



Study on the R-Based Dynamic Construction Techniques for Stand Density Management Diagrams

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ABSTRACT

With an investigation into the procedure and techniques involved in constructing a stand density management diagram (SDMD) and in light of users' real needs, this study designs a system for the dynamic construction of SDMDs based on R language, for the purpose of overcoming the complexities of model fitting in producing a diagram, the difficulties in constructing a diagram and the high demands for users' expertise. The interactive modelling technique between C# language and R language is applied to the research, with which different sets of model fitting results are compared and optimal results are chosen. The whole procedure, from data collection, model fitting (including outlier data elimination, prototype model fitting and model testing) and diagram construction, is streamlined and automated. Continuous forest inventory data for the *Larix principis-rupprechtii* plantation in China's Inner Mongolia is used and two sets of prototype fitting results of the SDMD are compared. With equivalent height curves as the example, this paper makes the goodness of fit of the binomial theory of density effect ($R^2=0.9231$) better than that of the power theory of density effect ($R^2=0.8354$). The model with the best goodness of fit is finally selected for the dynamic construction of a SDMD. Application of this generated SDMD indicates a relatively high accuracy and practical value.

INTRODUCTION

Stand density management diagrams (SDMDs) are constructed on the basis of density effect. It adopts such mathematical models as the equivalent height model, the equivalent diameter model, the equivalent density of stocking model, the maximal density model and the natural thinning model to describe the numerical relationship between stand density and stand description factors; it takes graphical forms to demonstrate a dynamic relation between stand density and growth (Sharma 2008). This diagram could help with planning and designing of afforestation, forest growth and harvest prediction and forest thinning—a supportive tool for decision-making that could be used for design, illustration and evaluation (Penner 2006, Newton 2015).

Since the 1970s, when Ando et al. (1968) created the SDMD, studies have been conducted by scholars both in China and abroad for different regions such as North America, South America, Asia, Africa and Europe, as well as for different tree species such as Douglas fir Weiskittel (Drew 1979), Lodgepole pine (Farnden 1996), White spruce (Saunders 2000), Balsam fir (Penner 2006, Weiskittel 2011), Black spruce (Newton 1993, 1994, 2005, 2015; Stankova 2007a), Longleaf pine (Shaw 2007), Jack pine (Archibald 1995; Sharma 2004, 2007; Newton 2009, 2015), Australian pine (Stankova 2007b), Scots pine (Giorgio 2008, Stankova

2013), Oak (Castaño Santamaría 2013), Masson pine (Jin 2009), Red pine (Li 2011), Larch (Xiang 2013) and Chinese fir (Tang 2015, Tian 2015). Because of the complexity of the multi-curve SDMD, its application has been limited. In order to eliminate the error from diagram construction to help users make more reasonable management decisions, forest managers have applied computer software to the production of a SDMD. Among them, Woods et al. (1999) have developed the Ontario Density Management Diagram (ODMD) that features interactive functions, for white pine, red pine, Jack pine and Black spruce. Compared with traditional manual drafting, this method could improve the accuracy of calculation and the efficiency of diagram construction. Exploring the black spruce in the middle and eastern parts of Canada, Newton (1998, 2003) has designed, with the FORTRAN language, a Stand Density Management Decision Support Program (SDMDSP), and with a comparison of the yields under different stand density conditions, provided suggestions for decision-making. With data collected from the permanent sample plots of Masson pine in Daqingshan region, Hong (1993, 2006) has derived the SDMD from the integrated stand growth model and with the software of Forstat, calculated the values of equivalent curves and put the diagram to the platform of Capsis.

Some other studies have resorted to such statistical analysis software as SAS (Sharma 2004, Tewari 2014) and

SPSS (Xiang 2013, Wang 2015), with which regression fit of models has been conducted, and Origin and Excel would then be adopted to construct a SDMD. The SDMDs mentioned above, however, have the following problems: (1) Data should be collected from sample plots for model fitting, and this asks that users should have some expertise on statistical analysis. Ordinary users, however, would find it difficult to operate, and the construction of a SDMD after model fitting would make the work more difficult. (2) The existing research mainly focuses on a specific tree species in a specific region, which would limit the scope of model application. (3) With the development of time and the diversification of forest management measures, original SDMDs need to be revised and adjusted, but since the diagram is closely linked to software and the two are highly coupled to each other, updating the diagram would be difficult.

In light of the weaknesses of previous researches, this research designs a system for the dynamic construction of SDMDs, with which the diagram could take shape automatically when users input such data as tree height, density of trees and stand volume. With the change of data, model refitting could be realized and SDMD could be reconstructed. In this way, the poor applicability of software to the construction of SDMDs, the difficulty of model updating and the high demands for users' operational expertise could be overcome.

MATERIALS AND METHODS

Stand Density Management Model (SDMM)

SDMM is used to describe the relationship among stand description factors of even-aged pure stands, which are composed of such models as equivalent height curves, equivalent diameter curves, equivalent density of stocking curves, maximal density curves and natural thinning curves. Stand description factors (e.g. stand volume) are dependent variables of the five types of curves, and stand density is the independent variable. Each model is relatively independent but associated with other models as well. According to different models of density effect, the prototype models of

SDMDs could take various expression forms. On this account, model prototype fitting could be conducted and fitting results should be sifted to obtain the best model. The most frequently used model prototypes in China are given in Table 1 (Yin 1978, 1984).

In Table 1, M is the stand volume per unit area (m^3/hm^2), HT is the average top height (m), N is the tree number per unit area (plant/ hm^2), p is the density of stocking, M_p is the stand volume per unit area at the density of stocking p (m^3/hm^2), N_p is the tree number per unit area at the density of stocking p (plant/ hm^2), N_0 is the initial density of trees (plant/ hm^2), a, b, c, K_1, K_2 and K_p are parameters. The relationships between parameters are calculated as follows:

$$(1) K_1 = \frac{b_{11}}{b_{12} - b_{11}}$$

$$(2) K_2 = 0.5a_{11}(0.5a_{11}/a_{12})^{K_1}(K_1 - 1)((K_1 - 1)/K_1)^{-K_1}$$

According to prototypes of the SDMM, model fitting requires different survey data that are collected from different sample plots with different stand densities. It also asks that, at each stage of tree height, a certain number of sample plots should be available to obtain mean diameter at breast height (DBH), average top height, and tree plant per unit area and stand volume per unit area. Given that the accuracy of the model fitting is largely influenced by data processing, data that are repetitive and obviously erroneous are eliminated with the method of twice standard deviation (SD).

The model precision should be verified since it would directly influence the value of a SDMD. t -test should be performed on each model. R^2 should be maximal and MSE should be minimal, so that the goodness of fit could be determined. Residual plots should be applied to model verification.

Data fitting should be conducted and initial parameters of model prototypes should be changed in different fitting operations. Based on the results of parameter estimation, and in light of the statistics that are used to evaluate the parameter estimation results, the fitting efficiency of different functions should be compared. Indices for model fitting and model verification are shown as follows:

Table 1: The most frequently used model prototypes of SDMD.

SDMM	Prototype model	Model theory
Equivalent height curves	$M = a_{11}HT^{b_{11}}N - a_{12}HT^{b_{12}}N^2$	Binominal theory of density effect
Maximal density curves	$M = aN^{-b}$	Power type of density effect
Equivalent density of stocking curves	$M_p = K_p N_p^{1-K_1}$	Power type of density effect
Natural thinning curves	$M = K_2(N_0 - N)N_0^{-K_1}$	Reciprocal binomial of density effect
Equivalent diameter curves	$M = aD^bN^c$	Inverted binomial of density effect

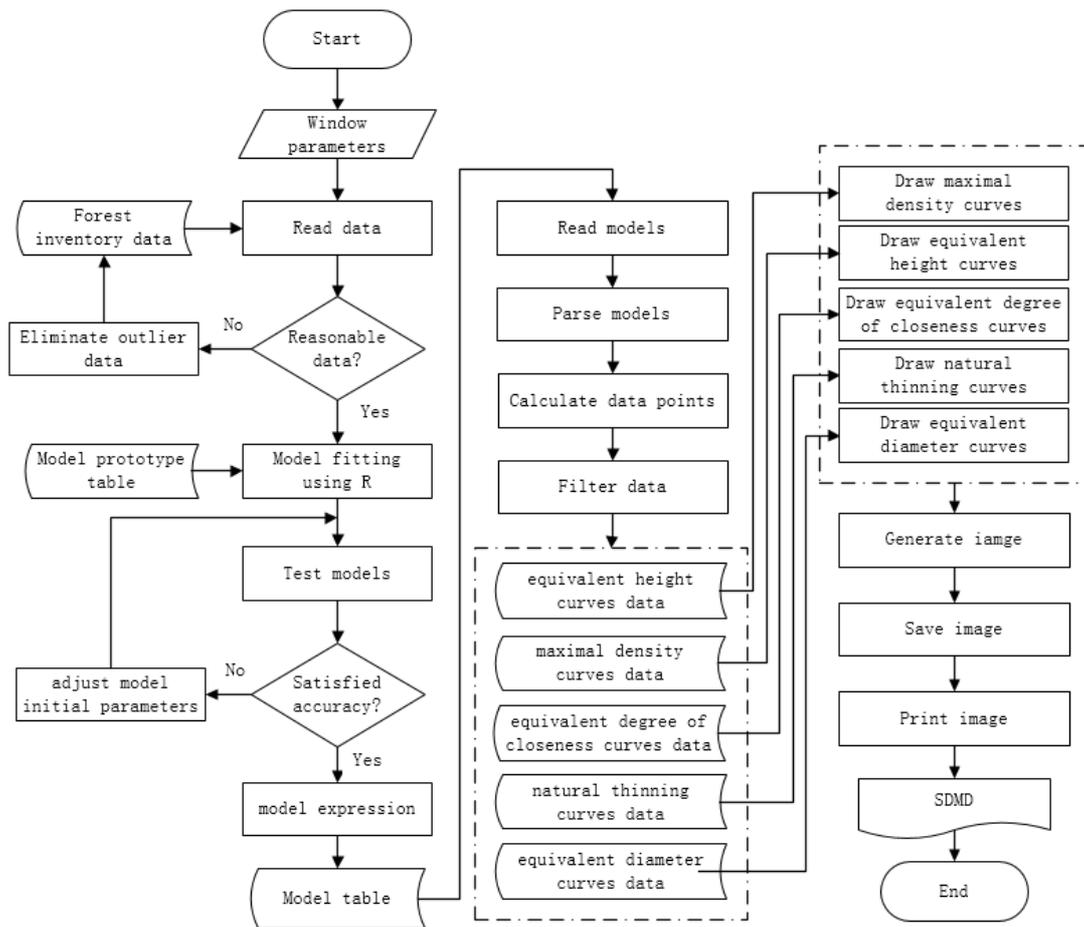


Fig.1: The drawing process of SDMD.

$$R^2 = 1 - \frac{\sum_{i=1}^m (y_i - \hat{y}_i)^2}{\sum_{i=1}^m (y_i - \bar{y}_i)^2} \quad \dots(1)$$

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad \dots(2)$$

System Design for the Dynamic Construction of SDMDs

System design procedure: Based on the constitutive characteristics of SDMDs, this paper combines the model fitting with graphic plotting, to automate and streamline the construction process of SDMDs. With users’ input of data collected from sample plots and window parameters into the system, it would automatically eliminate outlier data, fit model and verify fitted model, and with a comparison of optimal results, the expressions of a SDMD under a certain site condition could be determined. Through model reading, model parse, calculating and data filtering, point sets

of data could be obtained, and curves could be constructed in a log-log plot with these sets as the data source; after colour rendering, sets of SDMDs could be produced; and the diagrams should finally be saved and printed. The SDMD drawing process is shown in Fig. 1.

System function design: Based on users’ needs and the system procedure, two functions should be included into the system for the dynamic construction of SDMDs-model fitting and plotting: (1) The model fitting function should be used to fit the parameters of different sets of SDMDs to obtain expressions for the models. Since the precision of model parameters could influence the precision of diagram construction, regression analysis should be adopted based on statistical functions, and in light of nonprofessional users’ lack of expertise of regression analysis, such functions should be included into the model fitting module as data import, outlier data elimination, data input and output for model fitting and model expression saving. (2) The plot-

Table 2: Prototype examples of stand density control model.

Model Number	Tree Name	Model Type Name	Model Expressions	Model Variables	Parameters
010101	Larch	Equivalent height model	$a11*(H^{(b11)})^N - a1$	M, H, N	a11, a12,
010201	Larch	Maximal density model	$2*(H^{(b12)})^N * N$	M, N	b11, b12
010301	Larch	Equivalent density of stocking model	$a * N^{(-b)}$	M, N	a, b
010401	Larch	Natural thinning model	$Kp * N^{(1-K1)}$	Mp, N	K1, Kp
010501	Larch	Equivalent diameter model	$K2*(N0-N) * N0^{(-K1)}$	M, N	N0, K1, K2
			$a * D^b * N^c$	M, D, N	a, b, c

ting module should have such functions as model expression analysis, data source generation, graphic plotting, and file saving and printing.

Database design: The system database is comprised of a data table, a model prototype table, a data source table (equivalent height, equivalent density of stocking, natural thinning and equivalent diameter), and a table for the saving of model fitting results.

Model prototype table and model table: Considering that data could vary from one region to another, from one tree species to another, and from one sample plot to another, and that prototypes of SDMDs have different expressions, two tables have been designed for the ease of saving, updating and analysing models, including a model prototype table and a model table. The model prototype table could be used to save the prototype of SDMM and the model table could be used to save model expressions after fitting. The relational schema of the prototype table of SDMDs: Prototype of SDMMs (model number, tree name, model type name, model expressions, model variables, parameters). The relational schema of the model table of stand density control diagrams: SDMMs (model number, tree name, model type name, model expressions, model variables).

In the model prototype table, there are several sets of model prototypes, each of which contains different model types; the models of the same type may be comprised of different model expressions. AABBC is used to define model number. "AA" represents the model prototype group; "01" represents the first model prototype group; "BB" represents model types: "01" stands for the model of equivalent height curves, "02" stands for the model of maximal density curves, "03" stands for the model of equivalent density of stocking curves, "04" stands for the model of natural thinning curves and "05" stands for the model of equivalent diameter curves; "CC" represents the different model expressions: '010101' means the first expression for the equivalent height model in the first model prototype group. One example is given in Table 2.

Data tables: Data tables include a table for the forest inventory data collected from sample plots, a table for data sources

and a table for fitting results. Among them, the table for survey data would save data after abnormal data are eliminated. The relational schema is as follows: Inventory data (number, sample plot number, dominant height, stand density, DBH, stand volume).

In order to improve the efficiency of constructing a SDMD, five tables of data source are designed to save the data obtained through a calculation based on SDMDs. The relational schemes are as follows: Equivalent height curves (ID, tree height, density, stand volume), maximal density curves (ID, density, stand volume), equivalent density of stocking curves (ID, density of stocking, density, stand volume), natural thinning curves (ID, initial density, density, stand volume), equivalent diameter curves (ID, diameter, density, stand volume).

Fitting results table: In order to compare the fitting results of multiple groups of models, a table is designed to save model fitting results. The relational scheme is as follows: Fitting results (model number, model expressions, determination coefficient, mean square error).

RESULTS

R-Based Fitting of SDMMs

Statistical regression software is generally applied to the model fitting, to determine the parameters for SDMDs. The precision of fitting determines the precision and number of survey data. Different tree species could have different parameters, and trees of the same species could also have different parameters under different site conditions. On this account, when forest inventory data are adjusted, refitting should be conducted on the parameters of prototype, and statistical analysis software should be reapplied to parameter fitting-the work would be tedious and heavy (Guo 2013, Wu 2013).

R language is adopted in this research as the statistical analysis tool for model fitting of parameters. C # language and R language are applied by the system to the automatic fitting of parameters, and R. NET serves as the bridge between the two languages to realize interoperability. The realization process is as follows:

Table 3: Larch plantation plot data.

Sample/block	Dominant height/m	Stand density (plant/hm ²)	Stand Volume/(m ³ /hm ²)	Mean diameter/cm
246	3.5~19.0	160~2700	9.5~260.5	5.0~33.8

Table 4: SDMM fitting parameters.

Equivalent height model				Maximal density model		Natural thinning model		Equivalent diameter model		
a11	b11	a12	b12	a	b	K1	K2	a	b	c
1.36E-04	2.700	2.93E-09	3.590	3.256	2.4E+05	3.034	8.15E+09	0.026	1.56	0.64
Equivalent density of stocking model										
K1	P(0.2)	P(0.3)	P(0.4)	P(0.5)	P(0.6)	P(0.7)	P(0.8)	P(0.9)	P(1.0)	
3.034	1.23E+07	2.99E+07	5.76E+07	9.81E+07	1.56E+08	2.37E+08	3.57E+08	5.50E+08	1.19E+09	

- Initialize R.NET.
- Read forest inventory data, eliminate outlier data and obtain data for fitting.
- Read model prototype groups and read each expression and initial parameter of each prototype group.
- According to the linear characteristics of model expressions, different fitting functions should be chosen.
- Generate R format instructions and conduct model fitting.
- Based on model fitting results, analyse whether the residual plot is abnormal or not, and adjust the initial values of parameters continuously. Repeat d) and e) until satisfactory fitting results are achieved, and save the results in the model fitting results table 'Fitting Results'.
- Repeat c), d), e) and f) until all the model prototype groups are covered.
- Compare the coefficients of determination R^2 of the models of the same type in different model prototype groups and select the optimal model expression. Detailed procedure is shown in Fig. 2.

The number of independent variables of model prototypes is different; some of the prototypes are linear and some others are non-linear; the algorithms for fitting and the instructions to generate R language are also different. The adopted algorithms are as follows:

FALMR (Fitting algorithm of linear model based on R)

Algorithm: FALMR

Input: I_i (Independent variable), D_i (Dependent variable), A_i (Parameter initial values), model (Prototype model).

Output: R_t (Fitting results), R^2 (Determination coefficient).

- For $i=1 \leftarrow I_i, D_i$ #Data Input.
- To R Type (I, D) #Convert Data to R language format.
- End for #END loop.

- Linear (model) #Construct the linear model formula.
- To R Linear Model (model, A_i, \dots) #Converted model to R language format.
- Double $a=new$ double { a_0, a_1, \dots }; #Initial parameters input.
- Linear Fitting (lm, a, \dots) #Linear model fitting.
- Calculate Parameters () #Model parameter estimation
- $R_t \leftarrow$ Calculate (R^2, \dots) #Calculating goodness of model fitting.
- Show $R_t()$ #Result visualization.

FANMR (Fitting algorithm of nonlinear model based on R.NET)

Algorithm: FANMR

Input: I_i (Independent variable), D_i (Dependent variable), A_i (Parameter initial values), model (Prototype model).

Output: R_t (Fitting results), R^2 (Determination coefficient).

- For $i=1 \leftarrow I_i, D_i$ #Data Input.
- To R Type (I,D) # Convert data to R language format.
- End for #END loop.
- Non Linear (model) #Construct the linear model formula.
- To R Non linear model (model, A_i, \dots) # Converted model to R language format.
- Double $a=new$ double { a_0, a_1, \dots }; #Initial parameters input.
- Non Linear Fitting (lm, a, \dots) #Nonlinear model fitting.
- Calculate Parameters () # Model parameter estimation.
- $R_t \leftarrow$ Calculate (R^2, \dots) #Calculating goodness of model fitting.
- Show $R_t()$ # Result visualization

Plotting

Data source generation: String expressions used to save models should be analysed when in use. For this purpose, Iron Python is applied, which has the function of parsing

strings. Strings imported into the software should be changed into mathematical expressions that conform to Python language, and specific numerical values should be used to substitute model variables. The model analysis interface used for calculation is $f(\text{str Expression, strParameter, strValues})$, where strExpression is the model expression, strParameter is the model variables, strValues are the parameters of model variables.

Following the idea that “points form curves and curves comprise plots,” this research intends to obtain point sets through parsing model, calculating and filtering data, to form five curves; each curve model should be comprised of multiple curves that are formed from multiple point sets. The data source generation for equivalent height curves is taken as the example, and the point of intersection between equivalent height curves and maximal density curves is defined as A_i (i is an integer). When A_i is obtained, the filtering process can be described as follows:

Algorithm: Date source generation for equivalent height

curves.

Input: A_i (Points of intersection), H_i (Height), a (Height tolerance), N_0 (Initial plants), N_j (Stand density), model (Model expressions).

Output: Ph (Datasets of equivalent height curves).

1. For $i=2 \leftarrow H_i$ #height initial value
2. Read (model) #reading equivalent height curve models
3. For $j=N_0 \leftarrow N_j$ #density of trees
4. $Ph \leftarrow$ Calculate ($A_i, H_i, N_j, \text{model}$) # calculating datasets of equivalent height curves
5. SaveToDB (Ph) #generating data source of equivalent height curves
6. End for #end loop
7. End for #end loop

Plotting: This system adopts the techniques of XtraCharts to generate SDMDs. It has different series of curves, abundant legends and labels and user-defined functions as well; it also provides such services as saving and printing graphs. Data are filtered to form a series of point sets as the source of

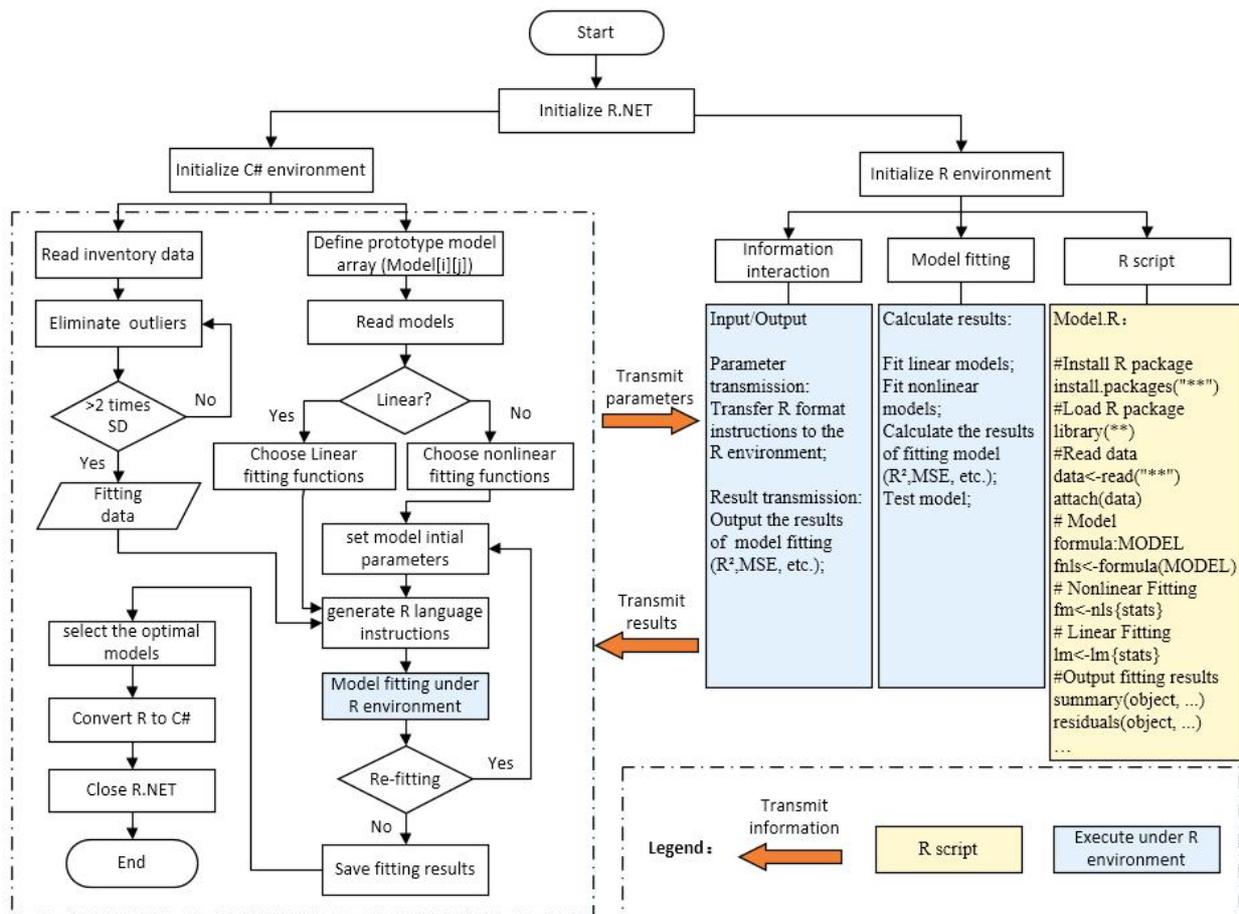


Fig. 2 The detailed procedure of SDMM fitting based on R.

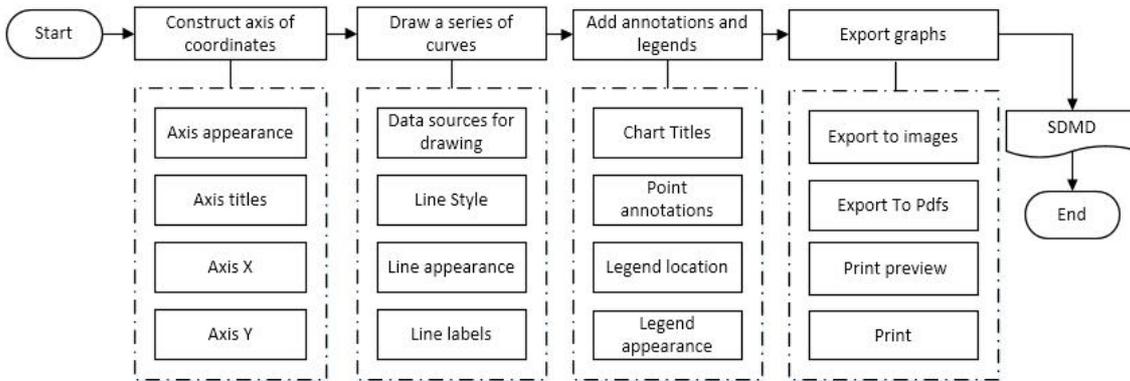


Fig.3: The drawing process of SDMD.

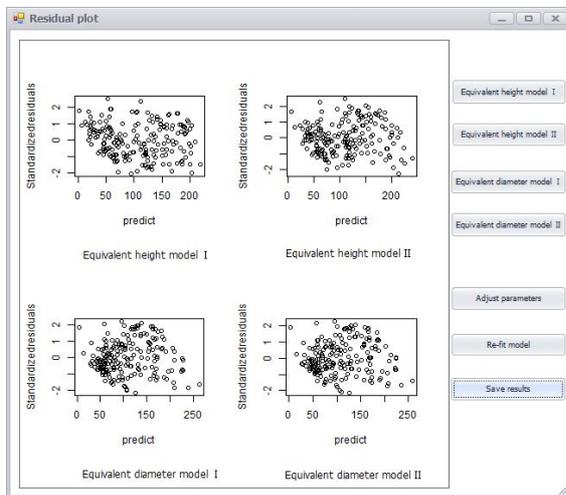


Fig. 4: Equiheight line model residual plots.

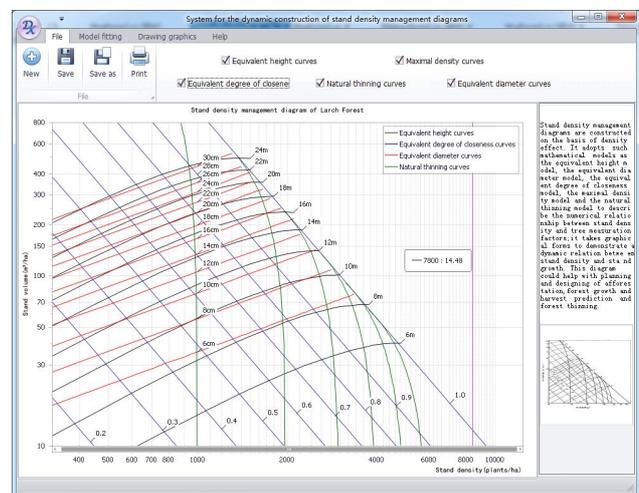


Fig. 5: SDMD of the Larch plantation.

plotting. In the process of plotting, axis of coordinates should be constructed, curves should be formed, legends should be added, and graphs should be exported. The making of the axis of coordinates involves the defining of coordinate scale, visual scope, axis appearance and axis titles. To form different series of curves, different view attributes should be set to them. Annotations are titles for figures and explanations for points on a series of curves. Legends help users tell the difference among figures with icons and descriptions. Graphs can be exported in the form of texts or graphic files, and users can obtain PDF files or image files; graphs can also be presented and exported through print preview. The process can be described in Fig. 3.

System Application

This research collects data from 246 sample plots in the *Larix principis-rupprechtii* plantation in China’s Inner Mongolia (Table 3). Two model prototypes

$M = a_{11}HT^{b_{11}}N - a_{12}HT^{b_{12}}N^2$ and $M = aH^bN^{cH^d}$ are applied to model fitting, with the equivalent height curve model fitting taken as the example.

Based on the residual plots of the two models (Table 4), it can be learned that the ratios of goodness of fit (R^2) for the two equivalent height curve models are 92.31% and 83.54% respectively. Since R^2 should be maximal, the first group of models is chosen as the SDMM (Fig. 4).

A SDMD is constructed for the *Larix principis-rupprechtii* plantations, where the ordinate is stand volume and the abscissa is stand density (Fig. 5). Equivalent height curves lean toward the top right part of the diagram, presented in black solid lines aligned upward with a difference of tree height of 2 m (unit: m). Equivalent diameter curves lean toward the top right part of the diagram, presented in red dashed lines aligned upward with a diameter class of 2 cm (unit: cm). Equivalent density of stocking curves lean

toward the bottom right part of the diagram, presented in blue solid lines aligned with a different density of stocking of 0.1, and the maximal density line has a density of stocking of 1.0. Natural thinning curves lean downward, presented in green solid lines, with such values as 1000, 2000, 3000, 4000, 5000 and 6000 (unit: plant/hm²).

CONCLUSION

Considering that SDMDs could change in different regions and with different species, this research combines model fitting with graphic plotting- a method different from the traditional one for SDMD construction-to streamline and automate survey data processing, model fitting and graphic exporting. With this new method, the poor applicability of software to the construction of SDMDs and the high demands for users' expertise could be overcome, the difficulties of plotting could be reduced substantially, and the work efficiency could be improved. In this research, we first use the R language to realize the automatic fitting of the model.

Model prototypes for SDMDs are saved into a relational database, with which it becomes easy to substitute and maintain model prototypes. When adjustments are to be made to SDMDs that have been plotted, a change of survey data and initial parameters would be enough to realize the rapid reconstruction of a diagram. Through comparisons of the fitting results of different sets of model prototypes, optimal models could be singled out.

If users read coordinate values with their own eyes from a SDMD, deviation would occur. Auxiliary markings, therefore, are designed in this research to solve the problem. With the move of computer mouse, those markings would also move and their values would appear. In this way, deviation could be reduced to a large degree and SDMDs could be of higher precision and practical value.

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