7.5 cm are measured

Figure 4: Dominant height calculation process

Table 1: Summary of the data set used to develop SDMD for *Pinus sylvestris and Pinus pinaster* mixed stands in the *Sierra de la Demanda*

Attributes (Variable)	**Mean**	**Minimum**	**Maximum**	**Standard desviation (SD)**
		n = 210		
DBH	24.92	9.13	45.28	8.00
QMD	26.43	9.19	48.22	8.00
H	12.95	4.70	22.88	4.00
Ho	15.78	6.50	26.17	3.84
N	741.30	101.29	3338.72	493.85
V	301.47	12.27	977.69	162.43
G	34.32	2.53	81.98	15.49
SDI	669.19	74.66	1712.22	289.47

n: total number of plots, DBH: average diameter at breast height (cm), QMD: quadratic mean diameter (cm), H: average tree height (m), Ho = dominant height (m), N: the number of trees per hectare, V: the over bark volume (m^3 ha^{-1}), G: basal area (m^2 ha^{-1}), SDI: Reineke's stand density index.

3.3. Model structure and statistical methods

The aimed SDMD model has the following fundamental components:

- Reineke's stand density index
- An allometric system of two linear equations [1] and [2]

$$\ln QMD = \beta 0 + \beta 1 . \ln N + \beta 2 . \ln Ho \quad \textbf{[1]}$$

$$\ln V = \beta 3 + \beta 4 . \ln QMD + \beta 5 . \ln Ho + \beta 6 . \ln N \quad \textbf{[2]}$$

where:

QMD: quadratic stem diameter (cm)

N: stand density (tree ha^{-1})

Ho: dominant height (m)

V: stand total volume (m^3 ha^{-1})

βi: regression coefficients

Equation [1] relates the quadratic mean diameter with stand density, and dominant height, while equation [2] relates the over bark volume with the quadratic mean diameter, dominant height, and stand density.

Ln QMD and Ln V are instrumental and dependent endogenous variables, while Ln Ho and Ln N are independent exogenous variables, but as Ln QMD is defined independently of the system in equation [2], so it is considered as an independent exogenous variable. As a consequence, the two equations were fit simultaneously to prevent error correlation.

In order to test mixing effect on QMD and V two models were developed from [1] and [2] by taking mixture proportions into account, in this regard a new variable (mixfrac) represents mixing degree was introduced into both equations [3] and [4] (Swift et al., 2007).

$$\ln QMD = \beta0 + \beta1.mixfrac + (\beta2 + \beta3.mixfrac).\ln N + (\beta4 + \beta5.mixfrac).\ln Ho$$ **[3]**

$$\ln V = \beta6 + \beta7.mixfrac + (\beta8 + \beta9.mixfrac).\ln QMD + (\beta10 + \beta11.mixfrac).\ln Ho + (\beta12 + \beta13.mixfrac).\ln N$$ **[4]**

Where:

$$mixfrac = 0.5 - |(sylfrac - 0.5)|$$

$$sylfrac = \frac{P.sylvestris\ basal\ area}{Total\ basal\ area}$$

The simultaneous fitting of the equations and the statistical analyses were done using the R (R Development Core Team 2019) (Annex 1).

SDMD was constructed using the format described by Barrio-Anta and Álvarez González (2005), with quadratic mean diameter (QMD) and density (N) on the major axes. QMD was represented on the (x) axis as a logarithmic scale, while N was represented on the (y) axis as a logarithmic scale too. Then isolines representing dominant height (Ho), over bark volume (V), and Reineke's stand density index (SDI) were superimposed on the bivariate graph.

4.- RESULTS

4.1. Models fitting and statistical analysis:

The results from the simultaneous fitting of equations [3] and [4] to estimate quadratic mean diameter and total stand volume, show that the coefficients of the mixture degree variable (mixfrac) were not significant at a 0.05 significance level, the coefficients estimated are presented in Table 2.

Validation statistics of simultaneous fitting of the two equations system are shown in Table 3, where R- squared (R^2) was 0.8376 for ln QMD equation, while it was quite high 0.9504 for ln V equation.

Table 2: Coefficients resulted from the simultaneous fitting of the equations [3] and [4] to estimate QMD and V for *Pinus sylvestris* and *Pinus pinaster* mixed stands.

Coefficients of regression		
Parameter	**Estimate**	**Pr(>|t|)**
QMD equation [3]		
β0 (Intercept)	2.66935	< 2e-16
β1	0.61017	0.5484
β2	-0.23221	2.4e-16
β3	-0.23966	0.0239
β4	0.76750	< 2e-16
β5	0.24811	0.3356
V equation [4]		
β6 (Intercept)	-7.96060	< 2e-16
β7	-1.13565	0.559
β8	1.85251	< 2e-16
β9	0.47175	0.374
B1	0.77648	1.05e-08
β11	-0.64931	0.217
β12	0.84664	< 2e-16
β13	0.19217	0.341

Table 3: Validation statistics of simultaneous fitting of the equations [3] and [4] to estimate QMD and V for *Pinus sylvestris* and *Pinus pinaster* mixed stands.

Equation	**Value**
QMD equation [3]	
RSE on 204 degrees of freedom	0.133
R^2	0.8376
Adjusted R^2	0.8336
p-value	< 2.2e-16
V equation [4]	
RSE on 202 degrees of freedom	0.1536
R^2	0.9504
Adjusted R^2	0.9487
p-value	< 2.2e-16

The mixture degree variable (mixfrac) was eliminated and another run of simultaneous fitting of the initial system of equation represented by equation [1] and [2] was done to estimate quadratic mean diameter and total stand volume, the results show that all the coefficients were quite significant at a 0.05 significance level, the coefficients estimated are presented in Table 4.

Validation statistics of simultaneous fitting of the two equations system are shown in Table 5, where R- squared (R^2) was 0.8376 for ln QMD equation, while it was quite high 0.9504 for ln V equation.

Table 4: Coefficients resulted from the simultaneous fitting of the equations [3] and [4] to estimate QMD and V for *Pinus sylvestris* and *Pinus pinaster* mixed stands.

Coefficients of regression		
Parameter	**Estimate**	**Pr(>|t|)**
QMD equation [1]		
β0 (Intercept)	2.73396	<2e-16
β1	-0.27044	<2e-16
β2	0.81594	<2e-16
V equation [2]		
β3 (Intercept)	-8.28660	< 2e-16
β4	1.98235	< 2e-16
β5	0.62759	9.69e-15
β6	0.89051	< 2e-16

Table 5: Validation statistics of simultaneous fitting of the equations [1] and [2] to estimate QMD and V for *Pinus sylvestris* and *Pinus pinaster* mixed stands.

Equation	**Value**
QMD equation [1]	
RSE on 207 degrees of freedom	0.1393
R^2	0.8191
Adjusted R^2	0.8173
p-value	< 2.2e-16
V equation [2]	
RSE on 206 degrees of freedom	0.1546
R^2	0.9488
Adjusted R^2	0.948
p-value	< 2.2e-16

Thus, the two linear models [1] and [2] exhibit efficient goodness-of-fit statistics, as R2 values were high, making it the appropriate choice to develop the aimed Stand Density Management Diagram.

Eventually, the two adjusted linear models to estimate quadratic mean diameter and total stand volume for *Pinus sylvestris-Pinus pinaster* mixtures in the *Sierra de la Demanda* were:

$$\ln QMD = 2.73396 - 0.27044. \ln N + 0.81594. \ln Ho \quad \textbf{[5]}$$

$$\ln V = -8.28660 + 1.98235. \ln QMD + 0.62759. \ln Ho + 0.89051. \ln N \quad \textbf{[6]}$$

where:

QMD: quadratic stem diameter (cm)

N: stand density (tree ha^{-1})

Ho: dominant height (m)

V: stand total volume (m^3 ha^{-1})

4.2. SDMD for *Pinus sylvestris-Pinus pinaster* mixed stands:

An SDMD for the mixed stands of *Pinus sylvestris* and *Pinus pinaster* in the *Sierra de la Demanda* was constructed using the data extracted from the Spanish national forest inventory, equation [5], equation [6] and the formula of Reineke's stand density index (Figure 5). Where quadratic mean diameter (QMD) and density (N) were plotted on (x) axis and (y) axis respectively as logarithmic scales. QMD ranged between 9 and 48 cm, and N ranged between 100 and 3500 tree per hectare, minimum and maximum values of data range. While the isolines of: dominant height (Ho) (in red), total volume (V) (in blue), and Reineke's index (SDI) (in green) were superimposed on the bivariate graph. The islolines in bold green represent the upper and lower growing stock limits and they are 60% of maximum SDI for the upper limits (Dean and Baldwin, 1993) and 35% of maximum SDI for the lower limit (Long, 1985). Optimal density levels should be found between these limits, it means, both bold green lines. Values above the maximum limit means silvicultural treatments like a thinning should be done and values below the minimum limit means density is inadequate.

5.- DISCUSSION

The value of the stand density management diagram developed in this study for *P.sylvestris–P.pinaster* mixed stands, emerges from the new current orientation of moving further in developing efficient tools and models in quantitative silviculture for mixed stands in order to enhance forest wood and non-wood production and ecosystem functions and services quantitatively and qualitatively, especially in light of lack information about mixed forests combined with raised interest in such forest systems.

Table 6: Silvicultural management alternative showed in Figure 6. N: density (trees ha^{-1}), QMD: quadratic mean diameter (cm), SDI: Reineke's stand density index,V: the over bark volume (m^3 ha^{-1}).

Entry	N (tree ha^{-1})		QMD (cm)		SDI		V (m^3)	
	Before	After	Before	After	Before	After	Before	After
I-II	1700	814.2	21	21	1252.7	600	472.9	210.6
III-IV	814.2	488.5	28.9	28.9	1000	600	505.7	288.5
V (Final cut)	488.5	—	39.7	—	1000	—	692.6	—

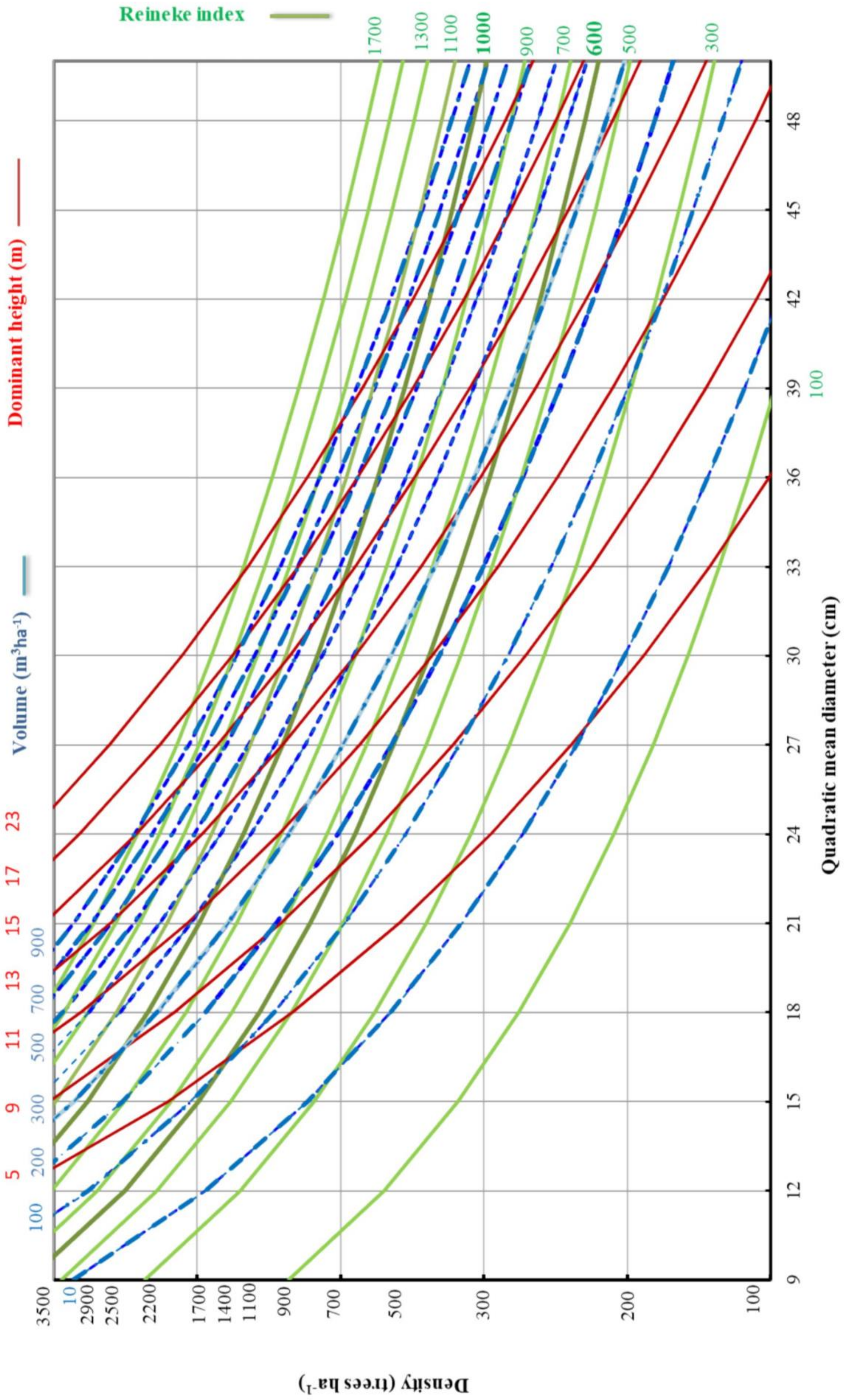


Figure 5: Stand Density Management Diagram for mixed stands of *Pinus sylvestris* and *Pinus pinaster* in the *Sierra de la Demanda*

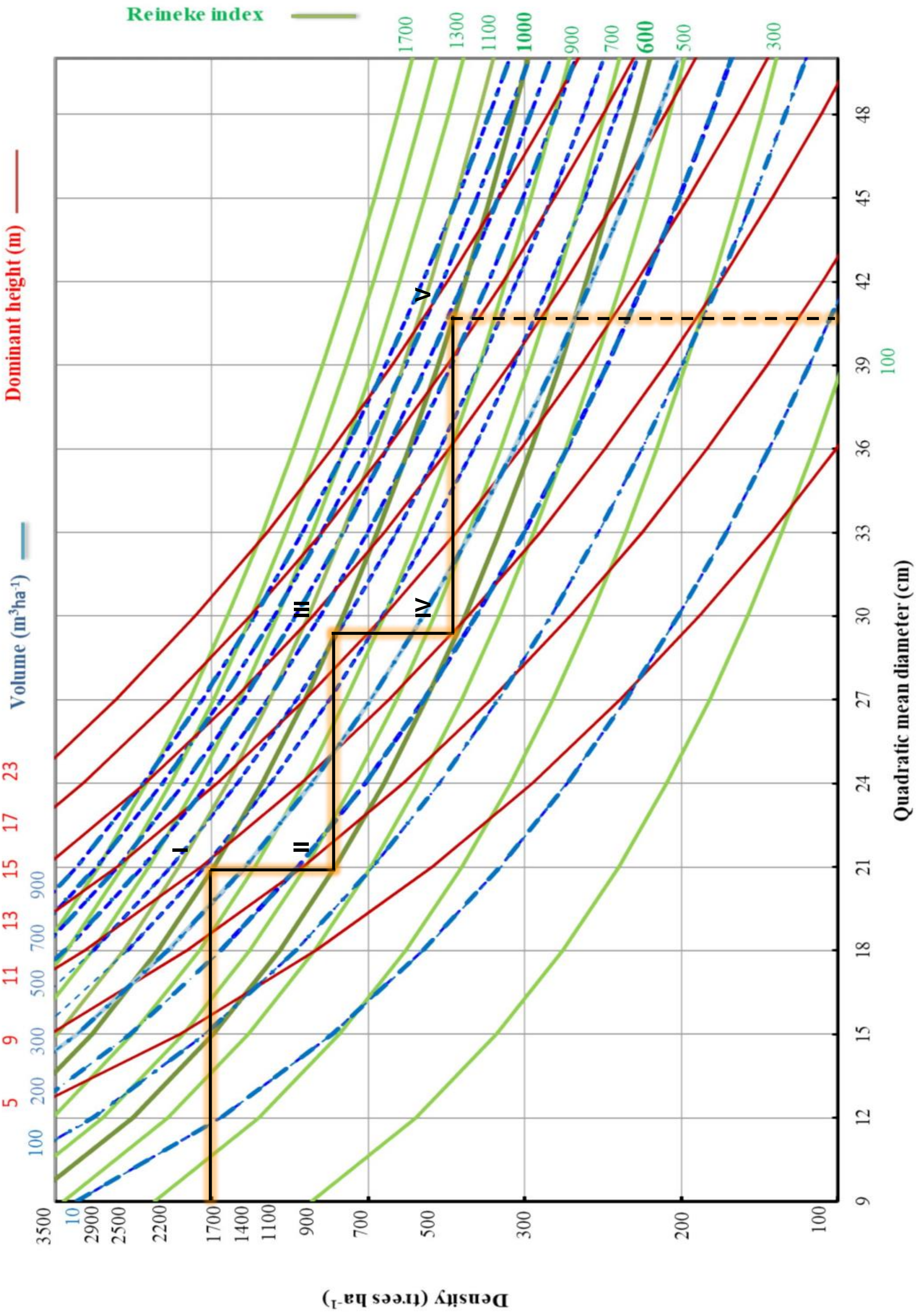


Figure 6: Silvicultural management alternative for mixed stands of *Pinus sylvestris* and *Pinus pinaster* in the *Sierra de la Demanda*

An example of a management alternative in this type of forest is showed in Table 6 and Figure 6. In this case a set of systematic thinning interventions were applied in two times and different intensities (I-II and II-III) and a final cut. The initial density was 1700 trees ha^{-1} and a quadratic mean diameter of 21 cm. The first systematic thinning was applied to obtain a density of 814.2 tree ha^{-1}. Then the stand grew considering no natural mortality until a quadratic mean diameter of 28.9 cm, when the second systematic thinning should be applied. The density decrease from 814.2 trees ha^{-1} to 488.5 trees ha^{-1} after this second thinning. Again the stand grew until a quadratic mean diameter of approximately 40 cm, when the final cut should be applied.

Mixed-species stands as diverse systems: show a greater increment in above-ground woody biomass than pure-species stands (Vilà et al. 2007 ; Paquette and Messier 2011), for example, the annual woody biomass production of mixed stands in the *Alto Tajo* region in Spain, which consist of two pine species (*Pinus sylvestris* and *Pinus nigra*) and two oak species (*Quercus ilex* and *Quercus faginea*), exceed the production of monocultures stands by more than 48% (Jucker et al., 2014). Moreover, mixed stands have a higher level of carbon storage in root system (Brassard et al., 2011), in addition to their role in enriching wildlife taxa (Castagneyrol and Jactel 2012),

Our results showed that introducing a new variable reflects species mixing effects into the system of equations was not significant, while it was significant in other studies and was retained in the models to formulate SDMD (Swift et al., 2007; Tesfaye et al., 2016), indicating that there was no impact of species mixing on stand yield represented by quadratic mean diameter and over bark volume. That is contrary to what Riofrío et al (2018) concluded that at stand level for the two species in mixture stands, there was a shared gain in productivity with respect to varying tree growth responses to inter-specific competition for each species. In another study of mixed stands, but this time the mixture is a combination between *Pinus sylvestris* and *Fagus sylvatica* species, the results were similar to the previous one, where it showed increased productivity in the stands with superior growth of *Pinus sylvestris* than *Fagus sylvatica* growth which was reduced (Pretzsch et al., 2015).

Meaning that the behavior of our two species in mixed stands could be quite similar in term of productivity. Based on that, we led to only fit the system of models that uses stand density and dominant height, and quadratic mean diameter as independent endogenous variables.

These result should not be generalized about various site conditions because of differing productivity relationships on-site. Moreover there is a lack of knowledge for mixed stands although it is increasing during the last years: Pretzsch and Schütze, 2016; Riofrío et al., 2019... Different cases of site–growth relationships in mixed stands can be observed based on different site conditions: In the first case, when the interactions between the two species are absent, the stand mutual gain in productivity would result in a proportional increase of each species, it means the total productivity summarize the productivity of each species individually as in pure stands. In other cases, when there are interactions between both species, the total productivity is not the same than the sum of the individual productivities in pure stands, facilitative or competitive effects affect final productivity (Pretzsch, 2009b). In the present work the interaction between both species is not clear because mixture degree was not significant in the quadratic mean diameter and volume models.

Dominant height is one of the main variables to characterize a forest stand at forest mensuration level. Assmann definition is widely used in Spain to estimate this variable but its estimation presents some inconveniences. One of them is the plot size. Dominant height is defined as the height corresponding to the tree that presents the average height of the 100 thickest trees per hectare. If your plot size is 100 m^2, only one tree is considered to define dominant height (Bengoa 1999). In the case of national forest inventory, plots consist of four circular subplots and minimum measured diameter at breast height is increasing along with subplots. Therefore expansion factors are necessary to know how many trees are representing each tree of NFI plots at hectare level. The number of trees to estimate the Assmann dominant height varies for each plot which complicates its estimation.

6. - CONCLUSIONS

- In the present master thesis a stand density management diagram for *Pinus sylvestris* and *Pinus pinaster* mixed forests from *Sierra de la Demanda* (Spain) has been developed. This diagram could be an easy tool for owners and managers of this region to manage mixed stands using simple variables like dominant height or density.

- Despite the increasing interest in mixed-species forests, due to its recognized role in reinforcing ecosystem functions and services. But as it is a complex system in terms of different mixing effects at different levels, there is still a lack of knowledge and a room for more studies in this area. This complexity of mixing effects is reflected in our results which showed that the interaction between both species is not clear, thus no effects on stand yield. Eventually, to examine the behavior and influences on productivity, further studies should be done by taking into account different levels and scales.

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ANNEX 1 STATSTICAL SCRIPT

```
########################################################################
#### SDMD for mixed stands of Pinus sylvestris and Pinus pinaster #####
####################### in Demandas mountains #########################
########################################################################

### work directory ###
setwd('E:/MScThesis_MEDFOR_UVa/Data/Processed')

################################################
################ Data selection ################
################################################

### Packages and libraries:


install.packages("Hmisc")
install.packages(pkgs='E:/MScThesis_MEDFOR_UVa/Data/
                 Processed/Rbasifor/Rbasifor_0.1.tar.gz', repos = NULL)

library(measurements)
library(Hmisc)
library(RODBC)
# package to extrac and compute variables from Spanish National Forest
Inventory:
library(Rbasifor)
# help(Rbasifor)
library(foreign)

## read tree data from url using Rbasifor:
bu.tree <- readNFI('https://www.mapama.gob.es/es/biodiversidad/
                   servicios/banco-datos-naturaleza/ifn3p09_tcm30-29392
3.zip')
so.tree <- readNFI('https://www.mapama.gob.es/es/biodiversidad/
                   servicios/banco-datos-naturaleza/ifn3p42_tcm30-29398
9.zip')

########################################################################
######################### volume calculation ##########################
########################################################################

### First calculate dendrometric variables to use metics2Vol function:

## Burgos provinces:

bu.de.met <- nfiMetrics(bu.tree) #(Burgos_dendrometric variables)
burgos <- metrics2Vol(bu.de.met)
head(burgos)

# Dendrometrics at plot level:
burgos.p <- dendroMetrics(burgos)
head(burgos.p)
```

```
#######################################################################
### A new coefficient represent the proportions of the species in #####
### the mixed stands (Pinus sylvestris as a reference)(Burgos): #######
#######################################################################

## P.sylvestris basal area (tree level)(m^2/tree)

bu.bas.P.syl<- burgos[burgos$Especie=="21",]

# P.sylvestris basal area per ha (tree level)(m^2/ha)
bu.bas.P.syl <- dendroMetrics(bu.bas.P.syl)
names(bu.bas.P.syl)[names(bu.bas.P.syl) == "ba"] <- "p.syl_ba"
bu.bas.P.syl$prv_plot  <- with(bu.bas.P.syl, paste(pr, Estadillo, sep='
_'))
head(bu.bas.P.syl)

#######################################################################
## Soria provinces:
so.de.met<- nfiMetrics(so.tree) #(Soria_dendrometric variables)
soria <- metrics2Vol(so.de.met)
head(soria)

# Dendrometrics at plot level:
soria.p <- dendroMetrics(soria)
head(soria.p)

#######################################################################
### A new coefficient represent the proportions of the species in #####
### the mixed stand (Pinus sylvestris as a reference)(Soria): #########
#######################################################################

## P.sylvestris basal area (tree level)(m^2/tree)

so.bas.P.syl<- soria[soria$Especie=="21",]

# P.sylvestris basal area per ha (tree level)(m^2/ha)
so.bas.P.syl <- dendroMetrics(so.bas.P.syl)
names(so.bas.P.syl)[names(so.bas.P.syl) == "ba"] <- "p.syl_ba"
so.bas.P.syl$prv_plot  <- with(so.bas.P.syl, paste(pr, Estadillo, sep='
_'))
head(so.bas.P.syl)

###########################################################
###### Dominant height calculation #######################
###########################################################

### Burgos:

bu.test<- nfiMetrics(bu.tree) #(Burgos_dendrometric variables)

head(bu.test)
bu.syl<- bu.test[bu.test$Especie==21,]
bu.pin<- bu.test[bu.test$Especie==26,]
bu.pinus <- rbind (bu.syl,bu.pin)
bu.pinus <- na.omit(bu.pinus)
```

```
head(bu.pinus)
bu.pinus$d <-(bu.pinus$d/10)
bu.pinus$h<-(bu.pinus$h/10)
max(bu.pinus$Especie)

## loop to calculate the dominante height (Burgos) :

plots<-bu.pinus$Estadillo

bu.domH<-data.frame()
for (i in plots){

  # i<-45
  # Plots selection:
  plot.i<-bu.pinus[bu.pinus$Estadillo==i,]

  # if (plot.i$Estadillo>0)

  # Order plot i according to DBH (bigger to smaller)
  ordering<-plot.i[order(plot.i$d,decreasing=TRUE),]

  # Calculate cumulative sums of the expansion factor:
  ordering$sum.exp.fact <- cumsum(ordering$n)

  # Select rows until 100 of cumulative sum of expansion factor:
  select.Pi <- ordering[0:(nrow(ordering[ordering$sum.exp.fact<100,]))+
1,]



if (nrow(select.Pi)>1) {

    ## we are going to change expansion factor of the last tree to
    # obtain exactly 100 trees per hectare:
    new.exp.fact <- replace(select.Pi$n,select.Pi$sum.exp.fact>=100,100
-select.Pi
                              [nrow(select.Pi)-1,'sum.exp.fact'])
    select.Pi<-as.data.frame(select.Pi) # select.Pi is a list, not a da
taframe
    select.Pi <-cbind(select.Pi,new.exp.fact)
    select.Pi$sum.exp.fact2 <- cumsum(select.Pi$new.exp.fact)

    # dominant height
    Ho<-sum(select.Pi$h*select.Pi$new.exp.fact)/100

  }else{

    if (select.Pi$n>100){
      Ho<- select.Pi$h

    }else{
      Ho<- 0
    }
  }
```

```
  Estadillo <-i
  domH<-cbind(Estadillo,Ho)
  bu.domH<-rbind(bu.domH,domH)
}

bu.domH <- na.omit(bu.domH)
bu.domH<-unique(bu.domH)
max(bu.domH$Ho)
bu.domH$prv_plot  <- with(bu.domH, paste("9", Estadillo, sep='_'))
head(bu.domH)

write.csv(bu.domH,file="bu.domH.csv")

################################################################
################################################################

### Soria:

so.test<- nfiMetrics(so.tree) #(Soria_dendrometric variables)

head(so.test)
so.syl<- so.test[so.test$Especie==21,]
so.pin<- so.test[so.test$Especie==26,]
so.pinus <- rbind (so.syl,so.pin)
so.pinus <- na.omit(so.pinus)
head(so.pinus)
so.pinus$d <-(so.pinus$d/10)
so.pinus$h<-(so.pinus$h/10)
max(so.pinus$Especie)

###loop to calculate the dominante height (Soria) :

plots<-so.pinus$Estadillo

so.domH<-data.frame()
for (i in plots){

  # i<-45
  # Plots selection:
  plot.i<-so.pinus[so.pinus$Estadillo==i,]

  # if (plot.i$Estadillo>0)

  # Order plot i according to DBH (bigger to smaller)
  ordering<-plot.i[order(plot.i$d,decreasing=TRUE),]

  # Calculate cumulative sums of the expansion factor:
  ordering$sum.exp.fact <- cumsum(ordering$n)

  # Select rows until 100 of cumulative sum of expansion factor:
  select.Pi <- ordering[0:(nrow(ordering[ordering$sum.exp.fact<100,]))+
1,]
```

```
  if (nrow(select.Pi)>1) {

    ## we are going to change expansion factor of the last tree to
    # obtain exactly 100 trees per hectare:
    new.exp.fact <- replace(select.Pi$n,select.Pi$sum.exp.fact>=100,100
-select.Pi
                            [nrow(select.Pi)-1,'sum.exp.fact'])
    select.Pi<-as.data.frame(select.Pi) # select.Pi is a list, not a da
taframe
    select.Pi <-cbind(select.Pi,new.exp.fact)
    select.Pi$sum.exp.fact2 <- cumsum(select.Pi$new.exp.fact)

    # dominant height
    Ho<-sum(select.Pi$h*select.Pi$new.exp.fact)/100

  }else{

    if (select.Pi$n>100){
      Ho<- select.Pi$h

    }else{
      Ho<- 0
    }
  }

  Estadillo <-i
  domH<-cbind(Estadillo,Ho)
  so.domH<-rbind(so.domH,domH)
}

so.domH <- na.omit(so.domH)
so.domH<-unique(so.domH)
max(so.domH$Ho)
so.domH$prv_plot  <- with(so.domH, paste("42", Estadillo, sep='_'))
head(so.domH)

write.csv(so.domH,file="so.domH.csv")

##################################################
## join data frames of "bu.domH" and "so.domH":##
##################################################

bu.so.domH <- rbind (bu.domH,so.domH)

#############################################################
###### selecting mixed plots in Demandas mountains #########
#############################################################


##   Makeing a new variable joins "Provincia" and "Estadillo"
# in both data frames of Bugros and Soria (estadillo is plot:


burgos.p$prv_plot  <- with(burgos.p, paste(pr, Estadillo, sep='_'))
```

```
head(burgos.p)
soria.p$prv_plot  <- with(soria.p, paste(pr, Estadillo, sep='_'))
head(soria.p)

## join data frames of "burgos.p" and "soria.p":

bu.so.p <- rbind (burgos.p,soria.p)
head(bu.so.p)

## join data frames of "bu.bas.P.syl" and "so.bas.P.syl":

bu.so.bas.P.syl <- rbind (bu.bas.P.syl,so.bas.P.syl)
head(bu.so.bas.P.syl)

### selecting the mixed plots in Demandas mountains:
####################################################

library("foreign", lib.loc="C:/Program Files/R/R-3.4.0/library")
demanda <- read.dbf("IFN-PsPt-Demanda.dbf")
head(demanda)

## Makeing a new variable joins "Provincia" and "Estadillo"
# in the data frame of Demandas mountains:

demanda$prv_plot  <- with(demanda, paste(Provincia, Estadillo, sep='_')
)
head(demanda)

## selecting the mixed plots:
demanda.mix <- demanda[demanda$Type=="M",]
head(demanda.mix)

#######################################################################
# selecting the common mixed plots between "demanda.mix" and "bu.so.p":
data.de <- bu.so.p[which(bu.so.p$prv_plot %in% demanda.mix$prv_plot),]
head (data.de)

# Merging and selecting common mixed plots between "data.de" and "bu.so
.bas.P.syl"
data.de.2<- merge(data.de,bu.so.bas.P.syl ,by="prv_plot")
head(data.de.2)
data.de.3<-data.de.2[,c("prv_plot","pr.x","Especie.x","X.x","Estadillo.
x","ba",
                        "p.syl_ba","d.x","dg.x","h.x","n.x","v.x")]
head(data.de.3)

names(data.de.3)[names(data.de.3) == "pr.x"] <- "pr"
names(data.de.3)[names(data.de.3) == "Especie.x"] <- "Especie"
names(data.de.3)[names(data.de.3) == "X.x"] <- "X"
names(data.de.3)[names(data.de.3) == "Estadillo.x"] <- "Estadillo"
names(data.de.3)[names(data.de.3) == "d.x"] <- "d"
names(data.de.3)[names(data.de.3) == "dg.x"] <- "dg"
names(data.de.3)[names(data.de.3) == "h.x"] <- "h"
names(data.de.3)[names(data.de.3) == "n.x"] <- "n"
names(data.de.3)[names(data.de.3) == "v.x"] <- "v"
```

```
########################################################################

## join data frames of "data.de.3" and "bu.so.domH" to get the final da
ta
# of the mixed plots in Demanda mountains with the needed variables:

Final.De <- merge(data.de.3,bu.so.domH,by="prv_plot")

Final.Demanda <- na.omit(Final.De)
Final.Demanda$syl.frac<-(Final.Demanda$p.syl_ba/Final.Demanda$ba)
Final.Demanda$mix.frac<-(0.5-abs(Final.Demanda$syl.frac-0.5))
Final.Demanda$SDI<- Final.Demanda$n*(Final.Demanda$dg/25.4)^1.605
max(Final.Demanda$Ho)
summary(Final.Demanda)
write.csv(Final.Demanda,file="Final.Demanda.csv")

################################################
############### Summary statistics #############
################################################

## install.packages

pkgs <- c("dplyr", "tidyr", "broom")
install.packages(pkgs) #install
sapply(pkgs, require, character.only = T)  #load

### summary of plots characteristics

head(Final.Demanda)
sumstat <- Final.Demanda %>%

  # Select and rename five variables
  select(
    `DBH` = d,
    `QMD` = dg,
    `H` = h,
    `Ho` = Ho,
    `N` = n,
    `V` = v,
    `G` = ba,
    `SDI` = SDI) %>%

  # Find the mean, min, max and st.dev.for each variable
  summarise_each(funs(mean, min, max, sd)) %>%

  # Move summary to columns
  gather(key, value, everything()) %>%
  separate(key, into = c("variable", "stat"), sep = "_") %>%
  spread(stat, value) %>%

  # Set order of summary statistics
  select(variable, mean, min, max, sd) %>%
```

```
 # Round all numeric variables to one decimal point
  mutate_each(funs(round(., 2)), -variable)

# Write to .txt
write.table(sumstat, file = "sumstats.txt", sep = ",",
            quote = FALSE, row.names = F)

summary(Final.Demanda)


########################################################################
###### Simultaneous fitting of a system of two linear equations #######
########################################################################

# logarithm of the variables (linearizing the two equations QMD and V):
head(Final.Demanda)

Final.Demanda$logdg <- log(Final.Demanda$dg)
Final.Demanda$logN <- log(Final.Demanda$n)
Final.Demanda$logHo <- log(Final.Demanda$Ho)
Final.Demanda$logV <- log(Final.Demanda$v)

pairs(~logdg+logN+logHo+logV, data=Final.Demanda, main="Matrix scatter
chart")

Final.Demanda$mixfrac.logdg <- (Final.Demanda$logdg*Final.Demanda$mix.f
rac)
Final.Demanda$mixfrac.logN <- (Final.Demanda$logN*Final.Demanda$mix.fra
c)
Final.Demanda$mixfrac.logHo <- (Final.Demanda$logHo*Final.Demanda$mix.f
rac)
Final.Demanda$mixfrac.logV <- (Final.Demanda$logV*Final.Demanda$mix.fra
c)

Final.Demanda$syl.frac.logdg <- (Final.Demanda$logdg*Final.Demanda$syl.
frac)
Final.Demanda$syl.frac.logN <- (Final.Demanda$logN*Final.Demanda$syl.fr
ac)
Final.Demanda$syl.frac.logHo <- (Final.Demanda$logHo*Final.Demanda$syl.
frac)
Final.Demanda$syl.frac.logV <- (Final.Demanda$logV*Final.Demanda$syl.fr
ac)

head(Final.Demanda)
write.csv(Final.Demanda,file="Final.Demanda.csv")


##(1) Simultaneous fitting of the two non-linear models (lnQMD) and (ln
V)
# with (mix.frac) variable:

# Adjustment of the linearized allometric model QMD:

model01l<- lm(logdg~mix.frac+logN+mixfrac.logN+logHo+mixfrac.logHo,
              Final.Demanda)
```

```
#Summary of the linear adjustment QMD:
summary(model01l)

# Adjustment of the linearized allometric model V:

model02l<- lm(logV~mix.frac+logdg+mixfrac.logdg+logHo+mixfrac.logHo+
                logN+mixfrac.logN,Final.Demanda)

# Summary of the linear adjustment V:
summary(model02l)

########################################################################
# Fitting without introducing the (mix.frac) variable into the models #
########################################################################

##(2) Simultaneous fitting of the two non-linear models (lnQMD) and (ln
V)
# without (mix.frac) variable:

## Adjustment of the linearized allometric model QMD:

model01lmod<- lm(logdg~logN+logHo,data=Final.Demanda)

# Summary of the linear adjustment QMD:
summary(model01lmod)

## MODIFICATION Adjustment of the linearized allometric model V:

model02lmod<- lm(logV~logdg+logHo+logN,data=Final.Demanda)

# Summary of the linear adjustment V:
summary(model02lmod)
############################################################
################## The Diagram (SDMD) #####################
############################################################

modlm1<-lm(logdg~logN+logH0,Final.Demanda)

summary(modlm1)
modlm2<-lm(logV~logdg+logH0+logN,Final.Demanda)
summary(modlm2)

modnls1 <- nls(dg~b0*N^b1*H0^b2, data=Final.Demanda, start=list(b0=2.73
396,
                                                      b1=-0.27044,
                                                      b2=0.81594))
summary(modnls1)
modnls2 <- nls(V~b3*dg^b4*H0^b5*N^b6, data=Final.Demanda, start=list(b3
=-8.28660 ,
                                                           b4=1.98235 ,
                                                           b5=0.62759,
                                                           b6=0.89051))
summary(modnls2)
deviance(modnls1)
```

```r
deviance(modnls2)
require(sqldf)
f01 <-sqldf("select Avg(dg) as AvgOfDg, Avg(V) as AvgOfV from Final.Dem
anda")
f02 <-sqldf("select Sum(power(dg a sAvgOfDg, 2)) as SCTdg, Sum(power(Vâ
€ AvgOfV, 2)) as
SCTV from Final.Demanda, f01")


f02 <-sqldf("select Sum(power(dg???AvgOfDg, 2)) as SCTdg, Sum(power(V??
?AvgOfV, 2)) as
SCTV from Final.Demanda, f01")
f02$R2dg <-1-deviance(modnls1)/f02$SCTdg # R² of the first model
f02$R2V <-1-deviance(modnls2)/f02$SCTV # R² of the second model
f02

H0 <-seq(5, 35, 2)
SDI<-seq(10, 54, 4)
Final.Demanda<-merge(H0,SDI)
names(Final.Demanda) <-c("H0", "SDI")

Final.Demanda$valor.ih<-(10000/(Final.Demanda$H0*Final.Demanda$SDI) )^2
N <-c(seq(50, 100, 10), seq(125, 400, 25), seq(450, 950, 50), seq(1000,
2000, 100),
      seq(2250, 3000, 250))
Nn <- c(100, 200, 300, 400, 500, 600, 700, 800, 1000, 2000, 3000)

parm <- data.frame(b0=2.73396
                   , b1=-0.27044, b2=0.81594, b3=-8.28660, b4=1.98235,
                   b5=0.62759, b6=0.89051)



parm$b304 <- parm$b3*parm$b0^parm$b4
parm$b245 <- parm$b2*parm$b4+parm$b5
parm$b146 <- parm$b1*parm$b4+parm$b6

library(lattice)
win.graph()
library(lattice)
win.graph()
xyplot(log10(valor.ih)~H0, data=Final.Demanda, groups=SDI
       , type="l", col=1, lwd=2, xlim=c(5,
                                        35), ylim=c(min(log10(N)), max(
log10(N))),
scales=list(y=list(
  at=log10(c(seq(50, 80, 10), seq(100, 200, 25), seq(250, 450, 50), seq
(500,
                    900, 100), seq(1000, 1800, 200), seq(2000, 3000, 50
0))),
  labels= c(seq(50, 80, 10), seq(100, 200, 25), seq(250, 450, 50), seq(
500,
                    900, 100), seq(1000, 1800, 200), seq(2000, 3000, 50
0)))
)
```

```r
key=list(text=list(c(" Reineke index", "Quadratic Mean diameter (cm)
(cm)","Volume (mA³/ha)")), lines=list(lwd=2.5, col=c("black", "red", "b
lue"),
                                      type="l"))
xlab="Dominant height (m)"
ylab="Density (Trees ha³)"
panel=function(x, y, ...){
  for(i in 5:35)
    panel.abline(v=i, col="grey", lty=1, lwd=0.5) # Isolines of H0
  for(i in log10(N))
    panel.abline(h=i, col="grey", lty=5, lwd=0.5)
  for(i in log10(Nn))
    panel.abline(h=i, col="grey", lty=1, lwd=1)

  panel.xyplot(x, y, ...)
  for(i in seq(8, 56, 2)){


  }
  for(i in seq(10, 38, 4)){
    panel.points(x=33, y=log10((10000/(33*i))^2), pch=15, col="white",
                 cex=2.5)
    panel.text(x=33, y=log10((10000/(33*i))^2), labels=i, cex=0.8, col=
1)
  }
  for(i in seq(8, 56, 4)){
    panel.points(x=34, y=log10((i/(parm$b0*34^parm$b2))^(1/parm$b1)),
                 pch=15, col="white", cex=2.5)
    panel.text(x=34, y=log10((i/(parm$b0*34^parm$b2))^(1/parm$b1)),
               labels=i, cex=0.8, col=2)
  }
}
```