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ORIGINAL PAPER

Alternative silvicultural stand density management options for Chilimo dry afro-montane mixed natural uneven-aged forest using species proportion in Central Highlands, Ethiopia

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Abstract Chilimo forest is one of the few remnants of dry afro-montane mixed uneven-aged natural forest located in Central Highlands of Ethiopia. Also it has been during the last century one of the most exploited and disturbed forest in the country. Stand density management diagram (SDMD) is a stand-level model that graphically illustrates the relationships between wood yield, density and mortality throughout all stages of stand development. SDMD is a useful tool for designing, displaying and evaluating alternative density management regimes for both even-aged and uneven-aged forest stands. However, information in this regard and other silvicultural management operations are lacking for most Ethiopian forests in general and Chilimo dry afro-montane forest in particular. The purpose of the study is to develop a SDMD model for the existing mixed natural forest using appropriate species proportion for *Juniperus procera* and *Podocarpus falcatus*. Two linear equations were simultaneously fitted to relate quadratic mean diameter with stand density and dominant height and relate it to total stand volume with quadratic mean diameter, stand density and dominant height. Moreover, dominant height and quadratic mean diameter were found to be the best endogenous variables for SDMD for Chilimo forest. The relationship between stand density, dominant height, quadratic mean diameter and stand volume is represented in the SDMD graph. Formulating SDMD using species proportion is better than treating each species independently. This SDMD is the first diagram model developed for mixed forest in Africa, and it can serve sustainable management of Chilimo dry afro-montane forest in particular and other dry afro-montane forests in general.

Keywords Chilimo · Dominant height · Mixed species · Species proportion · Thinning operation

Introduction

Stand density management control (through initial spacing in forestation and/or pre-commercial and commercial thinning) modifies the level of growing stock to achieve the management objectives established for a given stand (Newton 1997; Barrio-Antam et al. 2005; Castedo-Dorado et al. 2009). SDMD graphically illustrate the relationships between yield, density and density-dependent mortality during the stand development phases (Newton and Weetman 1994; Tesfaye 2015). SDMDs are management tools which facilitate decision-making process for forest managers under limited information. Appropriate decision-making process must be made to enhance future stand values, trees and wood properties and habitat characteristics. SDMDs are designed to assist managers in applying different density management regimes regarding the timing and intensity of thinning treatments based on the theory of self-thinning and the relationships between average

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diameter, top height and volume of stands within the stand (trees ha^{-1}) (Woods 1999; Farnden 2002; Álvarez-González et al. 2005). Due to the increasing interest on biomass, maximization of wood yield in addition to financial return became a key objective for foresters (Cole and Ewel 2006; Bravo et al. 2008; Castedo-Dorado et al. 2009). This objective requires estimating the distribution of trees as it is related with product price, so during the last decade, structural yield prediction has been included in SDMDs (Newton et al. 2005; Castedo-Dorado et al. 2009).

Since Ando's (1962) seminal paper on SDMDs, several improvements and modifications have been made such as the replacement of the original yield, density equations and the application of different density indexes (McCarter and Long 1986; Newton and Weetman 1994; Newton 1997; Díaz-Maroto et al. 2010). Due to its easy use and applicability, it is not surprising that SDMDs became an important management tool for even-aged stands in many regions across North America and Europe (Drew et al. 1979; Smith 1989; Wilson et al. 1999; Valbuena et al. 2008; Bravo et al. 2012; Tesfaye 2015). Moreover, during the last decade and late twentieth century, SDMDs were also developed for mixed stands (Newton 1997; Woodalle et al. 2005; Swift et al. 2007). Determining appropriate levels of growing stock at the stand level is a complex process involving both biological and technological aspect. It requires selection of upper and lower limits for growing stock (Dean and Baldwin 1996). SDMDs are one of the most effective methods available for the design, display and evaluation of alternative density management regimes for both even-aged and uneven-aged stands (Woodalle et al. 2005) due to the relative low effect of site variance on the diagram's shape (Kershaw and Fischer 1991). SDMDs are used in combination with data reflecting stand structure to project stand future development including yield prediction.

Recommendation of thinning operation through the management of stocking with SDMD for both natural and plantation forests is lacking for most tropical countries in general and Ethiopia in particular (Tesfaye 2015; Tesfaye et al. 2014, 2015, 2016). Thus, adequate research works should be made in this regard to explore whether or not SDMD can be applied for mixed stands to take it as silvicultural management options.

Chilimo forest is one of the few remnants of dry afro-montane forest, located in the Central Highland plateau of Ethiopia managed by local community through participatory forest management (Shumi 2009; Tesfaye 2015). Currently, the Oromiya forest and wildlife enterprise, which is a governmental institution, aimed at facilitating the management approach. In the process, they are advocating preservation and protection of the natural forest with little benefit to the local community (Tesfaye 2015). However, different assessment works showed that the forest is suffering from illegal harvesting (Shumi 2009; Tesfaye 2015). Hence, implementation of alternative forest management options should be explored to benefit the society by maintaining sustainability of the forest. SDMD is an option in both circumstances. Thus, we hypothesized that SDMD can be applied for the management of mixed uneven-aged tropical forest such as Chilimo. The specific objective of the study is to develop a SDMD for the management of Chilimo mixed dry afro-montane forest using appropriate species proportion for *Juniperus procera* (Hoechst. Ex. Endl) and *Podocarpus falcatus* (Thunb. Mirb).

Materials and methods

Study site location

The experimental site is located in the Chilimo dry afro-montane forest of the Western Shewa zone, in the Dendi district of the Central Highlands of Ethiopia (38°07′E–38°10′E longitude and 9°30′–9°50′N′ latitude), at an altitude of 2170–3054 m above sea level (Fig. 1). The mean annual temperature ranges between 15 and 20 °C, and the area receives an average of 1264 mm precipitation yearly (Shumi 2009). Köppen's typology classifies the Chilimo forest as a temperate highland climate with dry winters (CWB) (EMA 1988).

Reconnaissance survey

A preliminary discussion forum was held with higher officials of the Oromiya Wildlife and Forest Enterprise in Addis Ababa. Subsequently, a reconnaissance survey was conducted through a field visit and physical observation across the Chilimo forest. Three patches (Chilimo, Gaji and Gallessa) were selected based on accessibility and representativeness for further study. Then, an inventory work had been done starting from Chilimo and then proceeded to Gallessa and finally to Gaji forest patches.

Plot sampling

A total of thirty-five 20 × 20 m square sampled plots were marked based on the Neyman optimal allocation formula (Kangas and Maltamo 2006; Köhl et al. 2006). The plots were laid out along 100 m of ground distance, starting from the highest ridges to the lowest ridges of the mountains using measuring tape, GPS, altimeter and compass. The boundaries of the main plots were pegged and marked, then altitude, slope, latitude and longitude data were recorded from the center of each main plot. The distance between

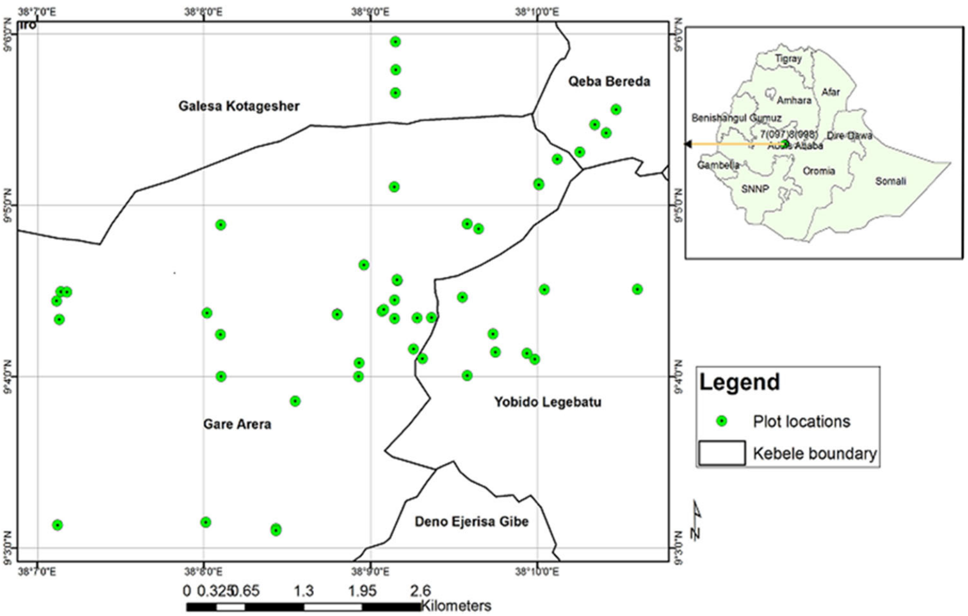

Fig. 1 Location map of Chilimo dry afro-montane forest

two consecutive transect lines was 300 m–1 km, depending on the accessibility of the next transect.

In this study, data from a single measurement of 35 plots were analyzed to develop stand density management diagram for *J. procera*, *P. falcatus* and *Juniperus*/*Podocarpus* mixed forests which will not only be useful for operational forestry in Chilimo forest but also can be used in other dry afro-montane forests too.

Data collection and sampling

Individual species were categorized into trees ($\geq$5 cm diameter at breast height), shrubs, saplings (height $\geq$1.3 m and dbh 2.5–5 cm) and seedlings (height 0.30–1.3 m and dbh $\leq$2.5 cm) following the Lamprecht classification (Lamprecht 1989). All trees and saplings found in the plots were then numbered and marked. Tree diameter (cm) was measured to the nearest two digits using a metallic calliper. Crown height and total height (meter) were measured using Vertex III digital electronics tree height measurement instrument. In cases where trees branched at or below the breast height, diameter was measured separately for each branch. Likewise, the diameter at each stem was measured separately for trees with multiple stems connecting near the ground. For irregularities and or buttresses on large trunks, measurement was taken at the nearest lower point. Diameter and height measurements were made for 822 stems. Basal area (BA) ($\mathrm{m}^2\ \mathrm{ha}^{-1}$), volume (*Vt*) ($\mathrm{m}^3\ \mathrm{ha}^{-1}$) and quadratic mean diameter (D_q) (cm) were calculated using inventoried data. Both commercial volume and total volume was calculated using the conventional volume equation because local volume equations were not available for these species:

$$V = \pi\left(\frac{\mathrm{DBH}}{4}\right)2 \times h \times f \text{ (Atta-Boateng and Moser 1998)} \quad (1)$$

where V = tree volume, DBH = diameter at breast height, h = total height and or commercial height and f = form factor (0.42) (Atta-Boateng and Moser 1998).

SDI (Reineke index) was calculated using the formula

$$\mathrm{SDI} = N\left(\frac{D_q}{25}\right)^{1.605} \quad (2)$$

where SDI = stand density index, D_q = quadratic mean diameter and N = number of stems $\mathrm{ha}^{-1.}$

Studied species proportion

The species proportion for *Juniperus procera* and *Podocarpus falcatus* was calculated using number of stems, basal area and total volume using with the general formula:

$$\mathrm{MSP}\ (N) = \frac{N_A}{N_A + N_B} \text{ (Pretzsch 2007)} \quad (3)$$

where MSP species proportion in stems, N_A: number of stems of species A and N_B: number of stems species B.

Data analysis

The data were analyzed by using density, quadratic mean diameter and total height primarily; Eq. 4 was fit by species group using least square regression:

$$\ln(\text{volume}) = \alpha - \beta \cdot \ln(\text{density}) \quad (4)$$

Volume is the mean tree gross total volume ($\text{m}^3\ \text{tree}^{-1}$) and density is the total number of stems per hectare. The magnitude of the coefficients in Eq. 5 appeared to be decreased for mixed species stands relative to pure *Juniperus procera* and *Podocarpus falcatus* stands. So according to Swift et al. (2007), an alternative form of Eq. 5 was fitted by expanding the coefficients to include a term for the mixture proportion as deviation from the pure stands (mixfrac) degree of departure from pure species condition using the formula (Swift et al. 2007):

$$\ln(\text{volume}) = \alpha_0 + \alpha_1 \cdot \text{mixfac} - (\beta_0 + \beta_1 \cdot \text{mixfrac}) \cdot \ln(\text{density}) \quad (5)$$

where

$$\text{mixfrac} \ = 0.5 - \text{ABC(JP(PF))frac} - 0.5)$$

$$\text{JP(Pf)fracBA} = \frac{\text{JP(pf) basal area}}{\text{total basal area}}$$

$$\text{JP(Pf)frac}N = \frac{\text{JP(PF)}N}{N_{\text{tot}}}$$

$$\text{JP(Pf)frac}V = \frac{\text{JP(PF)}Vi}{V_{\text{tot}}}$$

$$\text{MIX\_}N = \text{MIXFRANK} * \ln \text{\_}N \quad (6)$$

$$\text{MIX\_Ho} = \text{MIXFRANK} * \ln \text{\_Ho} \quad (7)$$

$$\text{MIX\_QMD} = \text{MIXFRANK} * \ln \text{\_QMD} \quad (8)$$

where MIXFRANK = mixed proportion, N = number of stems, Ho: dominant height and QMD: quadratic mean diameter, JP: *Juniperus procera*, PF: *Podocarpus falcatus*, ABS: absolute.

Dbhq isoline

The relationship between ln (volume) and ln (density) was found to be close to linear for a given quadratic mean diameter and parallel when quadratic mean diameter was changed. Thus, the relationship between ln (volume) and ln (density) was given by the equation:

$$\ln(\text{volume}) = \beta_0 + \beta_1 \cdot \ln(\text{dbhq}) + \beta_2 \cdot \ln(\text{density}) \quad (9)$$

The $\beta_0 + \beta_1 \ln(\text{dbhq})$ expands the intercept parameter of the linear relationship between ln (volume) and ln (density). In a similar way as Swift et al. (2007) did, we expanded each of the coefficients in Eq. 9 to include the *Juniperus–Podocarpus* fraction, resulting in the following equation:

$$\ln(\text{volume}) = \beta_{01} + \beta_{02} \cdot \text{Jpfrac} + \beta_{11} + \beta_{12} \cdot \text{Jpfrac} \cdot \ln(\text{dbhq}) + (\beta_{21} + \beta_{22} \cdot \text{Jpfrac}) \cdot \ln(\text{density}) \quad (10)$$

Total height isolines

We found a species-dependent relationship between volume and top height and density curve downwards as density increases and the slope of the relationship between ln (volume) and ln (density) increases as top height increases, so (Eq. 11) was developed by using weighted linear regression (the mean tree volume was used to weight the residuals) and including species proportions to expand parameters (Eq. 12):

$$\frac{1}{\text{volume}} = \beta^{\circ} \cdot \text{topht}\ \beta_1 + \beta_2 \cdot \text{density} \cdot \text{topht}\ \beta_3 \quad (11)$$

$$\frac{1}{\text{volume}} = (\beta_{00} + \beta_{01} \cdot \text{MIXFRAC}) \cdot \text{Ho\^{}}(\beta_{10} + \beta_{11} \cdot \text{MIXFRAC}) + (\beta_{20} + \beta_{21} \cdot \text{MIXFRAC}) * N \cdot \text{Ho\^{}}(\beta_{30} + \beta_{31} \cdot \text{MIXFRAC}) \quad (12)$$

Summary of model structure and data analysis

Two general linear models (Eqs. 13, 14) widely used for even-aged pure plantation relating to quadratic mean diameter and stand volume with density and dominant height were considered for SDMD model evaluation, and fitting process was used primarily for *J. procera* and *P. falcatus*. Moreover, these models were further expanded to accommodate mixed uneven-aged natural forest stand (Eqs. 15, 16) by incorporation of species proportion to calculate the coefficients:

$$\text{Ln QMD} = \beta_0 + \beta_1 \cdot \text{Ln}N + \beta_2 \cdot \text{LnHo} \quad (13)$$

$$\text{Ln VT} = \beta_3 + \beta_4 \cdot \text{LnQMD} + \beta_5 \cdot \text{LnHo} + \beta 6 \cdot \text{Ln}N \quad (14)$$

where N: stand density (stem ha^{-1}), QMD: Quadratic stem diameter (cm), Ho: Dominant height (m), VT: Stand volume ($\text{m}^3\ \text{ha}^{-1}$) and $_{\beta}i$ ($I = 0$–6): regression coefficients

$$\ln\text{\_QMD} = \beta_{01} + \beta_{02} * \text{MIXFRAC} + \beta_{11} * \ln\text{\_}N + \beta_{12} * \text{MIX\_}N + \beta_{21} * \ln\text{\_Ho} + \beta_{22} * \text{MIX\_Ho} \quad (15)$$

$$\ln\text{\_VT} = \beta_{31} + \beta_{32} * \text{MIXFRAC} + \beta_{41} * \ln_{\text{QMD}} + \beta_{42} * \text{MIX}_{\text{QMD}} + \beta_{51} * \ln\text{\_Ho} + \beta_{52} * \text{MIX\_Ho} + \beta_{61} * \ln\text{\_}N + \beta_{62} * \text{MIXFRAC} * \ln\text{\_}N \quad (16)$$

N: stand density (stem ha^{-1}), QMD: Quadratic stem diameter (cm), MIXFRAC: mixture fraction, MIX: mixture, Ho: Dominant height (m), VT: Stand volume ($\text{m}^3\ \text{ha}^{-1}$) and $_{\beta}i$ ($i = 01$–62): regression coefficients.

Thus, Ln N and Ln Ho are exogenous variables (defined) independent of the system, while VT and QMD are instrumental endogenous variables (Borders 1989). The best independent fitting variables were selected using volume, basal area and density. Model fitting and data analysis were performed using the MODEL procedure in the SAS/ETS software (SAS Institute Inc. 2012). Best fitting models were selected based on higher regression correlation coefficient and the quality of the graph performed.

The quadratic mean and total height isolines graphs were formulated using the fitted models. Besides, the density management diagram was developed using quadratic mean diameter on the x-axis (logarithmic scale) and the number of stems per hectare (logarithmic scale) on the y-axis. However, thinning operation was recommended using species proportion for overall Chilimo dry afro-montane forest.

Results

General description

The inventory results are summarized in Table 1, and it revealed that quadratic mean diameter (QMD), volume, dominant height (Ho) and number of stems (N) were varied among the tree species (Table 1). A total of 33 different native plant species (22 tree species and 11 shrub species) were recorded along the sampled plot. The density was varied from 2533 stems ha^{-1} recorded in the Chilimo forest patch to 848 stems ha^{-1} in the Gallessa forest patch. *J. procera* and *P. falcatus* accounted for 50 and 52 % of the total basal area and density, respectively. Moreover, preliminary local assessment results showed that these species have been of both economic and ecological importance for the local community and the existing ecosystem (Tesfaye 2015). In addition, *Juniperus procera* produced quality timber which is durable and resistant to termite attack. On the contrary, *Allophyllus abyssinicus*, *Olea europaea* ssp. *Cuspidiata*, *Olinia rochetiana*, *Ruth glutinosa* and *Scolopia theifolia* accounted for about 25 % of the total population of Chilimo dry afro-montane mixed uneven-aged natural forest in terms of basal area and density. They belong to the dominant and co-dominant structural function of the forest. However, they have been widely utilized for fuelwood, construction wood and lumber by the local community as compared with the above-mentioned two dominant species due to lack of legal intact.

Model evaluation and fitting

The model evaluation and simultaneous fitting results of the two dominant species and their proportion under study are summarized in Tables 2 and 3. The results revealed that dominant height and quadratic mean diameter were found to be the best endogenous fitting variables for stand density management diagram (Table 2). Goodness of fit was adequate (the R^2 adjusted validation data set was over 0.60 for the quadratic mean diameter equation and over 0.95 for the volume equation) in all models.

The correlated coefficient value for the estimated parameters is presented in Tables 3 and 4, and the model

Table 2 Results of the variance analysis, adjust and nonlinear regression obtained from making the simultaneous adjust of the system of equation to calculate the quadratic stem diameter [1] and the stand volume [2] using two equations and two species composition

Equation	*J. procera*		*P. falcatus*		Species proportion	
	QMD	*V*	QMD	*V*	QMD	*V*
DF model	3	4	3	4	6	8
DF error	19	18	13	12	29	27
SSE	1.67	1.59	1.24	0.89	1.45	6.43
MSE	0.09	0.09	0.10	0.07	0.05	0.24
RMSE	0.30	0.30	0.31	0.27	0.22	0.49
R^2	0.64	0.93	0.80	0.98	0.70	0.76
R^2 adj.	0.60	0.92	0.77	0.95	0.65	0.70

DF degree of freedom, *SSE* sum of squared error, *MSE* mean Residuals, *RMSE* root of the mean quadratic error, R^2 correlation coefficient, R^2*_adj* adjusted correlation coefficient, *QMD* quadratic mean diameter, *V* volume

Table 1 Summary of the data sets used to develop the *Juniperus–Podocarpus* SDMD: n = number of plot measurements

Attributes	*Juniperus procera*		*Podocarpus falcatus*		All species in the forest	
	n	Mean (range)	*n*	Mean (range)	*n*	Mean (range)
Density (stems/ha)	35	145.71 (0–525)	35	115 (0–475)	35	596.43 (125–1025)
Top height (m)	35	15.98 (0–32.10)	35	7.78 (0–22.73)	35	24.16 (13.29–34.24)
Basal area (m^2/ha)	35	12.39 (0–64)	35	2.23 (0–17)	35	25.92 (6.25–76.00)
Volume (m^3/ha)	35	114.55 (0–692.75)	35	20.99 (0–230.22)	35	228.11 (5.5–692.75)
QMD (cm)	35	23.90 (0–79.84)	35	8.65 (0–43.48)	35	24.29 (12.19–79.84)

QMD quadratic mean diameter

efficiency varied among the species. All the estimated parameters for *P. falcatus* and five parameters for *J. procera* were also significant ($p < 0.05$). However, for the species proportion, seven parameters in volume, six parameters in number of stems and five parameters in basal area were also significant. The estimated parameters for the volume data set were better than basal area and number of stems. The R^2 adjusted value for the validation data set for *P. falcatus* was higher, which was over 0.80 for the quadratic mean diameter and 0.95 for the volume model. However, the adjusted R^2 value for the validation data of diameter at breast height for *J. procera* was lower than *P. falcatus* (0.60). Thus, two linear equation models which consider the same sets of independent variables were selected to develop the SDMD.

Stand density management diagram using species proportion

Maximum density lines plus diameter and height isolines were graphed using actual data for *J. procera*, *P. falcatus* and *J. procera/P. falcatus* species proportion as shown in Figs. 2 and 3. The relationship between volume and density appeared to be linear for a given diameter at breast height (dbh) and parallel as dbh changed (Fig. 2). The graph produced using top height and density also showed a

Table 3 Values of the coefficients of the nonlinear regression obtained from the simultaneous adjust of the system of equations to calculate quadratic stem diameter [1] and stand volume [2] for *J. procera* and *P. falcatus* separately using (Eqs. 13, 14)

Coefficients	*J. procera*		*P. falcatus*	
	Estimate ± SE	Pr > /t/	Estimate ± SE	Pr > /t/
β_0	−0.804794 ± 0.87	0.3653	1.61596 ± 0.75	**0.0491**
β_1	−0.24993 ± 0.17	0.1608	−0.50234 ± 0.17	**0.0119**
β_2	1.388187 ± 0.28	<0.0001	3.119281 ± 0.50	**<0.0001**
β_3	−10.1877 ± 1.49	<0.0001	−11.9455 ± 1.50	**<0.0001**
β_4	1.55153 ± 0.23	<0.0001	2.418808 ± 0.23	**<0.0001**
β_5	1.942324 ± 0.58	0.0036	0.951593 ± 0.38	**0.0285**
β_6	1.039522 ± 0.25	0.0006	1.11629 ± 0.17	**<0.0001**

Bold indicated parameteres are statistically significant at *P* less than or equalt to 0.05

β_0 the *y*-intercept for QMD, β_3 *y*-intercept for VT, β_1 model parameter for *N*, β_2 model parameter for Ho, β_4 model parameter for QMD, β_5 model parameter for Ho and β_6 model parameter for *N*

Table 4 Values of the coefficients of the nonlinear regression obtained from the simultaneous adjust of the system of equations to calculate quadratic stem diameter [1] and stand volume [2] for studied mixed forest species using (Eqs. 15, 16)

Parameter	Volume			Basal area			Number of stems (*N*)		
	Estimate	SE	Pr > /t/	Estimate	SE	Pr > /t/	Estimate	SE	Pr > /t/
β_{01}	2.897416	0.654	**0.0001**	3.382004	0.879	**0.0006**	3.116092	0.632	**<0.0001**
β_{02}	−0.00117	0.002	0.5539	−3.57605	3.654	0.3358	−2.26465	1.421	0.1218
β_{11}	−0.58115	0.107	**<0.0001**	−0.56839	0.099	**<0.0001**	−0.67893	0.122	**<0.0001**
β_{12}	−0.06936	0.120	0.5688	−0.0674	0.115	0.5632	0.654378	0.482	0.1851
β_{21}	0.646314	0.180	**0.0012**	0.487582	0.257	0.0676	0.673544	0.168	**0.0004**
β_{22}	0.011675	0.083	0.8892	1.111381	1.125	0.3316	−0.00697	0.081	0.9321
β_{31}	−12.60544	2.237	**<0.0001**	−12.7042	2.746	**<0.0001**	−11.3893	1.935	**<0.0001**
β_{32}	2.444265	7.661	0.7521	5.230836	12.471	0.6783	−2.0532	3.972	0.6094
β_{41}	2.198373	0.494	**0.0001**	2.108279	0.508	**0.0003**	2.016638	0.460	**0.0002**
β_{42}	1.29198	2.967	0.6667	1.197907	3.576	0.7402	2.280185	2.900	0.4386
β_{51}	1.472016	0.523	**0.0090**	1.761332	0.581	**0.0053**	1.527939	0.563	**0.0114**
β_{52}	−1.14605	2.725	0.6790	−3.34268	3.057	0.2839	−2.07677	2.746	0.4560
β_{61}	0.972655	0.389	**0.0186**	0.782145	0.406	0.0643	0.671582	0.413	0.1154
β_{62}	−0.6712	2.106	0.7524	0.741133	1.888	0.6977	0.813058	1.305	0.5384

Number in bold are statistically significant $p < 0.05$

β_{01} the *y*-intercept for QMD, β_{02} model parameter for MIXFRAC, β_{11} model parameter for *N*, β_{12} model parameter for MIX_N, β_{21} model parameter for Ho, β_{22} model parameter for MIX_Ho, β_{31} the *y*-intercept for VT, β_{32} model parameter for MIXFRAC, β_{41} model parameter for QMD, β_{41} model parameter for MIX_QMD, β_{51} model parameter for Ho; β_{52} model parameter for MIX_Ho, β_{61} model parameter for *N*, β_{62} model parameter for MIXFRAC_N

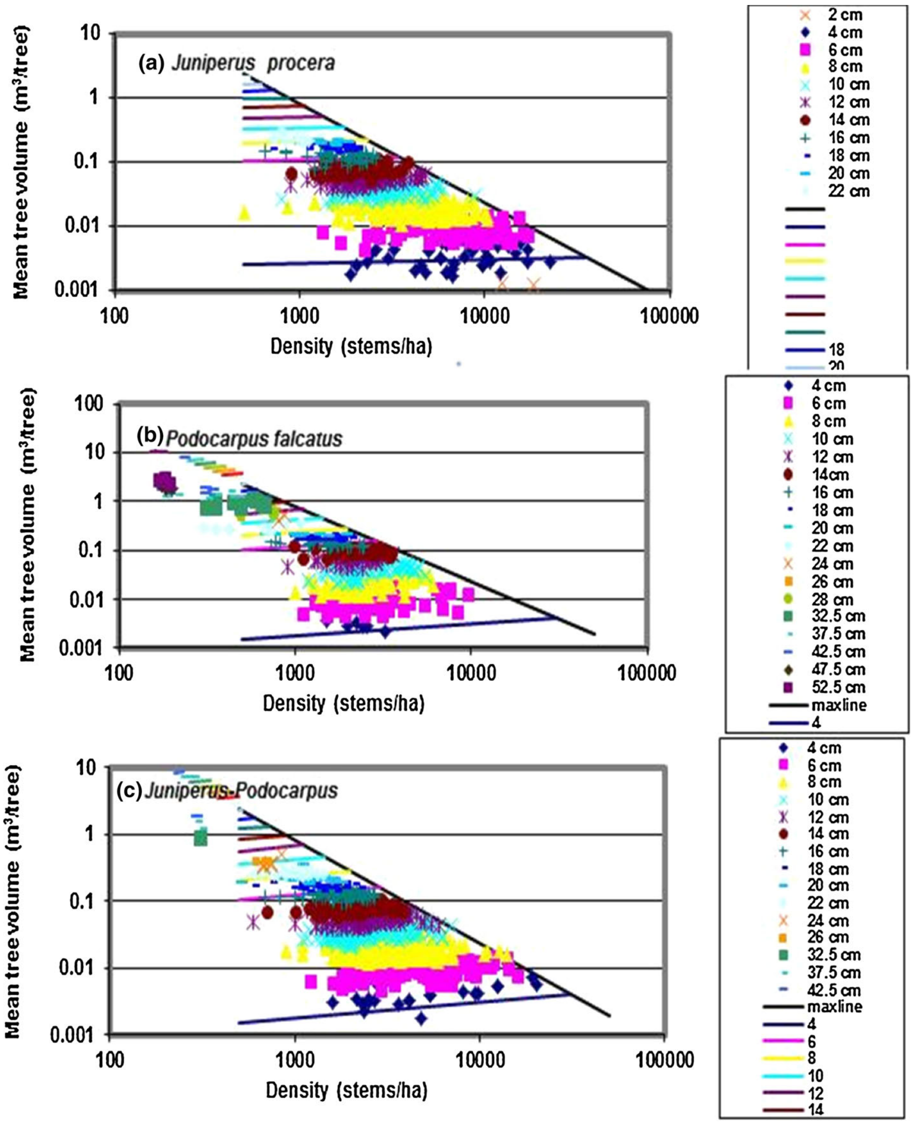

Fig. 2 Maximum size density line and the quadratic mean diameter isolines from Eq. 7 are plotted through the actual data

linear relationship between top height and density for both pure species and species proportion, though the relationship was very weak (Fig. 3).

The SDMD was formulated using quadratic mean diameter and total height for *J. procera, P. falcatus* and *Juniperus*/*Podocarpus* proportion, and the results are presented in Fig. 4. In the graph, the total volume, total height and number of stems were presented using different colors and features. The total volume was represented using blue dotted lines running diagonally from *x*-axis to *y*-axis, and the total height (m) was represented using red solid lines running from *x*-axis to *y*-axis with similar fashion. Similarly, the number of stems and stand density index was represented using black solid lines running in the same position as volume and total height do. In the graph, we can read any combinations of quadratic mean diameter, density, total volume and total height.

Volume, total height and number of stems per hectare were varied among the species. *J. procera* was dominated by large-stem-diameter trees with a mean quadratic mean diameter up to 80 cm, while *P. falcatus* was dominated by medium-sized stems with a higher regeneration status in the forest. The number of stems in the SDMD of Chilimo mixed forest was exceeded up to be 1025 stem ha^{-1}.

Alternative management options were developed for the Chilimo dry afro-montane forest by considering species proportion of *J. procera* and *P. falcatus*, because, species specific stand density management is not advisable for such a type of forest to maximize productivity through benefiting the local community (Fig. 4). The quadratic mean diameter, stand volume and number of stems to be retained and or removed before and after thinning were also estimated in the graph (Table 5). The volume after thinning

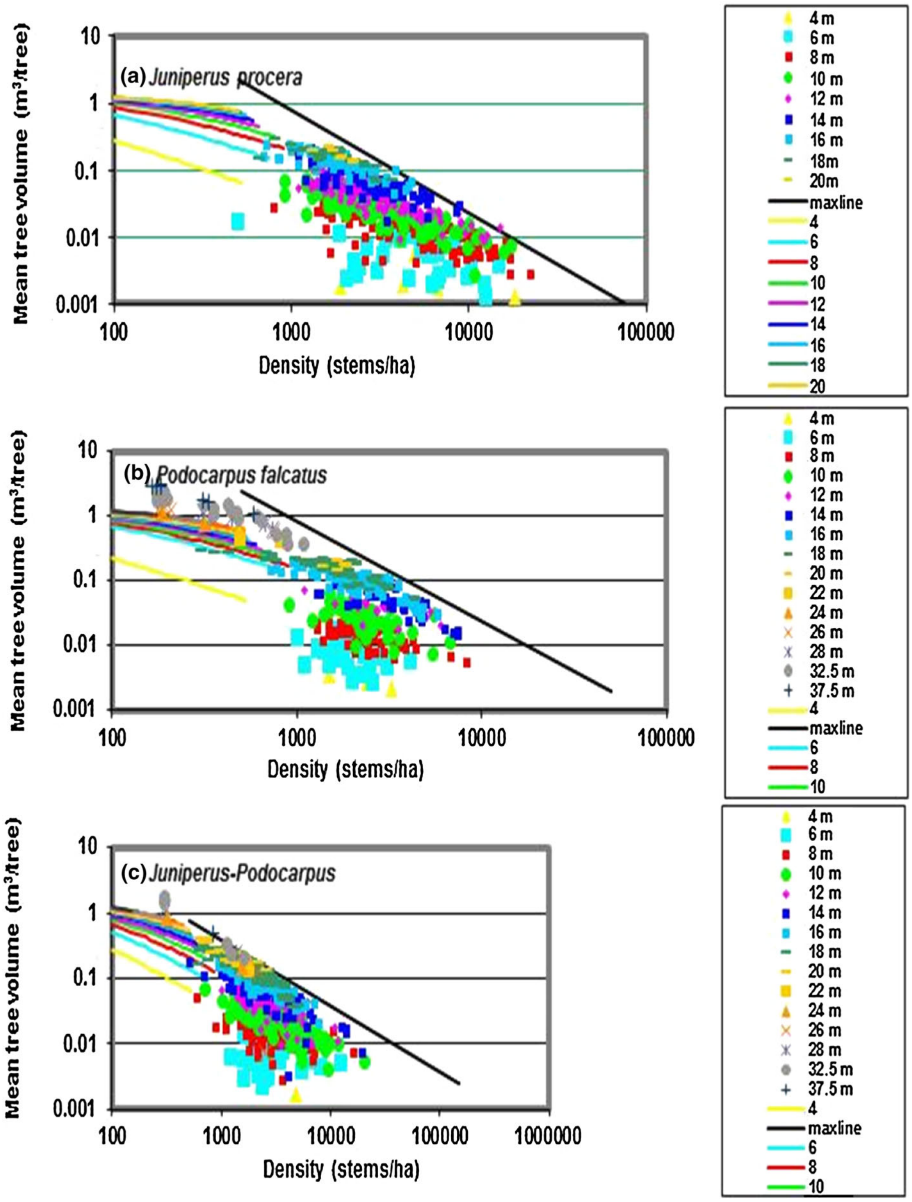

Fig. 3 Dominant height isolines from Eq. 8 are plotted through the actual data

was also increment (Table 6). The minimum and maximum quadratic mean diameters to be thinned will be 25 and 35 cm, respectively (Table 6). Natural mortality was not considered between thinning operations. Thus, thinning will be applied for *J. procera* and *P. falcatus*. A similar assumption was also reported in the previous SDMD development for other species (McCarter and Long 1986; Dean and Baldwin 1996; Barrio-Antam et al. 2005).

Discussion

It is important to estimate biomass and carbon stock productions using different forest management tools for tropical forests in order to have a better understanding about these forests for sustainable production and harvestable biomass utilization of fuel wood, timber and construction wood (Tesfaye et al. 2015, 2016). Moreover, forest management is a key tool in REDD + projects (Moges and Tenkir 2014), and proper biomass and carbon stock estimations in tropical forests will help foresters to better understand the importance of forest management in the global carbon cycle budgeting and how to implement sustainable management at operational level. Also this information could serve as a valuable tool for policy makers and stakeholders during the decision-making process to maintain and improve forest condition, while provisioning valuable environmental services (including timber and firewood). Thus, local communities could be engaged in forestry-related activities.

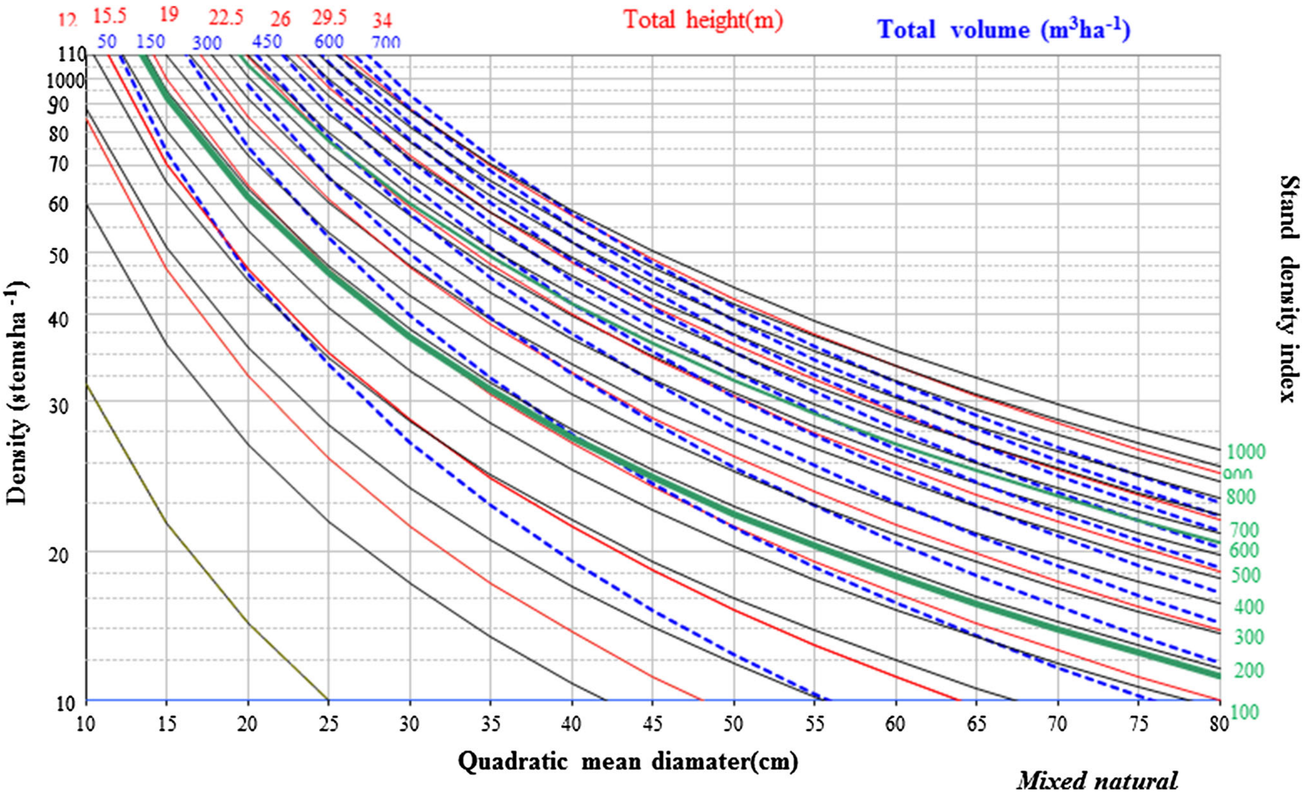

Fig. 4 Stand density management diagram for Chilimo dry afro-montane forest

Consequently, the growth and yield of trees and stands are fundamental tools for understanding the relationships between density management and wood production in Chilimo natural forest (Tesfaye 2015; Tesfaye et al. 2015, 2016). These silvicultural operations have their own effect on the control of crown and root development for the existing trees and their own impact on the quality of wood and productivity of the stand. The trees showed increment both in volume and height growth after thinning operations; similar findings are also reported by Woodalle et al. (2005). SDMD allows managers to take decisions in a cost-effective manner under low economic return silvicultural systems similar with Chilimo dry afro-montane forest. Other modeling approaches such as empirical individual-tree or process-based models can be more useful to understand ecosystem dynamics.

SDMD is an important tool for decision-making process for forest managers based on stand information of maximum and minimum densities of stems, dominant height, total stand volume and stand density index obtained from SDMD. In the graph, we can find total stand volume, total height, quadratic mean diameter and density directly for any point using the stand volume isolines (Fig. 4). Thus, the managers of Chilimo dry afro-montane forest can recommend appropriate thinning operations where the maximum yield will be obtained. Appropriate decision-making processes must also enhance future stand volume, wood properties and habitat characteristics. These SDMDs can help foresters to establish appropriate management guidelines including carefully designed thinning operations to benefit the local communities (Tesfaye 2015; Tesfaye et al. 2015). In the Chilimo natural forest, thinning operations were showed based on self-thinning rule starting from maximum Reineke index of 60 % and minimum Reineke index of 35 % (Fig. 4) (Dean and Baldwin 1993). From the findings, we can come with a concrete evidences that, though, SDMDs are widely used to manage even-aged pure stands in the past, and currently they can also be used for the management of mixed uneven-aged stands (Swift et al. 2007; Tesfaye 2015). Thus, SDMD can be implemented for the stand density management of Chilimo dry afro-montane mixed uneven-aged forest.

This information is important to show the role of Chilimo dry afro-montane forests for local, regional and global scales for climate change mitigation and carbon trade (Tesfaye 2015; Tesfaye et al. 2015, 2016), because the information has a significant impact on the structure, health and pattern of stand development, which influences stand composition and utility through time. Hence, appropriate decision-making processes enhance future stand volume, wood properties and habitat characteristics of the forest.

Table 5 Result of fitting Eqs. 9 and 10, Eqs. 11 and 12

Parameter	Equations 9 and 10			Equations 11 and 12		
	Estimate	SE	Pr > /t/	Estimate	SE	Pr > /t/
β_0	−44E–14	0.0982	**0.0001**	−388E−15	0.1094	**0.0001**
β_1	1.0000	0.0388	**0.0001**	1.0000	0.0388	**0.0001**
β_2	6.8E–14	0.0180	**0.0001**	1.2E−10	0.0002	**0.0001**
β_3				0.0001	0.00001	**0.0001**
$\beta_0{}^{\circ}$				−11.361	1.9982	**<0.0001**
β_{01}	−10.5325	1.9283	**<0.0001**	−0.38768	1.4603	0.7927
β_{02}	0.276774	0.2732	0.3193			
β_{10}				2.033989	0.4764	**0.0002**
β_{11}	2.814531	0.3605	**<0.0001**	0.346418	0.5071	0.5003
β_{12}	−0.01337	0.2984	0.9646			
β_{20}				1.469933	0.5584	**0.0138**
β_{21}	1.13389	0.3409	**0.0024**	−0.28699	0.4543	0.5329
β_{22}	0.025535	0.2704	0.9254			
β_{30}				0.726249	0.4206	0.1047
β_{31}				0.171168	0.4502	0.7068

Number in bold are statistically significant at $p < 0.05$

β_0 the *y*-intercept for volume Eq. 9 and the estimator parameter for top height Eq. 11, β_1 the estimator parameter for dbhq Eq. 9 and the power estimator for density Eq. 11, β_2 the estimator parameter for density Eq. 9 and the power estimator for density Eq. 11, β_{01} the *y*-intercept for volume Eq. 10 and the estimator parameter for MIXFRAC Eq. 12, β_{02} the estimator parameter for *J. procera* Eq. 10, β_{11} the *y*-intercept for *J. procera* density Eq. 10 and the estimator parameter for MIXFRAC_Ho Eq. 12, β_{12} the estimator parameter for dbhq Eq. 10: β_{21} the *y*-intercept for density, Eq. 10 and the estimator parameter for MIXFRAC_N Eqs. 9 and 10, β_{22} the estimator parameter for mixfrack *J. procera* Eq. 10, β_{31} the power estimator for density Eq. 11, $\beta_0{}^{\circ}$ the *y*-intercept for Eq. 12, β_{10} the *y*-intercept for MIXFRAC Eq. 12, β_{20} *y*-intercept for MIXFRAC Eq. 12, β_{30} the *y*-intercept Eq. 12, β_{31} the estimator parameter for MIXFRAC Eq. 12

Table 6 Alternative silvicultural density management options for Chilimo dry afro-montane forest

Alternative	Quadratic mean diameter (cm)		Stand volume ($\text{m}^3\ \text{ha}^{-1}$)		Density (stem ha^{-1})	
	Before	After	Before	After	Before	After
I–II	25	29.00	265.00	150.00	673	362
III–IV	29.00	33.00	150.00	210.00	362	350
V–IV	33.00	35.00	210.00	330.00	350	250

The density management diagram was developed by analyzing data generated from one inventory measurement plot due to lack of permanent plot in the study area (Chilimo natural forest). These diagrams are important to manage the forest in sustainably way by applying appropriate thinning operations as a management strategic tool to benefit the local community.

Dean and Baldwin's (1996) bounds of self-thinning and full site occupancy were adopted (Fig. 4). These maximum and minimum RDIs as mentioned above must be locally estimated in the near future by establishing a permanent sample plot. Other modeling approach such as empirical and or process-based models can be also useful to understand ecosystem dynamics and propose management guidelines. However, as Valbuena et al. (2008) stated SDMDs are practical tools that can be easily implemented where silvicultural knowledge is scarce and in low productivity forests where it is not realistic to invest funds to improve management tools (Fig. 5).

Conclusions

SDMDs can be used as a foundation tool to develop thinning operation schedules to benefit the local community living inside or outside Chilimo dry-afro-montane forest in particular and to enhance productivity of the forest. Moreover, the society can harvest wood from thinning operations either for their household consumption and or to generate income. Dominant height and quadratic mean

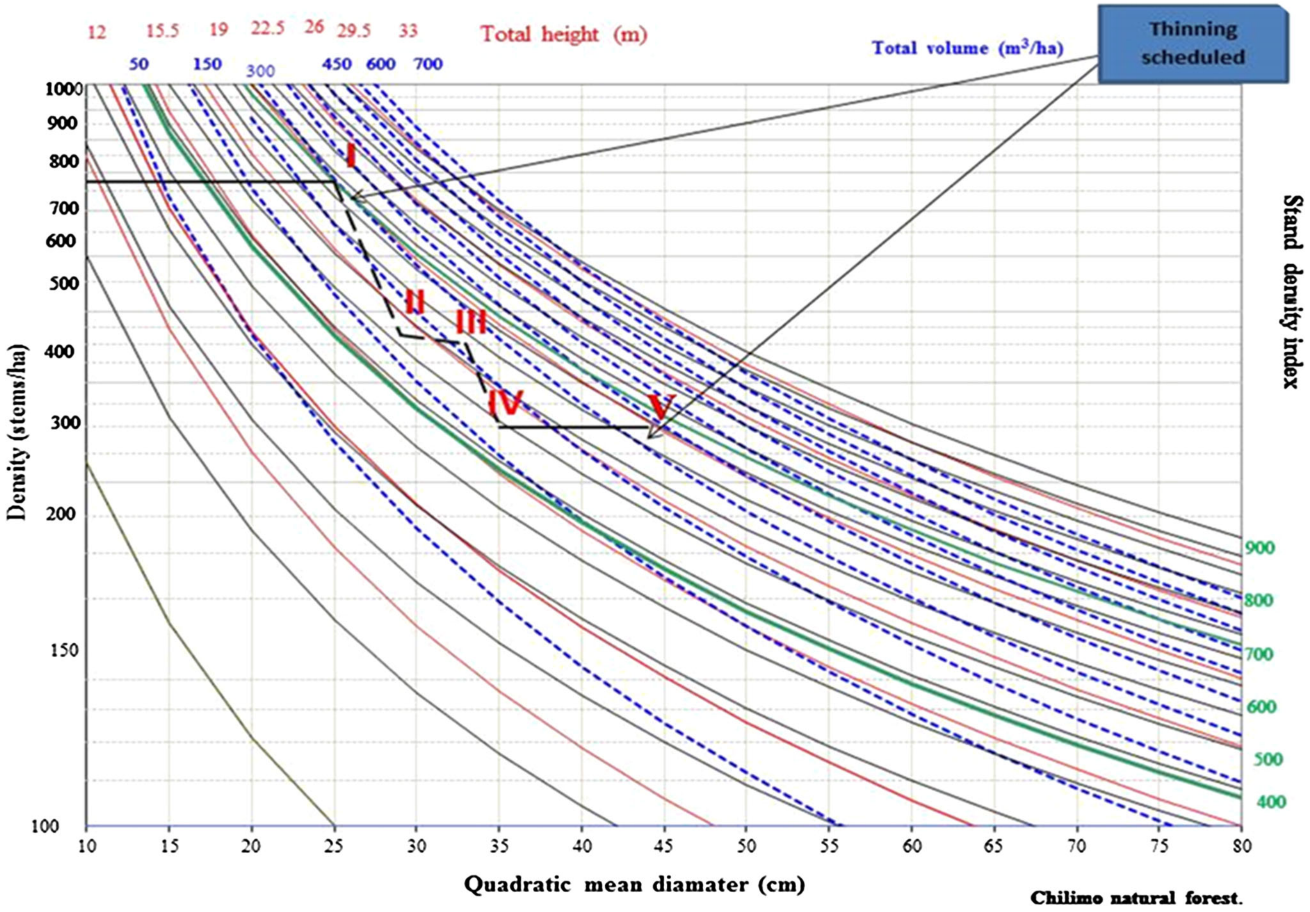

Fig. 5 Stand density management diagram and alternatives for Chilimo natural forest with *Juniperus* and *Podocarpus* proportion

diameter were found to be the best endogenous variables for SDMD for Chilimo forest. The SDMD fitted for the volume data set was better than basal area and number of stems. Formulating SDMD using species proportion is better than treating each species independently. SDMD can be applied for the sustainable management of *J. procera* and *P. falcatus* mixed forest. Similar studies should be continued in the different plantation and natural forest types of the country to apply and test the model. The SDMD for Chilimo dry afro-montane forest is the first diagram developed for mixed forest in Africa and can serve to support the sustainable management of Chilimo dry afro-montane forest in particular and other dry afro-montane forests in general. Similar studies should be continued for Chilimo dry afro-montane forest in particular and other natural and man-made plantation forest in general.

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References

Álvarez-González JG, Ruiz González AD, Rodiríguez-Soalleiro R, Barrio-Anta M (2005) Eco regional-based stand density management diagram for *Pinus pinaster* L. in Galicia (northwest Spain). Ann For Sci 62:115–127

Ando T (1962). Growth analysis on the natural stands of Japanese, red pine (*Pinus densiflora* seib.et.20 cc.). II. Analysis of stand density and growth. Bulletin No. 147. Government forest experiment station, Tokyo

Atta-Boateng J, Moser JR (1998) A method for classifying commercial tree species of an uneven-aged mixed species tropical forest doe growth and yield model construction. For Eco Manag 104:89–99. http://www.fao.org/forestry/25518/en/

Barrio-Antam MA, Castedo-Dorado F, Diéguez-Aranda U, Álvarez-González JG (2005) An Eco regional model for estimating volume, biomass and carbon pools in maritme pine stands in Galicia (north-western Spain). For Ecol Manag 223:24–34

Border B (1989) System of equations in forest stand modelling. For Sci 35:548–556

Bravo F, Bravo-Oviedo A, Diaz-Balteíro L (2008) Carbon sequestration in Spanish Mediterranean forests under two management alternatives: a modelling approach. Eur J For Res 127:225–234. doi:10.1007/s10342-2007-0198-y

Bravo F, Àlvarez-Gonzalez JG, del Río M, Barrio-Anta M, Bonet JA, Bravo-Oviedo A, Calama R, Castedo-Dorado F, Crecento-Campo F, Condés S (2012) Historica overview, contemporary examples and perspectives. Universidad de Valladolid-INIA and Unidad de Gestión Forestal Sostenible (Universidad de Santiago de Compostela) (eds), Palencia, Spain

Castedo-Dorado F, Crecente-Campo F, Àlvarez-Àlvares P, Barrio-Anta M (2009) Development of a stand density management diagram for radiate pine stands including assessment of stand stability. J For 82(1):1–15

Cole TG, Ewel JJ (2006) Allometric equations for four valuable tropical tree species. For Ecol Manag 229:351–360. doi:10.1016/j.foreeco.2006.04.017

Dean TJ, Baldwin UC (1993) Using a density-management diagram to develop thinning schedules for loblolly pine plantations. Research Paper SO-275. U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA, P 7

Dean TJ, Baldwin UC (1996) Crown management and stand density. In: Carter MC (ed) Symposium. Lousiana State University Agricultural Centre. Lousiana Agricultural Experiment Station, Baton Rousé, LA, pp 148–159

Díaz-Maroto IJ, Fernández-Paraje J, Vila-Lameiro P, Barcala PE (2010) Site index model for natural stands of rebollo oak (*Quercus pyrenaica* Willd.) in Galicia, Northwest Iberian Peninsula. Ceincia Florest 20:57–68

Drew T, John F, James W (1979) Stand density management: an alternative approach and its application to Douglas-fir plantations. For Sci 25(3):518–532

EMA (1988) National Atlas of Ethiopia. Ethiopian Mapping Authority, Addis Ababa, p 76

Farnden C (2002) Recommendations for constructing stand density management diagrams for the province of Alberta. Ministry of Sustainable Resource Development. Alberta Land and Forest Division. Div. For. Mgt. Sec., p 17

Kangas A, Maltamo M (2006) Forest inventory methodology and applications: managing forest ecosystems, vol 10. Springer, Dordrecht

Kershaw JA, Fischer BC (1991). A stand density management diagram for saw timber-sized mixed upland Central hardwoods. In: Proceedings of 8th Central hardwood forest conference: 1991 March 4–6: University park, PA Gen. Tech. Rep NF-148. Radnor, PA: US, department of Agriculture, Forest service, North Eastern Research Station, pp 414–428

Köhl M, Magnussen SS, Marchetti M (2006) Sampling methods, remote sensing and GIS multi resource forest inventory. Springer, Berlin

Lamprecht H (1989) Silvicultural in the tropics. In: Tropical forest ecosystems and their tree species-possibilities and methods for their long term utilization. Technical cooperation, Federal Republic of Germany, Eschborn

McCarter JB, Long JN (1986) A lode pole pine density management diagram. West J Appl For 1:6–11

Moges Y, Tenkir E (2014) Overview of REDD + process in Ethiopia, REDD + report. Ministry of Environment and Forest, Addis Ababa

Newton PF (1997) Stand density management diagrams: review of their development and utility in stand-level management planning. For Ecol Manag 98:251–265

Newton PF, Weetman GF (1994) Stand density management diagram for black spruce stands. For Chron 70:65–74

Newton PF, Lei Y, Zhang SY (2005) Stand-level diameter distribution yield model for black spruce plantations. For Ecol Manag 209:181–192

SAS Institute Inc (2012) SAS/ETS®. 9.2 User's guide. SAS Institute Inc., Carry, NC

Shumi G (2009). The structure and regeneration status of tree and shrub species of Chilimo forest-Ecological sustainability indicators for participatory forest management (PFM) in Oromiya, Ethiopia. M.Sc. Thesis, University of Dresden

Smith NJ (1989) A stand-density control diagram for western red-cedar, *Thuja plicata*. For Ecol Manag 27:235–244

Swift E, Penner M, Rolland G, Knox J (2007) A stand density management diagram for spruce-balsam fir mixtures in New Brunswick. For Chron 83(2):187–197

Tesfaye MA (2015) Forest management options for carbon stock and soil rehabilitation in Chilimo dry afro-montane forest, Ethiopia. Ph.D. Thesis, INIA- Palencia, University of Valladolid, Palencia

Tesfaye MA, Bravo-Oviedo A, Bravo F, Kidane B, Bekele K, Sertse D (2014) Selection of tree species and soil management for simultaneous fuelwood production and soil rehabilitation in the Ethiopian central highlands. Land Degrad Dev. doi:10.1002/ldr.2268

Tesfaye MA, Bravo-Oviedo A, Bravo F, Ruiz-Peinado R (2015) Aboveground biomass equations for sustainable production of fuelwood in a native dry tropical afro-montane forest of Ethiopia. Ann For Sci. doi:10.1007/s13595-015-0533

Tesfaye MA, Bravo F, Ruiz-Peinado R, Pando V, Bravo-Oviedo A (2016) Impact of changes in land use, species and elevation on soil organic carbon and total nitrogen in Ethiopian Central Highlands. Geoderma 261:70–79

Valbuena P, Peso del C, Bravo F (2008) Stand density management diagrams for two Mediterranean pine species in eastern Spain. Investigación Agraria Sistemas y Recursos Forestales 17(2): 97–104. ISSN:1131-7965

Wilson DS, Seymour RS, Maguire DA (1999) Density management diagrams for northeastern red spruce and balsam forests. North J Appl For 16:48–56

Woodalle CW, Miles DP, Vissage SJ (2005) Determining maximum stand density index in mixed stands for strategic-scale stocking assessments. For Ecol Manag 216:367–371

Woods ME (1999) Density management diagrams tools and uses. In: Bamsey C (ed) Stand density management: using panning tools. Clear Water Ltd., Edmonton, pp 27–33