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Article

Guía de densidad para el manejo de rodales naturales de *Pinus rudis* Endl. en Oaxaca

Density management guide for natural stands of *Pinus rudis* Endl. in *Oaxaca*

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Resumen

La densidad forestal asociada con la calidad de sitio determina la productividad del bosque, y su medición permite predecir tasas de crecimiento y mortalidad. El manejo a través de aclareos mejora las características del bosque, ya que reduce la competencia entre individuos. El propósito del presente estudio, fue construir una guía de densidad para el manejo de rodales naturales de *Pinus rudis* en la región Mixteca de Oaxaca, México. El índice de densidad de *Reineke* (IDR) se calculó a partir de los diámetros cuadráticos y número de árboles por hectárea de 81 sitios de muestreo de dimensiones variables, ubicados en masas puras*,* de ocupación completa y diferentes etapas de crecimiento. El factor de competencia de copas (FCC) se estimó mediante el ajuste del modelo de regresión lineal simple, con datos del diámetro normal-diámetro de copa de 54 árboles sin presencia de plagas o enfermedades, defectos físico-mecánicos y que estaban creciendo libres de competencia. El ajuste del modelo de *Reineke* y el de regresión lineal simple se realizó con la técnica de Mínimos Cuadrados Ordinarios. A partir del IDR y el FCC se construyó una guía de densidad, con la cual se determinó que los rodales objeto de estudio presentan niveles de densidad por arriba de 90 % de IDR, con un diámetro cuadrático de 15 cm.

Palabras clave: Aclareos, competencia, factor de competencia de copas, índice de densidad de *Reineke*, manejo forestal, silvicultura.

Abstract

Forest density associated with site quality determines forest productivity and its measurement allows prediction of growth and mortality rates. Management through thinning improves forest characteristics by reducing competition between trees. The aim of the present study was to construct a density guide for the management of natural stands of *Pinus rudis*, in the *Mixteca* region of *Oaxaca*, Mexico. The Reineke's Stand Density Index (SDI) was estimated from the quadratic diameters and number of trees per hectare of 81 variable size sampling sites, located in pure forest, with full occupation and different development stages of forest stands. The Crown Competition Factor (CCF) was estimated by fitting the simple linear regression model with normal diameter-crown diameter data from 54 healthy trees, without physical-mechanical defects and that grown without competition. The adjustment of the Reineke model and that of simple linear regression was carried out using the ordinary least squares technique. The density guide was developed through SDI and CCF, these measurements allowed to know that the stands under study have density levels higher than 90 % of the SDI, with a quadratic diameter of 15 cm.

Key words: Thinning, competition, crown competition, Reineke's density index, forest management, forestry.

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Introduction

Density management guides or diagrams are an important forest management tool which serves as an instrument for determining the optimum number of individuals that grow in a stand at different stages of development (Navarro *et al*., 2011). In addition, they can increase timber productivity through good planning and monitoring of forestry interventions (Gezan *et al.,* 2007; Hernández *et al*., 2013).

There are absolute and relative methods to assess the density of a stand or plantation; the former refer to the number of trees and basimetric area per hectare and provide an estimate of the number of individuals present in a population but do not provide information about competition on the site (Torres and Velázquez, 2000). Relative indexes, such as Reineke's Stand Density Index (SDI) (Reineke, 1933), Yoda's Density Index (YDI) (Yoda *et al.*, 1963), tree-area ratio (TAR) (Chisman and Schumacher, 1940), crown competition factor (CCF) (Krajicek *et al.*, 1961), and relative density (Curtis, 1970) describe the level of stand density and serve as indicators of the need for silvicultural treatments in the forest (Torres and Velázquez 2000; Torres and Magaña, 2001).

The SDI is one of the most widely used measures of relative density in the construction of density guides or diagrams (Tamarit *et al.*, 2020); it is based on the functional relationship between the number of trees per hectare of a stand and its quadratic diameter (Quiñonez *et al.,* 2017; Tamarit *et al*., 2020). Based on this, self-thinning lines have been generated for conifer, broadleaf and mixed-species forests (Gezan *et al*., 2007; Navarro *et al.,* 2011; Santiago *et al.,* 2013; Quiñonez *et al*., 2017; Tamarit *et al*., 2018).

The first density guide was developed by Gingrich (1967) for leafy taxa in the central states of the United States of America. In Mexico, such a guide was first generated in the 1980s, with authors such as Zepeda and Villareal (1987), who developed one such guide for *Pinus hartwegii* Lindl. in the center of the country. Márquez and Álvarez (1995) constructed a guide for the management of *Pinus cooperi* var. *ornelasi* (Martínez) Blanco stands in *Durango*, and García *et al.* (1996), one for the management of *Swietenia macrophylla* King plantations in the state of *Quintana Roo*. In the former cases, the density indices used were TAR, CCF, and SDI.

Santiago *et al.* (2013) and Tamarit *et al*. (2018) constructed density plots for *Pinus patula* Schiede ex Schltdl. & Cham. in the states of *Hidalgo* and *Puebla*, respectively; Quiñonez *et al*. (2017) did the same for the mixed forests of northern Mexico. The development of these tools has been mainly for prescribing thinning for timber production purposes.

Pinus rudis Endl. is a species widely distributed in the Mexico, in an altitudinal range of 2 200 to 3 300 m, although it is possible to find it above 3 300 masl. The height of its individuals varies between 20 and 30 m, and their diameter, between 40 and 70 cm. It is associated with *Pinus ayacahuite* Ehrenb. ex Schltdl., *P. montezumae* Lamb. and *P. hartwegii.* Its timber is used mainly for construction purposes (Perry, 1991).

Between 1998 and 2005, several populations of *P. rudis* were affected by forest fires in the agrarian community of *San Miguel El Grande*, in the *Mixteca* region of *Oaxaca* (Martínez, 2009). Consequently, these areas have a high density of post-fire natural regeneration (Caballero *et al*., 2018). In this context, the objective of this study was to construct a density guide for the management of natural stands of *Pinus rudis* in the *Mixteca* region of *Oaxaca*, Mexico.

Materials and Methods

Study area

The agrarian community of *San Miguel El Grande* is located in western *Oaxaca*, at an altitude ranging from 2 200 to 3 330 m, between 16°58'29" and 17°10'27" N, and 97°33'23" and 97°40'21" W. The study was conducted in the natural distribution area of *P. rudis*, in an area of approximately 1 242 ha (Figure 1). The predominant types of climates in the community are Cb'(w_2) and C(c_2), with summer rains (García, 1998). The soil types are regosols, lithosols, and vertisols (INEGI, 2014). The vegetation is represented by pine and pine-oak forests (INEGI, 2016), where the main species of conifers are *Pinus oaxacana* Mirov, *P. pseudostrobus* Lindl., *P. douglasiana*

Martínez*, P. rudis, P. oocarpa* Schiede and *P. leiophylla* Schltdl*. et* Cham*.* and *Abies hickelii* Flous & Gaussen; taxa of the *Quercus* genera and *Arbutus* grow in lesser proportions (Martínez, 2009).

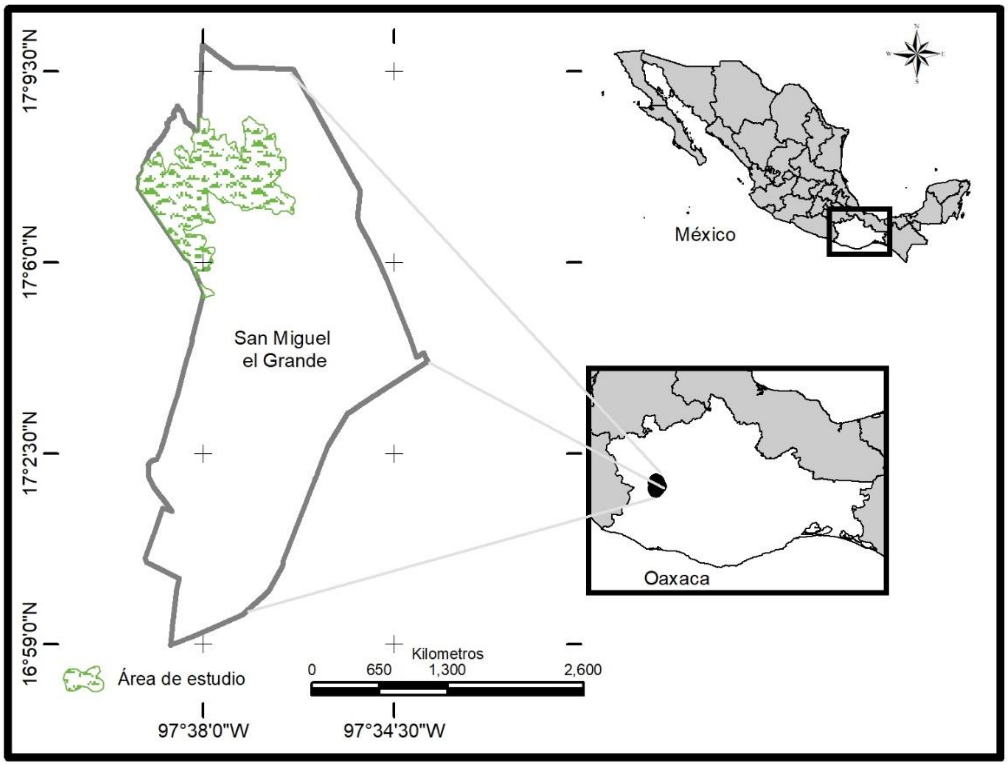


Figure 1. Geographic location of the study area.

Estimation of Reineke's Stand Density Index

For the estimation of this index, 81 sites of different dimensions were selectively located in the following areas, using the sampling method proposed by Prodan (1968), which considers the measurement of six trees and defines the sampling unit as a circular area whose radius extends from the center of the site to the center of the sixth tree (Figure 2). The site was selected considering areas of forest between scrubland and woodland (Müller *et al*., 2013; Aguilar, 2018), stands of which more than 90 % consisted of trees of the same species, homogeneous areas of full occupancy, and sites with healthy trees, free of physical damage (Lee and Choi, 2019).

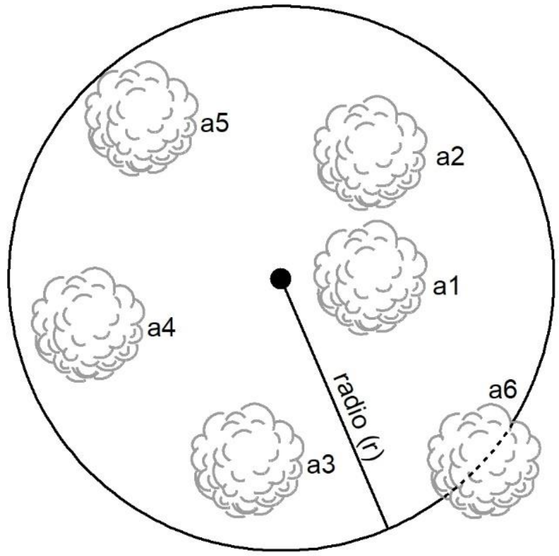


Figure 2. Six-tree sampling site.

The normal diameter (*D*) of all individuals at the sampling site was measured with a diameter tape (Forestry Suppliers, model 283d/160 cm), at a height of 1.3 m; this variable was used to estimate the basal area of the individuals present within the sampling site.

$$g=\frac{\pi}{4}\left(\frac{D}{100}\right)^2 \qquad (1)$$

Where:

g = Individual basimetric area (m^2)

D = Normal diameter (cm)

$\pi/4$ = Constant (0.7854)

Two measures of absolute density —basimetric area per hectare (*G*) and number of trees per hectare (*N*)— were estimated using the equations described by Ramos *et al.* (2017).

$$N = N_i\left(\frac{Sh}{Se}\right) \qquad (2)$$

$$G = G_i\left(\frac{Sh}{Se}\right) \qquad (3)$$

Where:

N = Number of individuals per hectare

N_i = Number of individuals per site

G = Basimetric area per hectare (m^2)

G_i = Basimetric area per site (m^2)

Sh = Area of one hectare (m^2)

Se = Area evaluated at sampling site (m^2)

Once these two indicators (G and N) were estimated, the quadratic diameter (Qd) of each sample plot was calculated, with the following expression (Santiago *et al*., 2013):

$$Qd = \sqrt{\frac{40000}{\pi} \times \frac{Ba}{Na}} \qquad (4)$$

Where:

Qd = Quadratic diameter (cm)

Ba = Basimetric area per hectare (m^2)

Na = Number of trees per hectare

π = Constant (3.1416)

The *Qd* and *Na* values per site were used to fit Reineke's model (5), which defined the maximum average density line of the guide (line A). For stand density comparison purposes, a *Qd* of 25 cm or 10 inches is considered in this index (Reineke, 1933; Santiago *et al*., 2013; Hernández *et al*., 2013).

$$Na = \beta_0 Qd^{\beta_1} \qquad (5)$$

Where:

Na = Number of trees per hectare

Qd = Quadratic diameter (cm)

β_0 = Intercept to the ordinate axis

β_1 = Slope

Ba was the product of the individual basimetric area at a given diameter, times the number of trees estimated with equation 5 (Rodríguez *et al*., 2009):

$$Ba = \frac{\pi}{4} \times \left(\frac{D}{100}\right)^2 \times Na \qquad (6)$$

Where:

Ba = Basimetric area per hectare (m^2)

D = Normal diameter (cm)

Na = Number of trees per hectare

$\pi/4$ = Constant (0.7854)

Estimation of the crown competition factor

This measure of density was estimated through a targeted sampling of 54 trees that grew free of competition, healthy and without physical-mechanical defects. The variables evaluated for each individual were diameter (*D*) and crown diameter (*Cd*), which were measured with a Pretul model Pro-30me longimeter, in a north-south and east-west direction, in order to obtain the average per individual (Rodríguez *et al*., 2009).

The 54 pairs of data (*D*-*Cd*) were used to estimate the *Cd* as a function of *D* (7), after which the crown areas (*Ca*) (8) corresponding to trees free of competition at a given diameter were calculated (Rodríguez *et al*., 2009; Hernández *et al*., 2013).

$$Cd = \beta_0+\beta_1 D \qquad (7)$$

$$Ca = \frac{\pi}{4} \times Cd^2 \qquad (8)$$

Where:

Cd = Crown diameter (m)

D = Normal diameter (cm)

β_0 = Intercept to the ordinate axis

β_1 = Slope

Ca = Crown area (m^2)

$\pi/4$ = Constant (0.7854)

The maximum crown area (*Mca*) of an individual, expressed as a percentage of the surface unit (ha) was determined with equation 9 (Rodríguez *et al*., 2009; Hernández *et al*., 2013):

$$Mca = \frac{Ca}{100} \qquad (9)$$

Where:

Mca = Maximum crown area

Ca = Crown area (m^2)

Finally, the number of trees and basimetric area per hectare were estimated with equations 10 and 11, respectively; based on these values, the sufficient density line of the guide (line B) was calculated (Rodríguez *et al*., 2009; Hernández *et al*., 2013):

$$Na = \frac{100}{Mca} \qquad (10)$$

$$Ba = \frac{\pi}{4} \times \left(\frac{D}{100}\right)^2 \times Na \qquad (11)$$

Where:

Na = Number of trees per hectare

Mca = Maximum crown area

Ba = Basal area per hectare (m^2)

D = Normal diameter (cm)

π/4 = Constant (0.7854)

Model fit

The adjustment of equations 5 and 7 was performed by the Ordinary Least Squares (OLS) method in STATISTICA 10 software (StatSoft Inc., 2011), through nonlinear and linear regression, respectively. The quality of fit of the models was evaluated by the value of the coefficient of determination (r^2), the root mean squared error (RMSE), as well as the value of their likelihood (Vargas, 1999; Hernández *et al*., 2013).

Density guide construction

In order to construct the density guide, line A or 100 % (average maximum density) was determined with the *Na* ha^{-1} and *Ba* ha^{-1} estimated from the Reineke model; based on these values, different density levels (30 to 110 %) were calculated at intervals of 10 %. The B line (sufficient density) was determined by the *Na* ha^{-1} and *Ba* ha^{-1} resulting from the CCF (Vargas, 1999).

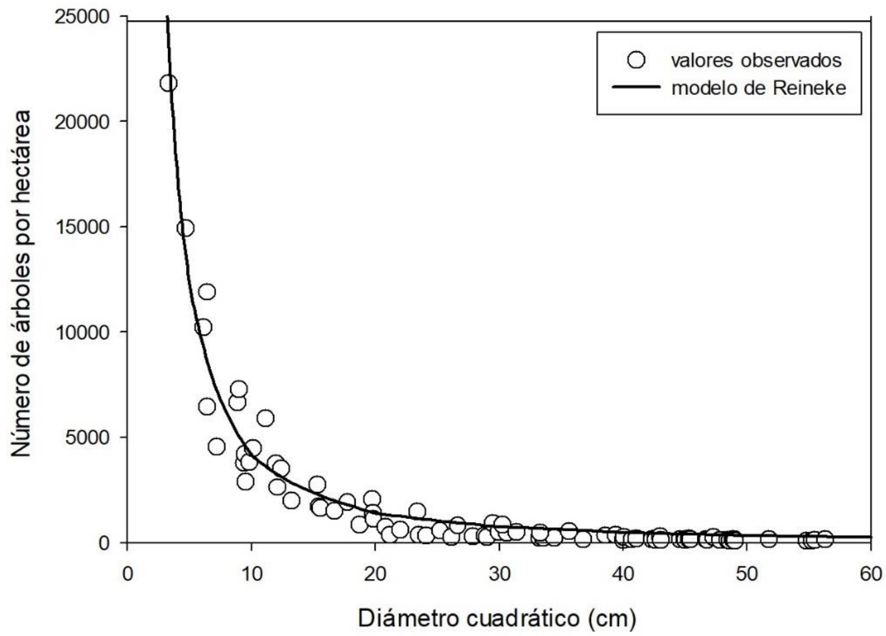
Results and Discussion

Reineke's density index

The *Qd* explained 94 % (r^2 = 0.94) of the variation in the number of trees per hectare, with a mean error (RMSE) of 831 and significant parameters at 95 % confidence (ɑ<0.0001). The resulting equation was as follows:

$$N = 149786.8 \times Qd^{-1.55442}$$

The graphical representation of the observed values (*Qd* and *Na* ha^{-1}) showed an inverted "J" dispersion, which is shown in Figure 3 with the fitting curve of the Reineke model (Figure 3).



Diámetro cuadrático = Quadratic diameter; *Número de árboles por hectárea* = Number of trees per hectare*; Valores observados* = Observed values; *Modelo de Reineke* = Reineke's model.

Figure 3. Relationship between the quadratic diameter and the number of trees per hectare.

The values of the average maximum densities, estimated from Reineke's model, were the basis for constructing the rest of the isolines of the density guide (Table 1).

Table 1. Average maximum densities estimated with Reineke's model.

Qd	***Na*·ha^{-1}**	***Ba*·ha^{-1}**
10	4179	32.82
15	2225	39.32
20	1423	44.70
25	1006	49.37
30	758	53.55
35	596	57.35
40	484	60.87
45	403	64.15
50	342	67.23

Qd = Quadratic diameter (cm); *Na* ha^{-1}= Number of trees per hectare; *Ba* ha^{-1} = Basimetric area per hectare.

Based on the reference *Qd* value (25 cm), an SDI of 1 006 was estimated. In this regard, Rodríguez *et al.* (2009) obtained a value of 1 663 for *P. montezumae* Lamb; while Hernández *et al.* (2013) recorded a value of 775 for *Pinus teocote* Schiede ex Schltdl. & Cham. Both studies were conducted in the state of *Hidalgo,* Mexico. Approximate SDI values can be calculated only in pure stands with full density consisting of trees of the same species and with the same average stand diameter (Reineke, 1933).

Several values of the slope (β_1) have been estimated for the Reineke´s model, most varying between -1.0151 (Rodríguez *et al*., 2009) and -2.18937 (Tamarit *et al.*, 2018). Likewise, studies have been developed to determine if the value of β_1 postulated by Reineke (1993) is statistically equal to -1.605; one of them is by Pretzsch and Biber (2005), who adjusted the equation for forests of *Fagus sylvatica* L., *Picea abies* (L.) Karst., *Pinus sylvestris* L. and *Quercus petraea* (Mattuschka) Liebl. in Germany; for these taxa, *P. sylvestris* L. excepted, the slope value was significantly different.

Guezan *et al.* (2007) developed density diagrams for *Nothofagus obliqua* (Mirb.) Oerst, *N. alpina* (Poepp. & Endl.) Oerst., *N. dombeyi* (Mirb.) Oerst. in Chile, and concluded that the value of the parameter β_1 is species-specific.

Santiago *et al.* (2013) constructed density guides for *Pinus patula* in the state of *Hidalgo*, Mexico. The estimated slopes were -1.565±0.208 for Reineke's model and 1.199±0.048 for Yoda's model. In the first case, it includes the value postulated by Reineke (1933). Likewise, Quiñonez *et al.*, (2017), in their density plot work in mixed forests of *Durango*, Mexico, obtained an interval from -1.541 to -1.778, which includes the value of -1.605.

Santiago *et al.* (2013), Quiñonez *et al*. (2017) and Tamarit *et al*. (2018) compared adjustment methods for defining the self-thinning line and used Ordinary Least Squares (OLS) and stochastic border regression (SBR), and they agree that SBR efficiently estimates the upper boundary of self-thinning. According to VanderSchaaf and Burkhart (2007) and Comeau *et al.* (2010), the OLS method is also appropriate for characterizing the maximum density line.

In general terms, the SDI has been widely used in the construction of density diagrams or guides (Vargas, 1999; Gezan *et al.*, 2007; Navarro *et al*., 2011; Santiago *et al*., 2013; Hernández *et al*., 2013; Quiñonez *et al*., 2017; Tamarit *et al*., 2018; Tamarit *et al*., 2020). These diagrams offer greater precision compared to those constructed with the Yoda index and the Relative Space index, since Reineke's model uses the *Qd* calculated from the normal diameter, which is a direct measurement variable; the other two use the volume and total height, respectively, which are generally estimated using some mathematical model (Tamarit *et al*., 2020).

Crown competition factor

Diameter (*D*) accounted for 83 % (r^2=0.83) of the variation in *Cd*, with a mean error (RMSE) of 1.05 and significant parameters at 95 % confidence (ɑ<0.0001). The resulting equation was defined as:

$$Cd = 1.438794 + 0.1354 \times D$$

Table 2 shows the results obtained from equations 7-11, whose objective was to estimate the *Na* ha^{-1} and *Ba* ha^{-1} in order to define the sufficient density line of the guide.

Table 2. Densities estimated based on the crown competition factor.

D	***Cd* (7)**	***Ca* (8)**	***Mca* (9)**	***Na* ha^{-1} (10)**	***Ba* ha^{-1} (11)**
10	2.79	6.13	0.061	1632	12.82
15	3.47	9.46	0.095	1058	18.69
20	4.15	13.51	0.135	740	23.26
25	4.82	18.28	0.183	547	26.86
30	5.50	23.77	0.238	421	29.74
35	6.18	29.97	0.300	334	32.10
40	6.85	36.90	0.369	271	34.05
45	7.53	44.55	0.446	224	35.70
50	8.21	52.92	0.529	189	37.10

D = Normal diameter (cm); *Cd* = Crown diameter (m); *Ca* = Crown area (m^2); *Na* ha^{-1} = Number of trees per hectare; *Ba* ha^{-1} = Basal area per hectare (m^2).

The trees in any stand below the CCF (line B) have sufficient resources to develop their full growth potential, since they do not compete with other individuals (Krajicek *et al.,* 1961; Álvarez *et al*., 2004). However, if the density is kept below the CCF until the trees reach their maturity, these will be of poor quality if pruning is not applied (Krajicek *et al.,* 1961). Within this context, the individuals are resistant to mechanical forces (wind and snow), but with disadvantages in sawing performance, since they have a low slenderness value and a high crown percentage (Arias, 2005).

When the stand is above line B, crown closure occurs. At this time, competition between individuals begins; however, there is no immediate mortality (Gezan *et al*., 2007). Philbrook *et al*. (1973) point out that the effect of competition starts when the stock is halfway between A and B, *i.e*., for this study, above 70 % of the SDI.

Santiago *et al*. (2013) estimated that natural mortality in *Pinus patula* occurs from 55 % of the SDI up. According to Quiñonez *et al.* (2017), in stands with a mixture of species, the effect of competition occurs when the value of the SDI is 70 %.

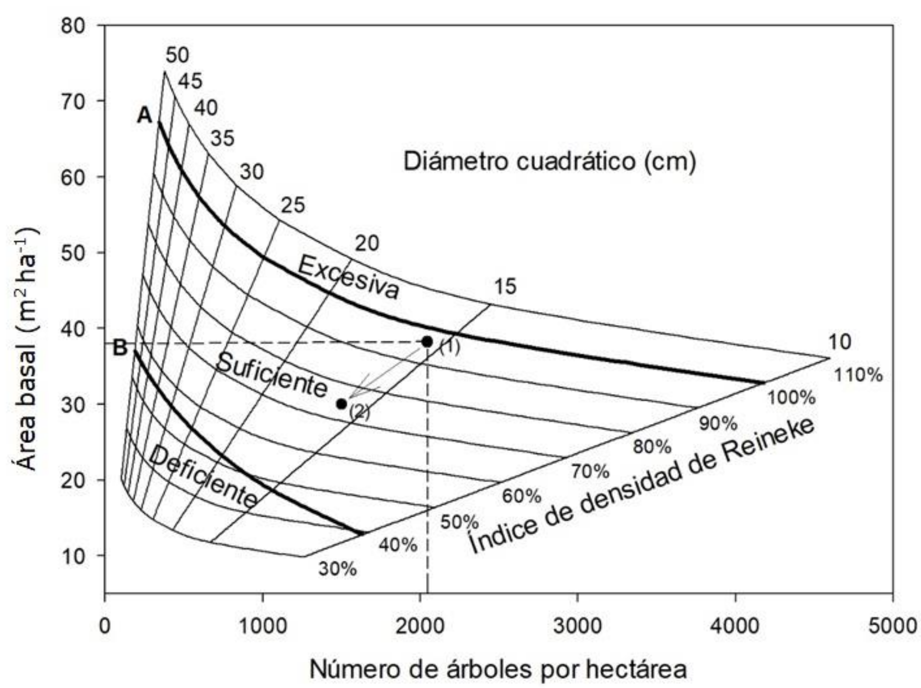
Density guide construction

Line A was determined based upon the average maximum densities estimated with Reineke's model; stands above this line are considered overpopulated areas, which require immediate cutting to improve the quality of the residual tree stock (Hernández *et al*., 2013; Santiago *et al*., 2013; Quiñonez *et al*., 2017; Tamarit *et al*., 2018).

Line B is represented by the CCF; any stand below this line is considered underpopulated or with poor density (Vargas, 1999; Rodríguez *et al*., 2009; Hernández *et al*., 2013). The density of the stand of the present study must be increased so that decisions can be made regarding its management, or if necessary, another intermediate treatment —such as fertilization, if the main objective is timber production— must be applied in order to achieve site improvement (Daniel *et al.,* 1982).

In order to exemplify the application of the guide, three sampling sites of 100 m^2 (10 × 10 m) were erected in an area of natural regeneration of *Pinus rudis*. The normal diameter of each individual was measured, and the number of trees per site was counted; based on these variables, the *Ba* ha^{-1} and *Na* ha^{-1} were calculated. The average values calculated were 38.27 m^2 of *Ba* ha^{-1} and 2 045 m^2 of *Na* ha^{-1}. By placing these values in the guide (1), an SDI of 96 % and an approximate *Qd* of 15.5 cm were graphically estimated.

If the stand is taken from condition 1 to condition 2, its density level will rise to 75 %, and 8.26 m^2 of Ba ha^{-1} and approximately 545 *Na* ha^{-1} will be removed. The purpose is to maintain the stand between lines A and B in a desired condition according to management objectives (Figure 4).



Diámetro cuadrático = Quadratic diameter; *Área basal* = Basimetric área; *Número de árboles por hectárea* = Number of trees per hectare; *Índice de densidad de Reineke* = Reineke's density index; *Deficiente* = Deficient; *Suficiente* = Sufficient; *Excesiva* = Excessive.

Figure 4. Density guide for *Pinus rudis* Endl.

Conclusions

The models adjusted for the estimation of the SDI and CCF show a good quality of fit using the Ordinary Least Squares technique, with coefficients of determination (r^2) of 0.94 and 0.83, respectively. The density guide described in this study is a support tool for foresters, as it will allow them to know the absolute and relative density levels of the forest, as well as the thinning needs and the thinning intensities required. The methodology presented is simple and easy to apply in the field, and it is a reliable foundation for the construction of density guides in natural stands and forest plantations.

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Conflict of interest

The authors declare no conflict of interests.

Contribution by author

Daniel Martínez Santiago: planning of activities, collection of field data, data analysis and drafting of the manuscript; Prudencia Caballero Cruz and Eduardo Filio Hernández: field data collection and review of the manuscript; Alejandro Garzón Trinidad, Rosalino Ortiz Barrios, Octavio Lemuel Cruz Santiago, Ithaiz Aparicio Cuevas and Carmela Sandoval García: field data collection.

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