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Growth and yield models for uneven-aged forest stands managed under a selection system in northern Iran

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Abstract

Predicting future forest growth and yield is a key element of sustainable forest management. Hyrcanian forests are the most valuable forests in the north of Iran, and industrial harvesting occurs only in this area of the country. While uneven-aged Hyrcanian forests are one of the most important vegetated areas, and the only commercial forests in Iran, there is a lack of growth and yield models for management and planning purposes. The aim of this study is to develop distance-independent individual tree growth and yield models for uneven-aged forests in northern Iran managed under selection systems. A distance-independent diameter growth model, a static height model, an ingrowth model, and a survival model for uneven-aged stands of *Fagus orientalis* Lipsky were developed using measurements from Sangdeh, within the Mazandaran providence in Iran. The models are based on 130 permanent sample plots established in 2009 and remeasured in 2014. For modeling diameter and height growth, we employed a mixed effect regression. For modeling survival, we used binary logistic regression analysis. Ingrowth was modeled using multilinear regression. Results showed the best growth and yield model had relative RMSE and bias values, respectively, that were 31.9% and 6.3% for the diameter growth model, 11.3% and 0.17% for the height model, and 22% and 0.14% for the ingrowth model. Wald tests and other model evolution parameters showed that the parameter estimates for tree mortality were statistically significant. Overall results indicated that growth and yield model performance was consistent with expectations, and that the general fit to the validation data was acceptable.

Keywords: Individual-tree model, mixed-effect regression, diameter and height growth, tree mortality, Sangdeh.

Introduction

Uneven-aged forestry is a popular and acceptable method of forest management in the Hyrcanian forest of northern Iran. Forests are long-lived dynamic biological systems that are continuously changing (Kimmins 1990). Moreover, growth models may play an important role in managing forests and in formulating the forest policy. Forest managers often need to project forest conditions into the future in order to make sound decisions (Peng 2000), because management decisions are often made based on knowledge of present and future resource conditions. Inventories collected at a single instant in time can provide data on current wood volumes and associated statistics. Models are needed to predict future forest growth and yield under different management scenarios, and thus they are a key element of sustainable forest management (Kimmins 1990, 1997). Progress in developing useful models for predicting forest growth is needed for managing these types of forests in Iran. Growth and yield models, which are based on functions to measurement data from an of the forest population of interest, are the tools that have mostly been utilized for providing decision support and fundamental operational needs (Mohren et al. 2004). There have been many studies involving growth and yield modeling (e.g., Biging 1985; Lappi 1986; Gregoire 1987; Budhathoki et al. 2008; Uzoh & Oliver 2008, Adame et al. 2008, Crecente-Campo et al. 2008, Pukkala et al. 2009; Subedi and Sharma 2011, Lhotka and Loewenstein 2011 (individual diameter growth); Fridman and Ståhl 2001; Shifley et al. 2006; Yao et al. 2001; Yang et al. 2003 (tree mortality); Moser 1972; Ek 1974; Curtis et al. 1981; Curtis et al. 1982; Bravo et al. 2008) and these provide guidance for our efforts.

Hyrcanian forests are the most valuable forests in the north of Iran and industrial harvesting occurs only in this area of the country. In general, Oriental beech (*Fagus orientalis Lipsky*) is the main species in these forests. Oriental beech is not only is economically important for producing timber, but also for soil and water conservation. Though uneven-aged stands generally exist in Iran, growth and yield models of uneven-aged forest management for this region of the world are rare. Only one previous study (Bayat et al. 2013) illustrated the development of growth and yield models for uneven-aged forests in northern Iran. Growth and yield models can be categorized as whole stand, individual tree, diameter distribution, gap models and others. The advantage of individual-tree models is the possibility of describing a stand much more thoroughly and simulating numerous treatments more simply comparing with other models (Pukkala ; Kolström 1988). De Groot et al. (2004) and Pukkala et al. (2009) recommended that individual-tree models may be the best types of models for describing the dynamics of uneven-aged stands. According to Vanclay (1994), the essential components would capture increment, mortality, and recruitment of trees. Developing models for uneven-aged forestry has also become important because of demands on forests by the public for more close to nature forest management and more forest diversity (Lähde et al. 1999). This research is therefore aimed at developing a system that facilitates distance-independent individual tree growth and yield for uneven-aged Oriental beech forests. The system contains a diameter increment model, a height model, an ingrowth model, and a survival model.

Buongiorno and Michie (1980) included ingrowth in the matrix growth model to deal with the problem of the exponential growth of the number of trees in each size class. The model is based on the probabilities of the transition of trees between diameter classes and ingrowth of new trees in the lowest diameter class (Kant 1990). Peng (2000) reviewed the literature regarding growth and yield models for uneven-aged stands, discusses basic types of models and their merits, and reports recent progress in modeling the growth and dynamics of uneven-aged stands

Ling (2010) used a matrix of stand growth model for managing uneven aged boreal forest in the south and central Alaska. This model was a simulator for a 300-year period with a cutting cycle of 40 years. Accurate predictions of tree growth and yield are needed for determining optimize timber harvesting operations, and to evaluate how stand and tree parameters change over time, and in response to silvicultural interventions. Some researchers believe that the use of growth models in the implementation of uneven management is difficult in Hyrcanian forests (Heshmatol Vaezin et al. 2008) and others consider this method to be feasible and applicable in these forests (Mohammadi-Limaei 2008; Bayat et al. 2013). In view of the importance of Hyrcanian forests, there is a need for a reliable system of growth and yield predictions that, with appropriate economic parameters and ecological models, will support multifunctional forest management and planning. Traditionally, the prediction of forest growth and yield in Iran has been mainly based on historical records or experience developed for specific forestry conditions. However, these approaches may not be sufficient when developing sound management plans for complex forest systems (mixed and any-aged stands). Although uneven-aged and mixed stands commonly exist in Iran, systematic uneven-aged forest management is rare (Bayat et al. 2013). There is only one study in growth and yield models for uneven-aged stands that can be used in simulation and numerical optimization (Bayat 2012) that this study is carreid out in a limited area of Hyrcanian forest (934 ha) and cannot be considered for the whole of the Caspian forests. Therefore, due to the high heterogeneity in forest type, initial and secondary topography characteristics and climate of the Hyrcanian forests and for achieved to accurate results, this study should be done in different parts of these forests. The aim of this study is to develop a set models including individual tree diameter growth, individual tree height growth, survival (mortality) and ingrowth in order to make proper decisions on the economic utilization of these renewable and valuable assets as well as exploit other benefits of these natural treasures in uneven-aged forests in northern Iran.

Methods

Study area

The research was conducted for forests located in the Hyrcanian forest of Iran, specifically District 3 of the Sangdeh's forests, in the northern part of the country (Fig. 1). The management plan for District 3 of Sangdeh's forest suggests that the total area is about 2,709 ha. The study area is comprised of uneven-aged forests that are dominated by Oriental beech (90 percent of the forest region). The elevation of the forest areas ranges from 320 to 1,350 m above sea level.

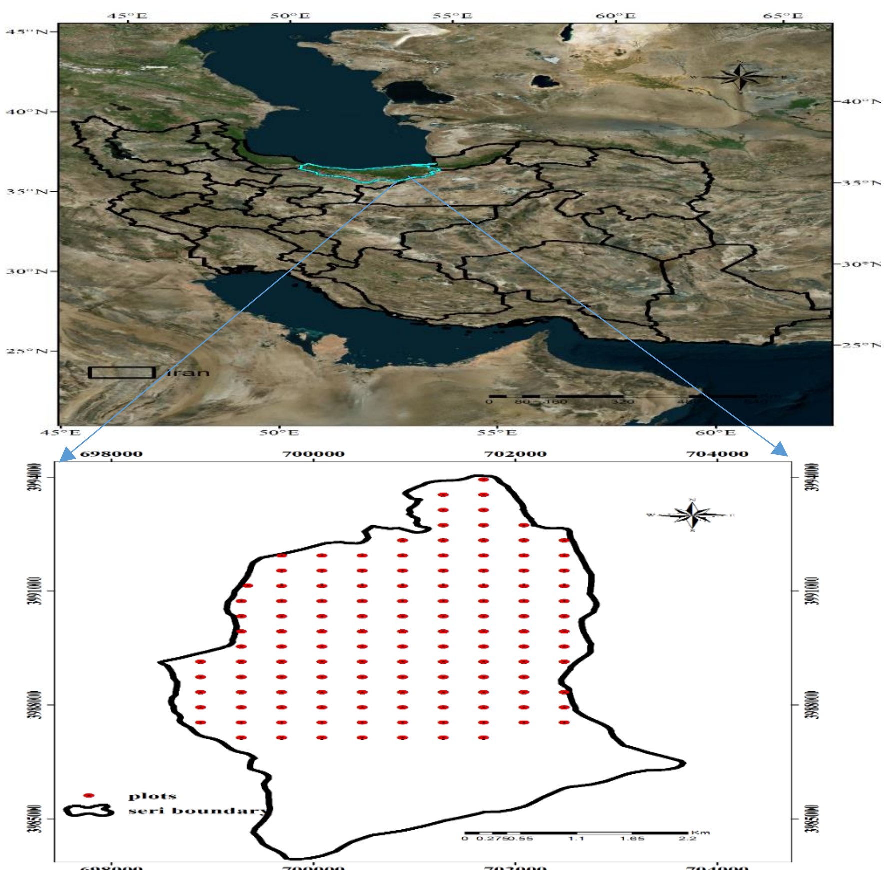

Fig. 1- Location of the research region and geographical distribution of the inventory sample plots.

The forest inventory includes 130 circular, 0.1 ha fixed area plots systematically located on a rectangular grid of 150 × 200 m, and remeasured every 5 years. All trees with a diameter at breast height (DBH) at least 12.5 cm were measured before the 2009 growing season and again following the 2014 growing season. Five-year diameter growth was determined as the difference between the two measurements. Every plot center was recorded using with GPS. Diameters were measured in a uniform direction in both measurements (2009 and 2014). Moreover, new ingrowth trees (trees that surpassed the 12.5 cm DBH threshold) were also measured in 2014. In addition, we recorded the status of each tree (living or dead).

For every plot, we computed the following stand or tree parameters: stand basal area (BA), number of trees per hectare (N), and basal area in the plot of all trees larger than the subject tree (BAL). Summary statistics of plot-level variables for model calibration are presented in Table 1.

Table 1 Summary statistics corresponding to plot-level variables for modelling.

Variable	N	Mean	Min	Max	SD
Dbh (cm)	130	33.46	16.43	110.00	17.18
Basal area (m^2/ha)	130	26.12	7.59	54.09	10.46
Density (trees/ha)	130	350	70	650	110.00
BAL (m^2/ha)	130	25.66	7.33	53.89	10.24

Growth and yield modeling

According to results Vanclay (1994), The more detailed approaches of forest stand modelling are not based on the overall growth of a forest stand, but need to discriminate several growth components in order to model these processes effectively (Vanclay 1994).In natural, mixed and uneven-even aged forestry, the following set of models are needed to support individual tree growth methods (e.g., Vanclay 1994; Trasobares et al. 2004):

- Individual tree diameter increment
- Individual tree survival
- Individual tree height increment
- Ingrowth estimation

The potential parameters for to the diameter increment model include: (1) tree size (DBH), (2) competition (BA, BAL, and its transformations ln (BAL), BAL/G, 1_BAL/G (see e.g., Wykoff, 1990; Vanclay 1994). Diverse types of diameter growth were considered for the dependent variable: diameter increment (DBH_{2014} – DBH_{2009}), 5-year diameter growth rate (*Drate* = [(DBH_{2014} – DBH_{2009}) / DBH_{2009})] and log transformed diameter growth. Linear mixed effect regression was used to model diameter increment following Calama and Montero (2005), Adame et al. (2008) and Lhotkaa and Loewenstein (2011).

The linear mixed model, incorporating the plot as a random variable, was (as described by West et al. 2007).

$Y_i = X_i\beta + Z_ju_j + \varepsilon_{ij}$ (1)

$\mu_j \sim N(0, \delta^2_{plot})$ (2)

$\varepsilon_{ij} \sim N(0, \delta^2)$ (3)

Where Yi is the vector corresponding to diameter increments for the ith tree. Xi represents the design matrix and coefficients of the fixed effects explaining tree size, competitive position and species composition. β is p × 1 vector of fixed effects. Zjuj is the design matrix and coefficients corresponding to the random plot impacts of the jth plot. δ2 is the residual error variance. Ɛij is an n × 1 vector of random errors. The model covariance structure considers residuals are not correlated and have a constant variance.

In this study, we used a binary logistic model to predict the possibility of tree survival. The explanatory variables were tree size (DBH and different derivatives) and competition factors (BA, BAL, N). There are numerous possibilities for transforming this variable that they have been used. Only significant variables ($p < 0.05$) with VIF (Variance inflation factor) less than 10 were chosen (eq. 5).

$$P_i = \frac{1}{1+e^{-[b(0)+b(1)\cdot x(1)+b(2)\cdot x(2)+\cdots+b(n)\cdot x(n)]}} \qquad 5$$

Where P_i represents the possibility of tree mortality, b_0–b_n are parameters to be estimated and x(1)–x (n) are descriptive variables.
The performance of this model was evaluated using tree criteria include area under the receiving Operation Characteristic (AUC), the Chi-square value and the Nagelkerke R2 statistics.
In this study, static height models associated with the second measurement period were developed due to errors in the height measurements associated with the first inventory. Consequently, height growth could not be estimated, and therefore we used the relationship between diameter and the height to model height. For modeling heights, we used a nonlinear mixed effect model:

$$H = 1.3 + a \times (1-\exp(-b \times d))^{(c)} \qquad 6$$

where H represents tree height (m) and d is the DBH (cm). a, b and c are parameters to be estimated.

For ingrowth, a linear model was prepared that had the ability to predict the trees per hectare entering the first DBH class (12.5 cm) over a growth period of 5 years.

$$IN = a_0 + a_1 Ba + a_2 BAL + a_3 \ln(Ba) + a_4 \ln(BAL) + a_5 (N) \qquad 7$$

where IN is the ingrowth (number of trees per hectare).
a0 to a4 are estimating the parameters of models.
BAL is the basal area in the plot of all trees larger than the subject tree.
Ba is the basal area (m^2/ha).

Model evaluation

With 30% of the data of plots, statistics were computed to assess bias, relative bias (*B*%), root mean square error (*RMSE*), and relative root mean square error (*RMSE%*). The definition of these statistics are as follows:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(est_i - obs_i)^2}{n}} \qquad (8)$$

Relative RMSE = 100 × (RMSE/mean observation value) (9)
est_i is an estimated value.
obs_i is observation value.

$$\text{BIAS} = \frac{\sum_{i=1}^{n}(est_i - obs_i)}{n} \qquad (10)$$

Relative bias = 100 × (Bias/mean observation value) (11)

Where: est_i represents the i^{th} predicted value; obs_i refers to the i^{th} experimental value and n is the number of observations.

For evaluating the binary logistic model, we used the following evaluation methods: the area under the receiver operating characteristic curve (ROC) to assess model fitness, Chi-squared values to assess the bias between diameter classes, and Pearson Chi-squared statistics to test the deviations between estimated and experimental values (Agresti, 1996).

Results

After summarizing the differences in plot growth between the first and second inventory measurements of the 130 plots, descriptive characteristics of the individual tree variables were developed (Table 2).

Table 2 Modeling results (Model columns represent outcomes from the modeling process. Evaluation columns represent used for Model evaluation).

Variable	Diameter growth (cm y^{-1})		Ingrowth (N $ha^{-1}y^{-1}$)		Survival (N $ha^{-1}y^{-1}$)	
	Model	Evaluation	Model	Evaluation	Model	Evaluation
Mean	0.48	0.47	3.57	2.71	2.40	2.50
Min	0.24	0.28	0	0	0	0
Max	0.76	0.80	12	12	20	20
SD	0.11	0.12	2.60	2.80	3.28	2.14

Different types of dependent variables were assessed for the diameter increment model. The natural logarithm corresponding to DBH increment plus a constant amount of one (log (DBH_{2014}–DBH_{2009} + 1)) was chosen, which resulted in a linear relation with the predictor variables, and normally distributed residuals. The following equation describes the model of the 5-year diameter increment:

$$\log(DBH_{2014\ ij} - DBH_{2009\ ij} + 1) = -0.943873 + u_j + 0.79424 \log(DBH_{2009\ ij}) - 0.08518\,(BAij) - 0.08678\,(BAL) + 0.02648\,(\mathit{Fagus}) + 0.04449\,(\mathit{Carpinus}) + \varepsilon_{ij} \quad (12)$$

where $DBH_{2009\ ij}$ and $DBH_{2014\ ij}$ are tree diameters (cm) of the *i*th tree on the *j*th plot in the year of 2009 and 2014, BAL equals the total basal area of trees larger than the subject tree, BA refers to the basal area of the tree, u_j * N (0, δ^2_e) represents a random plot parameter and ε_{ij} refers to the model residual of the *i*th tree on the *j*th plot. *Fagus* and *Carpinus* are indicator variables of different species (e.g., *Fagus* = 1 if species is Oriental beech and 0 otherwise). Results of the evaluation model and variance components for diameter growth model shown in Table 3. Findings indicated the most appropriate model has *RMSE* equal to 0.149 cm y^{-1}.

Table 3. Results of evaluating the model for individual diameter tree growth

Characteristic	Statistical model fitted					Variance components	
	R^2	RMSE	RMSE%	Bias	Bias%	δ^2 plot	δ^2residual

Diameter growth (cm y^{-1})	0.61	0.149	31.9	0.029	6.3	0.00815	0.08144

The height model was developed by modifying the Chapman-Richards model:

$$H = 1.3 + (a + u) \times (1\text{-exp}(\text{-}b \times DBH)^{(c + v)} \tag{13}$$

Where *u* and *v* are random impacts. Where H represents tree height (m) and d is the DBH (cm). The Tab. 4 shows the height model results for the best model developed. Results indicate that the best model has a relative RMSE and relative bias of 11.30% and 0.17%, respectively.

Table 4 Parameters and results for the tree height model.

Characteristic	*a*	*u*	*b*	*c*	*v*	RMSE	RMSE%	Bias	Bias%
Height (m)	35.46	-0.827	0.027	-1.1	-0.995	3.24	11.30	0.10	0.17

The logistic function for the probability of survival we developed was:

$$P_{ij} = \frac{1}{1+\exp\left[-(a_1 + a_2 \ln DBH_{ij} + a_3 \frac{BAL_{ij}}{BA_{ij}} + a_4 BA_{ij} + a_5 Carpinus)\right.} \tag{14}$$

Where P_{ij} represents the probability that tree *i* of plot *j* survives for a period of 5 years. The coefficients of the best model for survival can be found in Table 5.

Table 5 The statistical analysis outcomes for equations corresponding to individual tree mortality model.

Variable	Coefficients	Standard deviation	Z value	Pr(>|z|)
a_1	103.00	10.570	9.74	< 2e-16 ***
a_2	-3.78	1.891	-1.99	< 2e-16 ***
a_3	-109.14	10.890	-10.35	< 2e-16 ***
a_4	-0.23	0.015	15.22	< 2e-16 ***
a_5	1.08	0.028	3.92	8.53e-05***

* ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$).

Results of the assessment of the individual tree survival model are found in Table 6. Result indicate that the AUC value of the mortality model was 0.80. Additionally, the Chi-square value was 120.70 and the Nagelkerke R^2 statistics was 0.23 which suggests that the model had a reasonable fit to the data well.

Table 6 Results for the best model for tree mortality.

test	Value	*p*
Chi-Square value	120.70	0.000
AUC	0.80	0.000
Hosmer and Lemeshow Chi-square test	15.38	0.000
Nagelkerke R^2	0.23	
AIC	795.25	

Fig. 2 illustrates the ROC curve on the basis of the sensitivity, where the area under the ROC curve (AUC) was 0.80.

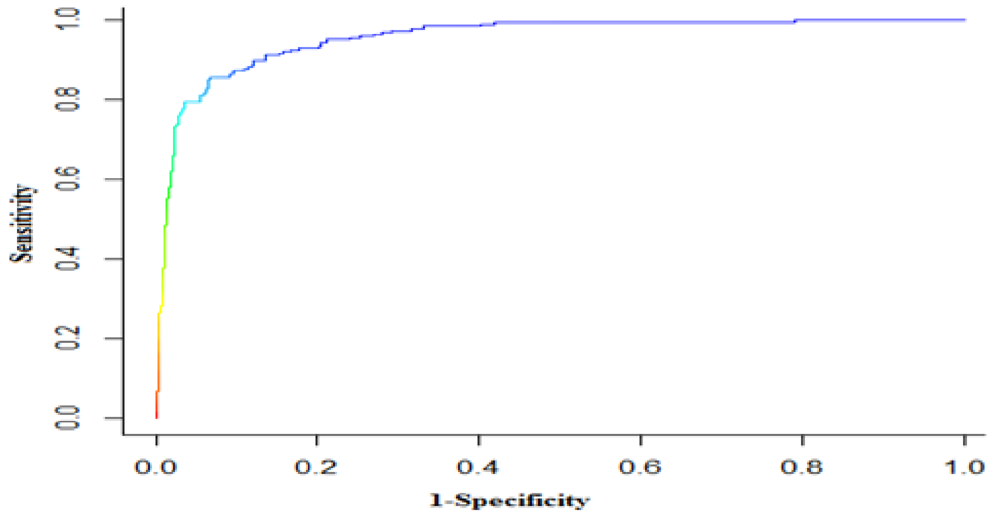

Fig 2- ROC curve of the mortality model.

Fig. 3 displays the results of comparing the estimated mortality possibility of reference trees with their experimental mortality possibility, and standardized residuals with predicted values for the most appropriate logistic model.

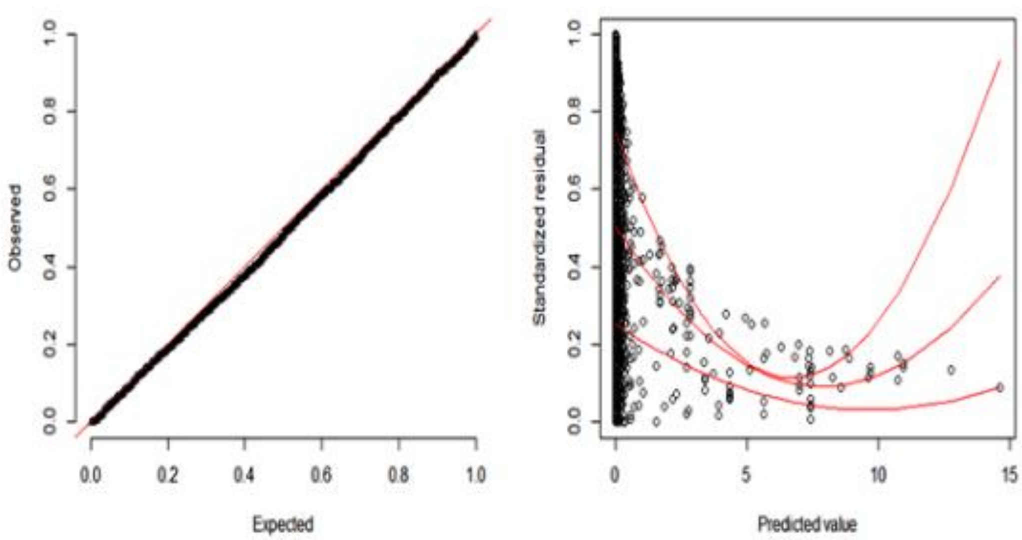

Fig 3- The estimated mortality possibilities for the most appropriate logistic model versus experimental and standardized residual mortality.

The ingrowth model estimates the number per unit area that grow into the 12.5 cm DBH class over the period of 5-year. The best model form for ingrowth was:

$$IN = 69.08 - 0.552930(BA) - 11.99400\,(\ln(BAL)) \qquad 15$$

Where *In* is the number of ingrowth trees per hectare. The model for ingrowth produced a coefficient of determination (R^2) of 0.86 (Tab. 7).

Table 7 Results of the best model for tree ingrowth.

Variable	R^2	RMSE	RMSE (%)	Bias	Bias (%)
Ingrowth (trees $ha^{-1}y^{-1}$)	0.86	3	22	0.02	0.14

The QQ plot, residual plot, and histogram (Fig. 4) associated with this model showed that distribution of residuals was normal without clear evidence of heteroscedasticity. The fitted values were completely in accordance with the modeled values.

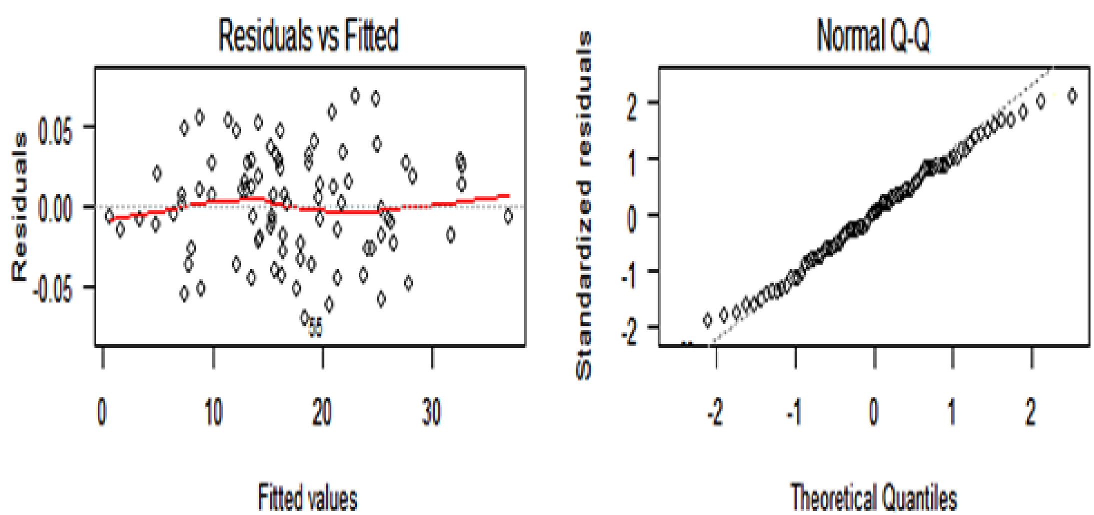

Fig. 4- Analysis of residuals and response values achieved by applying the application of the linear regression model.

Discussion

Hyrcanian forests are located in the northern region of Iran and across the south coast of the Caspian Sea, where they are also named Caspian forests. These forests generally contain mixtures uneven-aged stands of deciduous forests dominated by Oriental beech. There is expanding willingness of researchers, forest managers, and society towards the management of these forests without clear-felling, following continuous cover management practices. However, this endeavor has been delayed somewhat as a result of the absence of growth and yield models, and no instructions have been issued to manage the uneven-aged forests in this area so far (Bayat et al. 2013). Therefore, growth and yield models are needed for forest management planning to provide a reliable method for examining the impacts of silvicultural and harvesting choices (Vanclay 1994; Trasobares et al. 2004). The current research study showed that reasonably valid, individual tree, distance independent models for diameter increment, height growth, survival, and ingrowth of uneven-aged *Fagus orientalis* can be developed based on measurements of permanent sample plots. The predictor variables for all models are correlated with tree size and tree competition.

Distance independent, individual tree diameter growth models normally contain indicators of competitive position and/or stand density to account for the impact of tree competition when the tree positions are not known (Vanclay 1994). In prior research, tree diameter growth has commonly been expressed with deterministic linear or non-linear equations. Ordinary linear (OLS) and non-linear (ONLS) least squares regression methods have been extensively utilized for fitting these functions (Calama and Montero 2004). The absence of independence between tree measurement observations can lead to biased estimates when ordinary least squares regression methods are applied (Searle et al. 1992). Consequently, due to potential spatial correlation among observations from the same measurement plots (Fox et al. 2001), we utilized a mixed effects model for predicting five-year diameter increment in trees. Other diameter growth research considered these same issues (Biging 1985; Lappi 1986;, Gregoire 1987; Budhathoki et al. 2008; Uzoh and Oliver 2008; Pukkala et al. 2009).

Outcomes corresponding to the individual tree diameter growth model suggest that larger values of DBH caused greater annual growth increment, while larger values of the other variables (BA and BAL) caused smaller annual growth increment. The findings suggest that larger trees and trees located on better sites, and demonstrating greater vigor, had greater annual diameter growth increment. Increases in BAL suggest that competition causes a decrease in diameter growth increment, as the tree in question will be much smaller than others around it as BAL increases. BAL has been suggested as a proxy for the ability of trees to compete for light (Schwinning and Weiner 1998). Moreover, BA also impacts individual tree growth, as a reduction in the growth rate of individual trees was observed here as a measurement plot became more crowded or dense. These findings are in agreement with outcomes of other individual tree diameter growth models (Adame et al. 2008; Crecente-Campo et al. 2008; Subedi and Sharma 2011; Lhotka & Loewenstein 2011). Other studies have posited that competitive position, determined using BAL or modifications of BAL, may be the strongest predictors of diameter growth in both even-aged (Adame et al. 2008, Uzoh and Oliver 2008) and uneven-aged stands (Pukkala et al. 2009).

The R^2 and RMSE values for the best individual tree diameter growth model, using a mixed effect regression process, was 0.61 and 0.149 cm $ha^{-1}y^{-1}$, respectively. These are higher than those obtained in other studies (0.06 to 0.14 by Trasobares et al. (2004); 0.40 to 0.56 by Pukkala et al. (2009); 0.25 to 0.57 by Lhotka and Loewenstein (2011); 0.38 to 0.50 by Øyen et al. (2011)), therefore the fitness of the model seems sufficient. Furthermore, the RMSE we obtained achieved in this research was lower than previous studies (0.26 to 0.36 (cm $ha^{-1}y^{-1}$) in Lhotka & Loewenstein (2011) and 0.62 to 0.72 (cm $ha^{-1}y^{-1}$) in Trasobares et al. (2004)), suggesting model outcomes are reasonable.Data concerning heights of trees is inhibited through the complexity of its measurement in closed-canopy forests, and the associated time and cost required may be prohibitive. The predicted mixed effect regression height models from our work express tree height as a function of DBH; the best model we produced resulted in a RMSE value equal to 11.3%, which was noticeably lower in the present study than reported by Trasobares et al. (2004), where it ranged from 21 to 24%. The reason for these favorable results can be related to environmental conditions and forest structure. Moreover, the simulated stand dynamics does not seem to be affected by the use of static height models, as height never appears as a predictor in the diameter increment, ingrowth, and survival models. Height models are needed for predicting tree volume, and probable errors in height models can produce bias in volume predictions, yet they do not invalidate conclusions about, for example, the sustainability of diverse management plans.

Mortality is most suitably simulated through multiplying the frequencies corresponding of trees by their survival possibility (Vanclay 1994). If individual trees are considered, a decision must to be made whether a tree survives over the next few years (the model's time step) or not. In the current study, the possibility of a tree surviving for 5 years was best described using the BAL, the BA, and ln(DBH) for each tree. Wald tests indicated that the predictions of survival are significant ($p < 0.05$). Eid and Tuhus (2001) determined that the possibility of survival increased as DBH increased, and as BAL declined, which makes sense (larger trees, less competition). Trasobares et al. (2004) showed that the basal area at breast height played a major role in regeneration modeling. In another study, Fridman and Ståhl (2001) suggested that DBH, BAL, altitude, and BA were appropriate explanatory variables for survival models, which is similar to the outcomes of our work. Shifley et al. (2006) utilized crown class, BA of trees, and DBH as predictors of future mortality. Increasing competition (as expressed by BAL) reduces survival, and therefore BAL and the ratio of basal area of individual trees and their stand has been considered as variables for capturing competition for light sources. These have been used as a proxy for one-sided competition (Yao et al. 2001), while BA and number of trees have been used as a proxy for two-sided competition (Yang et al. 2003). In the current study, the Nagelkerke R^2 statistics was 0.23, and the AUC was 0.80, which suggests fair suitability of the proposed survival model. This value represents the extent to which the model can predict the dependent variable correctly; this value was between 0.5 and 1 in this study. The value of 0.5 represents the randomness of the model; the value of 0.7 represents a good accuracy of the model and a value more than 0.9 indicates the high accuracy of the model (Lei et al. 2004).

Generally, ingrowth is not considered in growth and yield models (Curtis et al., 1981; Curtis et al., 1982; Bravo et al. 2008) or, if it is taken in account, the obtained prediction is weak. For this study, the R^2 associated with our ingrowth model was 86%. By comparison, Trasobares et al. (2004a and 2004b) achieved lower fitness results for ingrowth models of *Pinus sylvestris* ($R^2 = 0.11$), *Pinus nigra* ($R^2 = 0.11$), and *Pinus halepensis* ($R^2 = 0.04$) in a study of Mediterranean forests. On the other hands, several others have developed ingrowth models with greater power. For example, Moser (1972) and Ek (1974) reported R^2 values over 0.70 for northern hardwoods forests of North America. Our results therefore seem robust for Hyrcanian forests in the northern region of Iran.

Conclusions

In this study we developed a set of empirical prediction models for periodic diameter growth, height growth, ingrowth, and mortality for uneven-aged beech (*Fagus orientalis*) stand types located in northern Iran. The model specifications were developed empirically from 130 permanent plots that were measured twice, then modeled using mixed effects regression procedures. Model selection was based on performance metrics. Results showed the best growth and yield model had relative RMSE and bias values, respectively, that were 31.9% and 6.3% for the diameter growth model, 11.3% and 0.17% for the height model, and 22% and 0.14% for the ingrowth model. Model evolution parameters showed that the parameter estimates for tree mortality were statistically significant. Overall results indicated that growth and yield model performance was consistent with expectations, and that the general fit to the validation data was acceptable. The results indicated that the empirical models performed relatively well in terms of amount of the variation explained. Therefore, they seem suitable for predicting tree growth in uneven-aged hardwood stand types in the region where the study was situated.

Authors' Contributions

Siavah Kalbi wrote the manuscript and conducted the analysis of data. Asghar Fallah contributed to the research design and data collection along with technical assistance and interpretation of data. Pete Bettinger, Shaban Shatee and Rassoul Yousfpour conducted an interpretation of data, and assisted in the writing and editing of the manuscript.

Competing interests

The authors declare that they have no competing interests.

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