

Is it needed to integrate mixture degree in Stand Density Management Diagram (SDMD)?

Ali Askarieh⁽¹⁻²⁾,
Irene Ruano⁽¹⁻²⁾,
Felipe Bravo⁽¹⁻²⁾

Stand density management diagrams (SDMDs) are robust decision-support tools available to forest managers under limited information. SDMDs which are based on 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, to meet various management objectives. Nowadays, there is a growing interest in mixed-species forests as an option for 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. This study aims to develop an SDMD for *Pinus sylvestris* L. and *Pinus pinaster* Ait. mixed stands in the Sierra de la Demanda (Spain) using data from the third Spanish National Forest Inventory. Both species are two of the most important conifers in Europe and the western Mediterranean basin. 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 were used. These equations were fit by simultaneous fitting including a new variable representing the proportion of both species in the mixed stand. 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 operations.

Keywords: Reineke Index, Dominant Height, Silviculture, Thinning, *Pinus sylvestris* L, *Pinus pinaster* Ait.

Introduction

Maintaining and promoting functionally vigorous forests entails the sound regulation of tree numbers per unit area versus average tree size, such a process impacts how a stand develops over a rotation period. Density management is 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 harmful effects of climate change and site degradation. In this regard, stand density management diagrams (SDMDs) have emerged as a time-saving and cost-effective approach. On the contrary to thinning trials which have some critical restrictions (Dean & Baldwin 1993, Valbuena et al. 2008, Schnell et al. 2012), 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 & Long 1996, Newton 2003) to predict what stand post-thinning density would be. In terms of operating costs, SDMDs are an inexpensive tool, making them a favorable option in a region such as the Mediterranean, where the silvicultural practice must be enacted under critical budget constraints (Valbuena et al. 2008) due to low productivity and management based on public fundings.

The main principle of any SDMD is based on the stand self-thinning rule. SDMDs are defined as empirical models at stand level. This graphically represents 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 are based on size-density relationships, Reineke's stand density index (SDI – Reineke 1933) was the most widely used (Shaw & Long 2007, Valbuena et al. 2008, VanderSchaaf & Burkhart 2012, Quiñonez-Barraza et al. 2017). Moreover, Reineke's index is more accurate in Mediterranean pine forests than Hart's index (Rodríguez et al. 2008).

Practically, SDMDs are used to define 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 & Rodríguez-Soalleiro 2009); creating and

□ (1) Instituto Universitario de Investigación y Gestión Forestal Sostenible (iuFOR), Unidad Asociada de I+D+i al CSIC, Universidad de Valladolid, Avda. Madrid s/n, 34004 Palencia (Spain); (2) Departamento de Producción Vegetal y Recursos Forestales, ETS de Ingenierías Agrarias, Universidad de Valladolid, Palencia (Spain)

@ Ali Askarieh (ali.askarieh@uva.es)

Received: Oct 25, 2021 - Accepted: Aug 21, 2023

Citation: Askarieh A, Ruano I, Bravo F (2023). Is it needed to integrate mixture degree in Stand Density Management Diagram (SDMD)? *iForest* 16: 274-281. - doi: [10.3832/ifor4005-016](https://doi.org/10.3832/ifor4005-016) [online 2023-10-28]

Communicated by: Emanuele Lingua

conserving habitat for wildlife endangered species (Shaw & Long 2007); reducing vulnerability to beetles' attacks (Anhold et al. 1996, Long & Shaw 2005); or 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 on monoculture stands where *Quercus robur* L. (Barrio Anta & Alvarez González 2005), *Pinus banksiana* Lamb. (Sharma & Zhang 2007), *Pinus palustris* P. Mill. (Shaw & Long 2007), *Pinus halepensis* Mill. and *Pinus pinaster* (Valbuena et al. 2008), *Pinus radiata* D. Don (Castedo-Dorado et al. 2009), *Picea abies* (L.) Karst. (Vacchiano et al. 2013), *Cunninghamia lanceolata* (Lamb.) Hook. (Tang et al. 2016), *Eucalyptus grandis* W. Hill RS (Marangon et al. 2017) or *Castanea sativa* Mill. (Patrício & Nunes 2017) were the target species. In comparison, there are very few SDMDs for mixed-species forests: *Abies balsamea* (L.) Mill., *Picea rubens* Sarg., *Picea mariana* (Mill.) BSP. and *Picea glauca* (Moench) Voss forests in northeastern North America (Swift et al. 2007), Mixed-Conifer Stands in Sierra Nevada (Long & Shaw 2012), *Juniperus procera* Hochst. Ex. Endl and *Podocarpus falcatus* Thunb. Mirb natural mixed forests in Ethiopia (Tesfaye et al. 2016), and *Pinus-Quercus* natural mixed forests in Mexico (Cabrera-Pérez et al. 2019). Studies have revealed that species mixing can provoke changes in above-ground species allometries in both pine-pine mixtures, including *P. pinaster*-*P. sylvestris* mixtures, involving five pine species covering different biogeographical distributions (Condés et al. 2020), and coniferous-broadleaf mixtures (Dieler & Pretzsch 2013). In view of the foregoing, it is important to develop SDMDs in mixed forest.

Scots pine (*Pinus sylvestris*) and Maritime pine (*Pinus pinaster*) are two of the impor-

tant coniferous species in Europe and the Mediterranean basin. Where *P. sylvestris* is widely distributed over the Eurasian continent (Mátyás & 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 (Alia & Martin 2011). For the time being, the 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 for adaptive forest management (Ammer 2017).

Mixed forests are increasingly becoming more worthwhile in comparison to monoculture forests, as their 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), consequently, enhancing the contribution to climate change mitigation and adaptation. Species mixing dilutes the risk of biotic or abiotic stress and disturbances that emerged from climate change. This response pattern can be attributed to diverse susceptibilities among species to particular disturbances. As a consequence, the number of surviving trees is directly proportional to the number of tree species in a stand (Pretzsch et al. 2017). Moreover, these remaining trees can rather provide a base structure for the stand functioning and recovery (Jactel et al. 2009). Although there are many studies reporting the notable effects of mixed forests in terms of stability and important productive capacity, there is still an inadequate knowledge of the mechanisms and trade-offs underlying these effects, and the need for more understanding of the spatial and temporal

levels at which these effects are operating (Coll et al. 2018).

The main objective of this study is to develop an SDMD for *Pinus sylvestris* and *Pinus pinaster* mixed stands in the Sierra de la Demanda, Burgos and Soria, Spain. In parallel with developing the SDMD, we aimed at studying the behavior of both species in mixed stands.

Material and methods

Study area

The Sierra de la Demanda (Northern Spain) is an elongated mountainous massif, rising in the extreme northwest of the Iberian system (Fig. 1).

Scots pine (*Pinus sylvestris*) forests in the study area cover 296.02 km² of land (about 19.19% of the total forest cover) while Maritime pine (*Pinus pinaster*) cover only 20.57 km² 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 in February. Temperatures range from annual isotherms of 3.48 to 18.78 °C (AGALSA 2006).

Data

Data from the third Spanish National Forest Inventory (SNF13, 1997- 2007) were 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. The origin of the stands is either natural or plantation; maps with information about stand origin data are available at <https://sites.google.com/site/sigforestspecies/home>. Mixed plots were defined based on the criterion of the combined proportion of basal area for

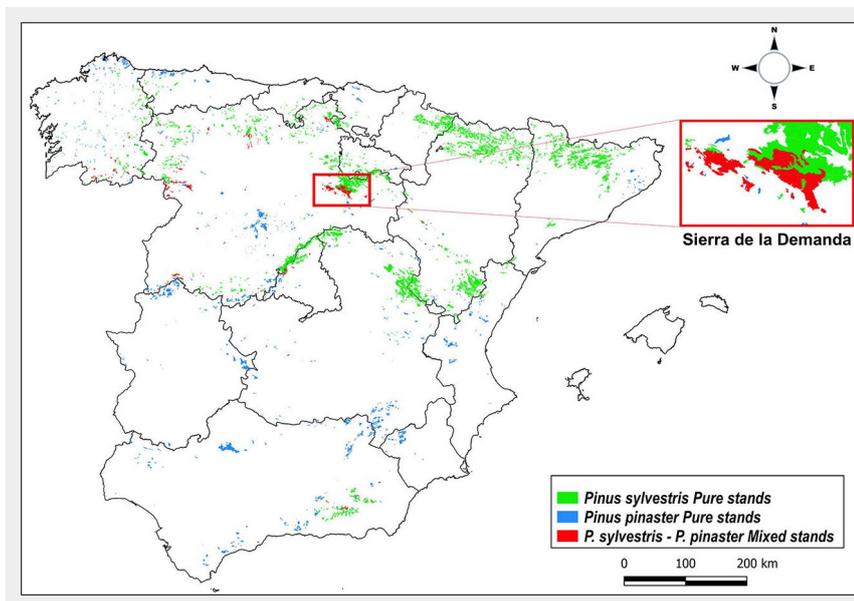


Fig. 1 - Study area (Sierra de la Demanda, Northern Spain).

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. 2017). A total of 165 mixed plots were analyzed. The main plots characteristics are summarized in Tab. 1.

The plots of the Spanish National Forest Inventory are permanent plots systematically distributed on UTM square grids with a resolution of 1 × 1 km 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 5 m circle, trees with a diameter at breast height (DBH) that exceed 7.5 cm are taken into account; in the 10 m subplot, those that exceed 12.5 cm; for trees in the 15 m circle, those greater than 22.5 cm; and lastly, in the 25 m subplot, those exceeding 42.5 cm. Variables taken into account include height (h), species, distance, and azimuth of trees measured from plot center. Forest type, erosion factors, anthropogenic activity, tree damage, shrub species, cover (in the 10 m subplot), and plot identification are other data recorded from the concentric subplots. 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. 2021) in R (R Core Team 2019).

The dominant height was calculated according to the criterion of Assmann, which is the definition most widely used in Spain (Bengoa 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).

Due to the NFI design, trees are considered in different subplots depending on their DBH, therefore the 100 thickest trees should be defined using the expansion factors. For this reason, the following equation derived from Assmann’s formula was used to calculate the dominant height (eqn. 1):

$$Ho = \frac{\sum_{i=1}^n H_i \cdot \text{expfact}}{100} \quad (1)$$

where Ho is the dominant height (m), H is the tree total height (m), i takes values from 1 to n of thickest trees, expfact is the expansion factor, n is the number of thickest considered trees; this value can vary depending on each NFI plot.

Reineke’s index (SDI) was used as a stand density index. The optimal density-growth interval was determined by upper and

Tab. 1 - Summary of the data set (n = 165) from the third Spanish National Forest Inventory used to develop SDMD for *Pinus sylvestris* and *Pinus pinaster* mixed stands in the Sierra de la Demanda (Spain). (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 (m³ ha⁻¹); (G): basal area (m² ha⁻¹); (SDI): Reineke’s stand density index.

Attributes (Variable)	Mean	Minimum	Maximum	Standard deviation (SD)
DBH	26.96	9.13	45.28	7.56
QMD	28.53	9.19	48.22	7.43
H	13.58	4.7	22.88	4.07
Ho	16.26	6.5	26.17	3.93
N	535.32	101.29	977.99	228.67
V	300.44	12.27	977.69	163.3
G	32.5	2.53	73.44	14.54
SDI	599.92	74.59	1250.36	250.42

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 & Baldwin 1993), while the lower limit was defined by 35% of maximum SDI aiming to ensure adequate site occupancy (Long 1985).

SDI was calculated by summing up the SDI for *P. sylvestris* (SDI_{syl}) and the SDI for *P. pinaster* (SDI_{pin}) as described in eqn. 2 and eqn. 3, respectively, to take into account the area occupied by each species in mixed stands (Riofrío et al. 2017):

$$SDI = SDI_{syl} + SDI_{pin} \quad (2)$$

$$SDI_{syl(pin)} = N_{syl(pin)} \left(\frac{QMD}{25.4} \right)^{1.605} \quad (3)$$

where SDI is the Reineke’s stand density index, N is the number of trees per hectare, QMD is the quadratic mean diameter, syl indicates *Pinus sylvestris* and pin indicates *Pinus pinaster*.

Model structure and statistical methods

The aimed SDMD model has the following fundamental components: (i) Reineke’s stand density index; (ii) an allometric system of two linear equations (eqn. 4, eqn. 5):

$$\ln(QMD) = \beta_0 + \beta_1 \cdot \ln(N) + \beta_2 \cdot \ln(Ho) \quad (4)$$

$$\ln(V) = \beta_3 + \beta_4 \cdot \ln(QMD) + \beta_5 \cdot \ln(Ho) + \beta_6 \cdot \ln(N) \quad (5)$$

where QMD is the quadratic stem diameter (cm), N is the stand density (tree ha⁻¹), Ho is the dominant height (m), V is the stand to-

Tab. 2 - Coefficients resulted from the simultaneous fitting of the eqn. 6 and eqn. 7 to estimate quadratic mean diameter (QMD) and volume (V) respectively, for *Pinus sylvestris* and *Pinus pinaster* mixed stands.

Variable (eqn.)	Coefficients of regression			
	Coeff.	Parameter	Estimate	Pr(> t)
QMD (eqn. 6)	β_0	Intercept	2.56371	9.69E-12
	β_1	<i>mixfrac</i> (Mixture degree)	0.82466	0.486
	β_2	ln N (Density)	-0.1976	1.69E-06
	β_3	<i>mixfrac</i> (Mixture degree)	-0.34979	0.024
	β_4	ln Ho (Dominant height)	0.73041	< 2e-16
	β_5	<i>mixfrac</i> (Mixture degree)	0.41264	0.145
V (eqn. 7)	β_6	Intercept	-7.58942	< 2e-16
	β_7	<i>mixfrac</i> (Mixture degree)	-2.24766	0.3391
	β_8	ln QMD (Quadratic mean diameter)	1.64388	< 2e-16
	β_9	<i>mixfrac</i> (Mixture degree)	1.0148	0.1153
	β_{10}	ln Ho (Dominant height)	0.9352	1.5E-08
	β_{11}	<i>mixfrac</i> (Mixture degree)	-1.07111	0.0818
	β_{12}	ln N (Density)	0.82928	< 2e-16
	β_{13}	<i>mixfrac</i> (Mixture degree)	0.26548	0.313

Tab. 3 - Validation statistics of simultaneous fitting of the eqn. 6 and eqn. 7 to estimate quadratic mean diameter (QMD) and volume (V) respectively, for *Pinus sylvestris* and *Pinus pinaster* mixed stands.

Variable (eqn.)	Parameter	Value
QMD (eqn. 6)	RSE (Relative standard error) on 159 degrees of freedom	0.1317
	R ² (Coefficient of determination)	0.795
	Adjusted R ²	0.7885
	p-value (Probability value)	< 2.2e-16
V (eqn. 7)	RSE (Relative standard error) on 157 degrees of freedom	0.1596
	R ² (Coefficient of determination)	0.9506
	Adjusted R ²	0.9484
	p-value (Probability value)	< 2.2e-16

Tab. 4 - Coefficients resulted from the simultaneous fitting of the eqn. 4 and eqn. 5 to estimate quadratic mean diameter (QMD) and volume (V) respectively, for *Pinus sylvestris* and *Pinus pinaster* mixed stands.

Variable (eqn.)	Coefficients of regression			
	Coeff.	Parameter	Estimate	Pr(> t)
QMD (eqn. 4)	β_0	(Intercept)	2.69703	<2e-16
	β_1	ln N (Density)	-0.26759	<2e-16
	β_2	ln Ho (Dominant height)	0.82344	<2e-16
V (eqn. 5)	β_3	(Intercept)	-8.18200	< 2e-16
	β_4	ln QMD (Quadratic mean diameter)	1.90971	< 2e-16
	β_5	ln Ho (Dominant height)	0.68569	2.05e-12
	β_6	ln N (Density)	0.88702	< 2e-16

Tab. 5 - Validation statistics of simultaneous fitting of the eqn. 4 and eqn. 5 to estimate quadratic mean diameter (QMD) and volume (V) respectively, for *Pinus sylvestris* and *Pinus pinaster* mixed stands.

Variable (eqn.)	Parameter	Value
QMD (eqn. 4)	RSE (Relative standard error) on 162 degrees of freedom	0.1369
	R ² (Coefficient of determination)	0.7743
	Adjusted R ²	0.7715
	p-value (Probability value)	< 2.2e-16
V (eqn. 5)	RSE (Relative standard error) on 161 degrees of freedom	0.1618
	R ² (Coefficient of determination)	0.9479
	Adjusted R ²	0.9469
	p-value (Probability value)	< 2.2e-16

tal volume (m³ ha⁻¹), and β_i are the regression coefficients.

Eqn. 4 relates the quadratic mean diameter with stand density and dominant height, while eqn. 5 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 exoge-

Tab. 6 - Silvicultural management alternative shown in Fig. 3. (N): density (trees ha⁻¹); (QMD): quadratic mean diameter (cm); (Ho): dominant height; (V): the over bark volume (m³ ha⁻¹).

Entry	N (tree ha ⁻¹)		QMD (cm)		Ho (m)		V (m ³)	
	Before	After	Before	After	Before	After	Before	After
I-II	1000	409	22.7	26.5	15.3	14.3	294.3	187.5
III-IV	409	181	37.1	44	21.5	20.3	471.8	304.8
V (Final cut)	181	-	54	-	26	-	534.3	-

nous variables, but as ln(QMD) is defined independently of the system in eqn. 5, therefore it is considered as an independent exogenous variable. 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 eqn. 4 and eqn. 5 by taking mixture proportions into account. In this regard, a new variable (*mixfrac*), calculated using eqn. 8 and eqn. 9, representing mixing degree, was introduced into both eqn. 6 and eqn. 7 (Swift et al. 2007).

$$\ln(QMD) = \beta_0 + \beta_1 \text{mixfrac} + (\beta_2 + \beta_3 \text{mixfrac}) \cdot \ln(N) + (\beta_4 + \beta_5 \text{mixfrac}) \cdot \ln(Ho) \quad (6)$$

$$\ln(V) = \beta_6 + \beta_7 \text{mixfrac} + (\beta_8 + \beta_9 \text{mixfrac}) \cdot \ln(QMD) + (\beta_{10} + \beta_{11} \text{mixfrac}) \cdot \ln(Ho) + (\beta_{12} + \beta_{13} \text{mixfrac}) \cdot \ln(N) \quad (7)$$

where (eqn. 8, eqn. 9):

$$\text{mixfrac} = 0.5 - \left| \left(\text{sylfrac} - 0.5 \right) \right| \quad (8)$$

$$\text{sylfrac} = \frac{P \cdot \text{sylvestris basal area}}{\text{Total basal area}} \quad (9)$$

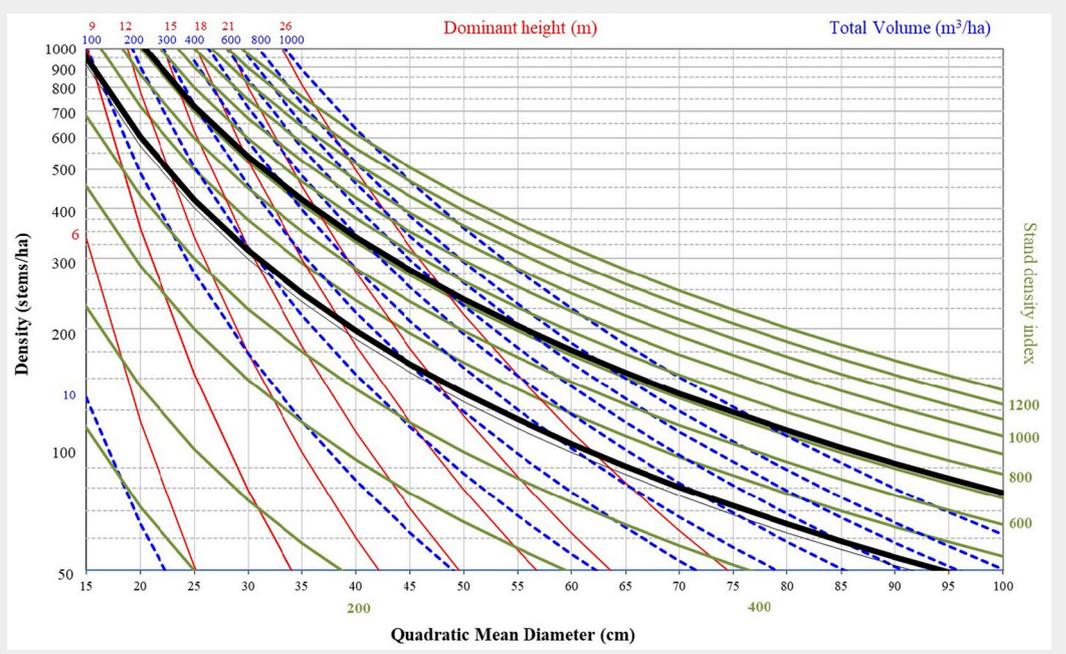
The simultaneous fitting of the equations and the analyses were done using the R statistical environment.

SDMD was constructed using the format described by Barrio Anta & Alvarez 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.

Results

The results from the simultaneous fitting of eqn. 6 and eqn. 7 to estimate quadratic mean diameter and total stand volume, show that all coefficients were significant at a 0.05 significance level, except for the mixture degree variable (*mixfrac* - Tab. 2). R-squared (R²) for ln(QMD) and ln(V) equations were quite high (0.795 and 0.9506 respectively), reflecting efficient goodness-of-fit statistics (Tab. 3). Due to the non-significant effect of the mixture degree variable (*mixfrac*), it was eliminated and another run of simultaneous fitting of the initial system of equations represented by eqn 4 and eqn. 5 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 (Tab. 4). Again, from the validation statistics of simultaneous fitting of the two equations system formed by eqn. 4 and eqn. 5 (Tab. 5), R-squared (R²) values for ln(QMD) and ln(V) equation were quite high (0.7743 and 0.9479 respectively). These results indicate efficient

Fig. 2 - Stand Density Management Diagram (SDMD) for mixed stands of *Pinus sylvestris* and *P. pinaster* in the Sierra de la Demanda.



goodness-of-fit statistics and the right choice of both the equation form and the independent variables.

Thus, the two linear models eqn. 4 and eqn. 5 without the mixture degree are the appropriate choices 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 (eqn. 10, eqn. 11):

$$\ln(QMD) = 2.69703 - 0.26759 \ln(N) + 0.82344 \ln(Ho) \quad (10)$$

$$\ln(V) = -8.18200 + 1.90971 \ln(QMD) + 0.68569 \ln(Ho) + 0.88702 \ln(N) \quad (11)$$

where QMD is the quadratic stem diameter (cm), N is the stand density (tree ha⁻¹); Ho is the dominant height (m), and V is the stand total volume (m³ ha⁻¹).

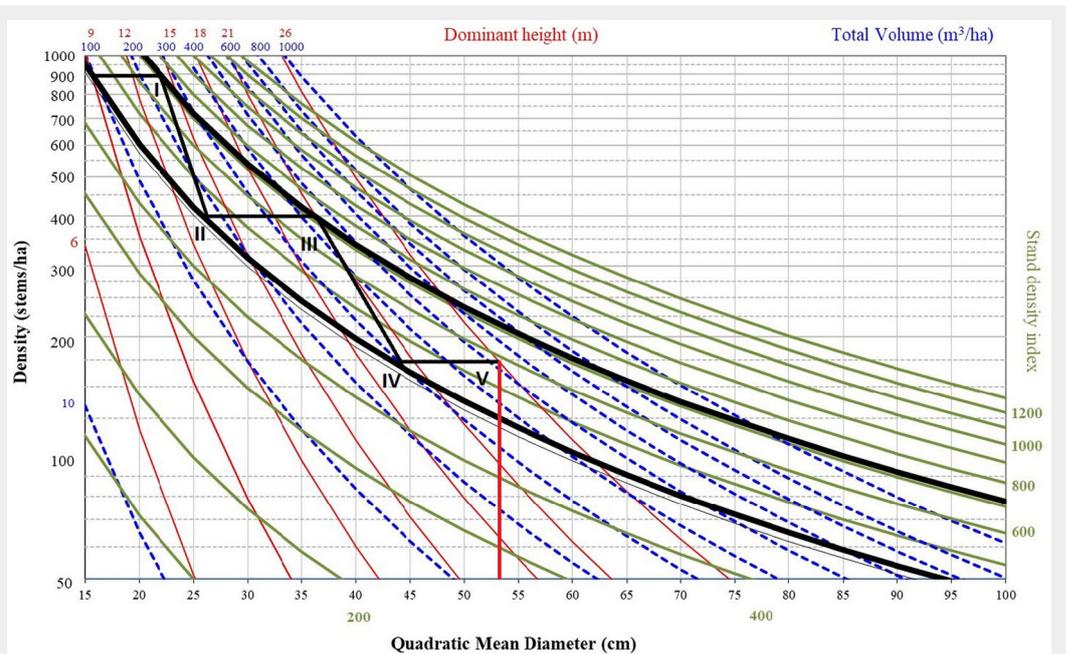
An SDMD for the mixed stands of *Pinus sylvestris* and *P. pinaster* in the Sierra de la Demanda was elaborated using the data obtained from the Spanish National Forest Inventory (eqn. 10 and eqn. 11), and the formula of Reineke's stand density index (Fig. 2), where quadratic mean diameter (QMD) and density (N) were plotted on x-axis and y-axis respectively as logarithmic scales, 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 isolines in bold black represent the upper and lower growing stock limits and they are

60% of maximum SDI for the upper limits (Dean & Baldwin 1993) and 35% of maximum SDI for the lower limit (Long 1985). Optimal density levels should be found between these limits, meaning both bold black lines. Values above the maximum limit mean silvicultural treatments like thinning should be done and values below the minimum limit mean the density is inadequate.

Discussion

The value of the stand density management diagram developed in this study for *Pinus sylvestris* – *P. pinaster* mixed stands, emerges from the current orientation of moving further in developing efficient tools and models in quantitative silviculture for mixed stands, to quantitatively and qualita-

Fig. 3 - Silvicultural management alternative for mixed stands of *Pinus sylvestris* and *Pinus pinaster* in the Sierra de la Demanda.



tively enhance forest wood and non-wood production and ecosystem functions and services, especially in light of the lack of information on mixed forests combined with a raised interest in such forest systems.

An example of alternative management in this type of forest is shown in Tab. 6 and Fig. 3. In this case, a set of thinning interventions was applied two times and different intensities (I-II and III-IV) and a final cut, which was defined by a dominant height of 26 m. The initial density was 900 trees ha⁻¹ and a quadratic mean diameter of 22.7 cm. The first thinning was applied to obtain a density of 409 tree ha⁻¹. Then the stand grew considering no natural mortality until a quadratic mean diameter of 26.5 cm when the second thinning should be applied. The density decreased from 409 trees ha⁻¹ to 181 trees ha⁻¹ after this second thinning. Again, the stand grew until a quadratic mean diameter of approximately 54 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 (Vià et al. 2007, Paquette & 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* J.F. Arnold) and two oak species (*Quercus ilex* L. and *Quercus faginea* Lam.), 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 the root system (Brasard et al. 2011), in addition to their role in enriching wildlife taxa (Castagneyrol & Jactel 2012).

Our results showed that introducing a new variable reflecting 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). Our results indicated that there was no impact of species mixing on stand yield represented by quadratic mean diameter and over bark volume. This is contrary to what Riofrío et al. (2019) concluded that at stand level for the two species in mixed 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 (a combination between *Pinus sylvestris* and *Fagus sylvatica* L.), the results were similar to the previous one, where it showed increased productivity in the stands with superior growth of *Pinus sylvestris* compared to *Fagus sylvatica* growth, which was reduced (Pretzsch et al. 2015).

The reasons behind these discrepancies can be attributed to the smaller scale of our data compared to the data in the study of Riofrío et al. (2019). Moreover, the mixing degree variable (*mixfrac* – Swift et al. 2007) as a way of explaining the proportion of each species in the two allometric models, total stand volume and quadratic

mean diameter, does not capture the effects on stand yield in the mixed stands of study. There is a lack of knowledge about mixed stands though it is increasing during the last few years (Pretzsch & 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 summarizes the productivity of each species individually as in pure stands. In other cases, when there are interactions between both species, the total productivity does not correspond to the sum of individual productivities in pure stands, as facilitative or competitive effects affect final productivity (Pretzsch et al. 2015). Moreover, Aldea et al. (2018) reported that drought events in the Mediterranean sites where mixed stands of co-existing species of *Pinus pinaster* Ait. and *Quercus pyrenaica* Willd might affect both species' growth, putting the stability of such mixed stands at risk.

Therefore, increased temperatures and higher frequency of drought events, which are forecasted for the Mediterranean region based on climate change scenarios, may alter radial variation cycles and cause a similar reduction in radial growth for both species.

In the present work, the interaction between both species is not clear because mixture degree was not significant in both the quadratic mean diameter or volume models.

Reineke's index (*SDI*) is being used worldwide and not just for pure even-aged stands, where it has been generalized to be used in all types of stands including mixed stands (Shaw & Long 2007). Reineke's index can be computed based on the 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.

Conclusions

In the present study, a stand density management diagram for *Pinus sylvestris* and *Pinus pinaster* mixed forests has been developed. This diagram could be a user-friendly tool for owners and managers to manage mixed stands using simple variables like dominant height or density.

The increasing interest in mixed-species forests is due to their recognized role in reinforcing ecosystem functions and services. Although, the advantages have prompted growing research to understand the mechanisms behind their functioning and stability compared to monocultures, resulting in notable insights in this regard.

But at the same time, there is still a gap in the applied knowledge, i.e., the need for silvicultural tools and management guidelines for forest managers to plan, establish and sustain mixed forest systems. However, as the mixed forest is a complex system in terms of different mixing effects at different levels, there is still a lack of knowledge and 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 considering different levels and scales.

Acknowledgments

This contribution has been supported by the Project REFORM (PCIN-2017-027) of the Spanish Ministry of Science and Innovation. A. Askarieh acknowledges the Erasmus Mundus Program MEDFOR scholarship offered by the European Commission. The authors would like to thank the reviewers for their constructive and insightful comments that helped to improve this paper.

References

- AGALSA (2006). Plan de Desarrollo Local [Local Development Plan] 2007-2013. AGALSA Sierra de la Demanda, Spain, pp. 104. [in Spanish]
- Aldea J, Bravo F, Vázquez-Piqué J, Rubio-Cuadrado A, Del Río M (2018). Species-specific weather response in the daily stem variation cycles of Mediterranean pine-oak mixed stands. *Agricultural and Forest Meteorology* 256 (257): 220-230. - doi: [10.1016/j.agrformet.2018.03.013](https://doi.org/10.1016/j.agrformet.2018.03.013)
- Alia R, Martin S (2011). EUFORGEN technical guidelines for genetic conservation and use of maritime pine (*Pinus pinaster*). International Plant Genetic Resources Institute, Rome, Italy, pp. 6. [online] URL: http://www.euforgen.org/uploads/tx_news/857
- Ammer C (2017). Unraveling the importance of inter- and intraspecific competition for the adaptation of forests to climate change. In: "Progress in Botany", vol. 78 (Cánovas FM, Lüttge U, Matyssek R eds). Springer International Publishing, Cham, Switzerland, pp. 345-367. - doi: [10.1007/124_2016_14](https://doi.org/10.1007/124_2016_14)
- Anhold JA, Jenkins MJ, Long JN (1996). Management of lodgepole pine stand density to reduce susceptibility to mountain pine beetle attack. *Western Journal of Applied Forestry* 11: 50-53. - doi: [10.1093/wjaf/11.2.50](https://doi.org/10.1093/wjaf/11.2.50)
- Assmann E (1970). The principles of forest yield study. Studies in the organic production, structure, increment and yield of forest stands. Pergamon Press, Oxford, UK.
- Barrio Anta M, Alvarez González JG (2005). Development of a stand density management diagram for even-aged pedunculate oak stands and its use in designing thinning schedules. *Forestry* 78: 209-216. - doi: [10.1093/forestry/cpi033](https://doi.org/10.1093/forestry/cpi033)
- Bengoa J (1999). Estimación de la altura dominante de la masa a partir de la "altura dominante de parcela": ventajas frente a la altura dominante de Assman [Estimation of the domi-

- nant height of the stand from the “dominant height of the plot”. Advantages over Assman’s]. *Investigación Agraria. Sistemas y Recursos Forestales* 8: 311-322. [in Spanish]
- Brassard BW, Chen HYH, Bergeron Y, Pare D (2011). Differences in fine root productivity between mixed- and single-species stands. 238-246. - doi: [10.1111/j.1365-2435.2010.01769.x](https://doi.org/10.1111/j.1365-2435.2010.01769.x)
- Burkhardt HE (2013). Comparison of maximum size-density relationships based on alternate stand attributes for predicting tree numbers and stand growth. *Forest Ecology and Management* 289: 404-408. - doi: [10.1016/j.foreco.2012.10.041](https://doi.org/10.1016/j.foreco.2012.10.041)
- Cabrera-Pérez RS, Corral-Rivas S, Quiñonez-Barrera G, Nájera-Luna JA, Cruz-Cobos F, Calderón-Leal VH (2019). Density management diagram for mixed-species forests in the El Salto region, Durango, Mexico. *Revista Chapingo - Serie Ciencias Forestales y del Ambiente* 25: 17-29. - doi: [10.5154/r.rchscfa.2018.03.026](https://doi.org/10.5154/r.rchscfa.2018.03.026)
- Castagneyrol B, Jactel H (2012). Unraveling plant-animal diversity relationships: a meta-regression analysis. *Ecology* 93: 2115-2124. - doi: [10.1890/011-1300.1](https://doi.org/10.1890/011-1300.1)
- Castedo-Dorado F, Crecente-Campo F, Alvarez-Alvarez P, Barrio-Anta M (2009). Development of a stand density management diagram for radiata pine stands including assessment of stand stability. *Forestry* 82: 1-16. - doi: [10.1093/forestry/cpm032](https://doi.org/10.1093/forestry/cpm032)
- Coll L, Ameztegui A, Collet C, Löf M, Mason B, Pach M, Verheyen K, Abrudan I, Barbati A, Barreiro S, Bielak K, Bravo-Oviedo A, Ferrari B, Govedar Z, Kulhavy J, Lazdina D, Metslaid M, Mohren F, Pereira M, Peric S, Rasztovits E, Short I, Spathelf P, Sterba H, Stojanovic D, Valsta L, Zlatanov T, Ponette Q (2018). Knowledge gaps about mixed forests: what do European forest managers want to know and what answers can science provide? *Forest Ecology and Management* 407: 106-115. - doi: [10.1016/j.foreco.2017.10.055](https://doi.org/10.1016/j.foreco.2017.10.055)
- Condés S, Aguirre A, Del Río M (2020). Crown plasticity of five pine species in response to competition along an aridity gradient. *Forest Ecology and Management* 473: 118302. - doi: [10.1016/j.foreco.2020.118302](https://doi.org/10.1016/j.foreco.2020.118302)
- Dean TJ, Baldwin VC (1993). Using a density-management diagram to develop thinning schedules for loblolly pine plantations. USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA, USA, pp. 12. - doi: [10.2737/SO-RP-275](https://doi.org/10.2737/SO-RP-275)
- Del Río M, Pretzsch H, Ruiz-Peinado R, Ampoorter E, Annighöfer P, Barbeito I, Bielak K, Brazaitis G, Coll L, Drössler L, Fabrika M, Forrester DI, Heym M, Hurt V, Kurylyak V, Löf M, Lombardi F, Makrickiene E, Matović B, Mohren F, Motta R, Den Ouden J, Pach M, Ponette Q, Schütze G, Skrzyszewski J, Sramek V, Sterba H, Stojanovic D, Svoboda M, Zlatanov TM, Bravo-Oviedo A (2017). Species interactions increase the temporal stability of community productivity in *Pinus sylvestris*-*Fagus sylvatica* mixtures across Europe. *Journal of Ecology* 105: 1032-1043. - doi: [10.1111/1365-2745.12727](https://doi.org/10.1111/1365-2745.12727)
- Dieler J, Pretzsch H (2013). Morphological plasticity of European beech (*Fagus sylvatica* L.) in pure and mixed-species stands. *Forest Ecology and Management* 295: 97-108. - doi: [10.1016/j.foreco.2012.12.049](https://doi.org/10.1016/j.foreco.2012.12.049)
- Farmden C (1996). Stand density management diagrams for lodgepole pine, white spruce and interior Douglas-fir. Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, Canada, pp. 1-41.
- Gamfeldt L, Snäll T, Bagchi R, Jonsson M, Gustafsson L, Kjellander P, Ruiz-Jaen MC, Fröberg M, Stendahl J, Philipson CD, MikusiA, Andersson E, Westerlund B, Andrén H, Moberg F, Moen J, Bengtsson J (2013). Higher levels of multiple ecosystem services are found in forests with more tree species. *Nature Communications* 4: 1340. - doi: [10.1038/ncomms2328](https://doi.org/10.1038/ncomms2328)
- Jack SB, Long JN (1996). Linkages between silviculture and ecology: an analysis of density management diagrams. *Forest Ecology and Management* 86: 205-220. - doi: [10.1016/S0378-1127\(96\)03770-X](https://doi.org/10.1016/S0378-1127(96)03770-X)
- Jactel H, Bauhus J, Boberg J, Bonal D, Castagneyrol B, Gardiner B, Gonzalez-Olabarria JR, Koricheva J, Meurisse N, Brockerhoff EG (2017). Tree diversity drives forest stand resistance to natural disturbances. *Current Forestry Reports* 3: 223-243. - doi: [10.1007/s40725-017-0064-1](https://doi.org/10.1007/s40725-017-0064-1)
- Jactel H, Nicoll BC, Branco M, Gonzalez-Olabarria JR, Grodzki W, Långström B, Moreira F, Netherer S, Christophe Orazio C, Piou D, Santos H, Schelhaas MJ, Tojic K, Vodde F (2009). The influences of forest stand management on biotic and abiotic risks of damage. *Annals of Forest Science* 66: 1-18. - doi: [10.1051/forest/2009054](https://doi.org/10.1051/forest/2009054)
- Jucker T, Bouriaud O, Avacaritei D, Danila I, Duduman G, Valladares F, Coomes DA (2014). Competition for light and water play contrasting roles in driving diversity-productivity relationships in Iberian forests. *Journal of Ecology* 102: 1202-1213. - doi: [10.1111/1365-2745.12276](https://doi.org/10.1111/1365-2745.12276)
- Lara W, Ordonez C, Bravo F (2021). basifoR: retrieval and processing of the spanish national forest inventory. R package version 0.4, web site. [online] URL: <http://cran.r-project.org/package=basifoR>
- Long JN (1985). A practical approach to density management. *The Forestry Chronicle* 61: 23-27. - doi: [10.5558/tfc61023-1](https://doi.org/10.5558/tfc61023-1)
- Long JN, Shaw JD (2005). A density management diagram for even-aged ponderosa pine stands. *Western Journal of Applied Forestry* 20 (4): 205-215. [online] URL: <https://www.fs.usda.gov/research/treearch/25005>
- Long JN, Shaw JD (2012). A density management diagram for even-aged Sierra Nevada mixed-conifer stands. *Western Journal of Applied Forestry* 27: 187-195. - doi: [10.5849/wjaf.11-036](https://doi.org/10.5849/wjaf.11-036)
- López-Sánchez C, Rodríguez-Soalleiro R (2009). A density management diagram including stand stability and crown fire risk for *Pseudotsuga menziesii* (Mirb.) Franco in Spain. *Mountain Research and Development* 29: 169-176. - doi: [10.1659/mrd.1070](https://doi.org/10.1659/mrd.1070)
- Marangon GP, Schneider PR, Zimmermann APL, Longhi RV, Cavalli JP (2017). Density management diagrams for stands of *Eucalyptus grandis* W. Hill, RS, Brazil. *Revista Árvore* 41 (1): e410108. - doi: [10.1590/1806-90882017000100008](https://doi.org/10.1590/1806-90882017000100008)
- Mátyás CLA, Samuel CJA (2004). EUFORGEN Technical guidelines for genetic conservation and use for Scots pine (*Pinus sylvestris*). International Plant Genetic Resources Institute, Rome, Italy, pp. 6.
- Newton PF (1997). Stand density management diagrams: review of their development and utility in stand-level management planning. *Forest Ecology and Management* 98: 251-265. - doi: [10.1016/S0378-1127\(97\)00086-8](https://doi.org/10.1016/S0378-1127(97)00086-8)
- Newton PF (2003). Stand density management decision-support program for simulating multiple thinning regimes within black spruce plantations. *Computers and Electronics in Agriculture* 38: 45-53. - doi: [10.1016/S0168-1699\(02\)00107-2](https://doi.org/10.1016/S0168-1699(02)00107-2)
- Paquette A, Messier C (2011). The effect of biodiversity on tree productivity: from temperate to boreal forests. *Global Ecology and Biogeography* 20: 170-180. - doi: [10.1111/j.1466-8238.2010.00592.x](https://doi.org/10.1111/j.1466-8238.2010.00592.x)
- Patrício MS, Nunes L (2017). Density management diagrams for sweet chestnut high-forest stands in Portugal. *iForest* 10: 865-870. - doi: [10.3832/ifer2411-010](https://doi.org/10.3832/ifer2411-010)
- Pretzsch H, Del Río M, Ammer C, Avdagic A, Barbeito I, Bielak K, Brazaitis G, Coll L, Dirnberger G, Drössler L, Fabrika M, Forrester DI, Godvold K, Heym M, Hurt V, Kurylyak V, Löf M, Lombardi F, Matović B, Mohren F, Motta R, Den Ouden J, Pach M, Ponette Q, Schütze G, Schweig J, Skrzyszewski J, Sramek V, Sterba H, Stojanovic D, Svoboda M, Vanhellefont M, Verheyen K, Wellhausen K, Zlatanov T, Bravo-Oviedo A (2015). Growth and yield of mixed versus pure stands of Scots pine (*Pinus sylvestris* L.) and European beech (*Fagus sylvatica* L.) analysed along a productivity gradient through Europe. *European Journal of Forest Research* 134: 927-947. - doi: [10.1007/s10342-015-0900-4](https://doi.org/10.1007/s10342-015-0900-4)
- Pretzsch H, Schütze G (2016). Effect of tree species mixing on the size structure, density, and yield of forest stands. *European Journal of Forest Research* 135: 1-22. - doi: [10.1007/s10342-015-0913-2](https://doi.org/10.1007/s10342-015-0913-2)
- Pretzsch H, Forrester DI, Bauhus J (2017). Mixed-species forests. Ecology and management. Springer, Berlin, Germany, pp. 653. - doi: [10.1007/978-3-662-54553-9](https://doi.org/10.1007/978-3-662-54553-9)
- Quiñonez-Barrera G, Tamarit-Urias JC, Martínez-Salvador M, García-Cuevas X, De los Santos-Posadas HM, Santiago-García W (2017). Maximum density and density management diagram for mixed-species forests in Durango, Mexico. *Revista Chapingo - Serie Ciencias Forestales y del Ambiente* 24: 73-90. - doi: [10.5154/r.rchscfa.2017.09.056](https://doi.org/10.5154/r.rchscfa.2017.09.056)
- R Core Team (2019). R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. [online] URL: <https://www.r-project.org>
- Reineke LH (1933). Perfecting a stand-density index for even-aged forests. *Journal of Agricultural Research* 46: 627-638.
- Riofrío J, Del Río M, Bravo F (2017). Mixing effects on growth efficiency in mixed pine forests. *Forestry* 90: 381-392. - doi: [10.1093/forestry/cpw056](https://doi.org/10.1093/forestry/cpw056)
- Riofrío J, Del Río M, Maguire DA, Bravo F (2019). Species mixing effects on height-diameter and basal area increment models for scots pine and maritime pine. *Forests* 10: 1-22. - doi: [10.3390/f10030249](https://doi.org/10.3390/f10030249)
- Rodríguez JR, Serrada R, Lucas JA, Reyes A, Del Río M, Torres E, Cantero Amiano A (2008).

- Selvicultura de *Pinus pinaster* Ait. subsp. *mesogeensis* Fieschi and Gausen [Silviculture of *Pinus pinaster* Ait. subsp. *mesogeensis* Fieschi and Gausen]. Compendio de Selvicultura Aplicada en España, Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA), Madrid, Spain, pp. 399-430. [in Spanish]
- Schnell S, Kleinn C, Alvarez González JG (2012). Stand density management diagrams for three exotic tree species in smallholder plantations in Vietnam. *Small Scale Forestry* 11: 509-528. - doi: [10.1007/s11842-012-9197-z](https://doi.org/10.1007/s11842-012-9197-z)
- Sharma M, Zhang SY (2007). Stand density management diagram for jack pine stands in Eastern. *Northern Journal of Applied Forestry* 24: 22-29. - doi: [10.1093/njaf/24.1.22](https://doi.org/10.1093/njaf/24.1.22)
- Shaw JD, Long JN (2007). A density management diagram for longleaf pine stands with application to red-cockaded woodpecker habitat. *Southern Journal of Applied Forestry* 31: 28-38. - doi: [10.1093/sjaf/31.1.28](https://doi.org/10.1093/sjaf/31.1.28)
- Swift E, Penner M, Gagnon R, Knox J (2007). A stand density management diagram for spruce-balsam fir mixtures in New Brunswick. *Forestry Chronicle* 83: 187-197. - doi: [10.5558/tfc83187-2](https://doi.org/10.5558/tfc83187-2)
- Tang X, Pérez-Cruzado C, Vor T, Fehrmann L, Alvarez-González JG, Kleinn C (2016). Development of stand density management diagrams for Chinese fir plantations. *Forestry* 89: 36-45. - doi: [10.1093/forestry/cpv024](https://doi.org/10.1093/forestry/cpv024)
- Tesfaye MA, Bravo F, Bravo-Oviedo A (2016). Alternative silvicultural stand density management options for Chilimo dry afro-montane mixed natural uneven-aged forest using species proportion in Central Highlands, Ethiopia. *European Journal of Forest Research* 135: 827-838. - doi: [10.1007/s10342-016-0976-5](https://doi.org/10.1007/s10342-016-0976-5)
- Vacchiano G, Derose RJ, Shaw JD, Svoboda M, Motta R (2013). A density management diagram for Norway spruce in the temperate European montane region. *European Journal of Forest Research* 132: 535-549. - doi: [10.1007/s10342-013-0694-1](https://doi.org/10.1007/s10342-013-0694-1)
- Valbuena P, Del Peso C, Bravo F (2008). Stand density management diagrams for two Mediterranean pine species in Eastern Spain. *Investigación Agraria: Sistemas y Recursos Forestales* 17: 97. - doi: [10.5424/srf/2008172-01026](https://doi.org/10.5424/srf/2008172-01026)
- Van Der Plas F, Manning P, Allan E, Scherer-Lorzen M, Verheyen K, Wirth C, Zavala MA, Hector A, Ampoorter E, Baeten L, Barbaro L, Bauhus J, Benavides R, Benneter A, Berthold F, Bonal D, Bouriaud O, Bruelheide H, Bussotti F, Carnol M, Castagneyrol B, Charbonnier Y, Coomes D, Coppi A, Bastias CC, Muhie Dawud S, De Wandeler H, Domisch T, Finér L, Gessler A, Granier A, Grossiord C, Guyot V, Hättenschwiler S, Jactel H, Jaroszewicz B, Joly FX, Jucker T, Koricheva J, Milligan H, Müller S, Muys B, Nguyen D, Pollastrini M, Raulund-Rasmussen K, Selvi F, Stenlid J, Valladares F, Vesterdal L, Zielinski D, Fischer M (2016). Jack-of-all-trades effects drive biodiversity-ecosystem multifunctionality relationships in European forests. *Nature Communications* 7: 1-11. - doi: [10.1038/ncomms11109](https://doi.org/10.1038/ncomms11109)
- Vanderschaaf CL, Burkhart HE (2012). Development of planting density-specific density management diagrams for loblolly pine. *Southern Journal of Applied Forestry* 36: 126-129. - doi: [10.5849/sjaf.10-043](https://doi.org/10.5849/sjaf.10-043)
- Vilà M, Vayreda J, Comas L, Ibáñez JJ, Mata T, Obón B (2007). Species richness and wood production: a positive association in Mediterranean forests. *Ecology Letters* 10: 241-250. - doi: [10.1111/j.1461-0248.2007.01016.x](https://doi.org/10.1111/j.1461-0248.2007.01016.x)