Pre-growth mortality of *Abies cilicica* trees and mortality models performance

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Abstract: *In this study, we compared tree-growth rates (basal area increment) from recently dead and living Taurus fir (Abies cilicica Carr.) trees in the Kovada lake Forest of Isparta, Turkey. For each dead tree, tree-growth rates were analyzed for the presence of pre-death growth depressions in the study area (number of sample plots=11) in 2006. However, we compared both the magnitude and rate of growth prior to death to a control (living) group of trees. Basal area increment (BAI) averaged substantially less during the last 10 years before death than for control trees. Trees that died started diverging in growth, on average, 50-60 years before death. About 18% of trees that died had chronically slow growth, 46% had pronounced declines in growth, whereas 36% had good growth up to death. However, tree-ring-based growth patterns of dead and living Taurus fir trees were compared and used 12 mortality models that were derived using logistic regression from growth patterns of tree-ring series as predictor variables. The four models with the highest overall performance correctly classified 43.8-56.3% of all dead trees and 75.0-87.5% of all living trees, and they predicted 25.0-43.8% of all dead trees to die within 0-15 years prior to the actual year of death.*

Key words: *Abies cilicica, Growth pattern, Mortality prediction, Tree mortality*
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Introduction

The widest natural distribution of Taurus fir (*Abies cilicica* Carr.), one of the most important forest trees of Turkey, is in the Taurus mountains of Turkey with a total of about 350,000 ha. Taurus fir is significant from historical, cultural, aesthetic, scientific and economic perspectives. It grows for up to 400 years (Bozkus, 1987).

In 2006, local forestry personnel reported that canopy Taurus fir trees in the Kovada Lake Forest-Isparta had sudden mortality. Tree-ring analyses revealed that trees dead at time of sampling in 2007 had been growing slower in seven of the 11 sample plots (size 200 m^2 or 275 m^2) during the previous decade than were the surviving trees. Tree mortality ranged from 21 to 60 percent per sample plot (FDE, 2007).

There are some apparent indicating characteristics of natural mortality of trees. The most distinguishing factor is the continuous decrease in annual tree rings width as a result of extensive competition for nutrients, light and environmental condition (Kalipsiz, 1982). Pronounced drought causes sustain ably reduced tree vigor and increased mortality risk, which is ultimately caused by pathogens (fungi, insects) and semi-parasitic mistletoe (*Viscum album* L. ssp. *austriacum*). Therefore, tree development and mortality process should be carefully analyzed. To help identify the difference and find the cause of growth retarding and mortality, dendrochronology and dendroclimatology are proven effective (Mast and Veblen, 1994; Bigler *et al*., 2006). Comparison of growth

trends of healthy vs. declining populations of trees may provide insight as to when a current decline was initiated and possible causes.

Tree-ring patterns provide an indication of both tree vigor and periods of suppression and damage. Thus, dendroecology can be used to evaluate growth prior to mortality and provide insights into possible causal factors. Sudden mortality from agents such as fire or bark beetles can have a tenuous relationship to tree condition. In contrast, mortality that is the end result of a gradual decline in tree vigour over a number of years may be a result of multiple factors. The studies that have examined ring-growth prior to mortality have found a variety of patterns. Declining growth prior to mortality appears common in many situations, including conifers in Europe (Bigler and Bugmann, 2003, 2004a; Bigler *et al*., 2004; Misir *et al.*, 2007; Wunder *et al*., 2008). Low growth rates are often associated with mortality resulting from self-thinning or from some types of disturbance (Wycoff and Clark, 2000, 2002). The pattern and magnitude of growth prior to mortality can in a sense be considered as a fingerprint that can help distinguish causal agents. For example, different pathogens can cause different patterns of growth prior to death of the host tree (Cherubini *et al*., 2002). Although the number of studies is rather limited, it is clear that tree ring patterns can provide critical information about mortality prospects and agents related to mortality.

With this study, we present a new approach to model a tree's mortality probability across time, and asses the potential of this method for predicting the time of tree death based on longitudinal

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growth data (Bigler and Bugmann, 2004b). The mortality models are applied to predict the time of tree death using measured tree-ring data of dead and living Taurus fir trees. Such knowledge in turn improves the understanding of tree mortality processes and increases the reliability of models of long-term forest dynamics. The objectives of this study have been (1) to determine if the actual rate of growth of trees that died was low relative to trees that survived, (2) to determine if the trend in growth shows a pronounced decline (abrupt or gradual decrease in rate of growth) before death, (3) to evaluate how much individual trees differed in their rate and trend of growth before death, (4) to interpret these patterns in terms of the possible factors that could be leading to tree mortality, (5) to use characteristics growth patterns for predicting the time of individual tree death based on a logistic mortality model and (6) to compare the performance of several mortality models.

Materials and Methods

Study sites: Study area is most important natural Taurus fir forests, the forest (37°38'N, 30°51'E) with an extension of nearly 150 ha in the Kovada Lake Forest of Isparta. Taurus fir is the dominant tree species in the study area. The study area is ranged in elevation from 1200 to 1750 m. Its exposure is east, the altitude is 1540 m asl and the mean slope is 11%. Soil is sandy loams with a hard clay layer, usually >60cm below the surface, although there are local seepage areas throughout the stand. The study area is an uneven aged Taurus fir stand. In the study area, average number of stems is 164 ha^{-1}, mean diameter is 40 cm, mean tree height is 16.9 m, dominant tree height is 20.3 m, age is 107 years and site class is poor.

Tree-ring measurements: Sample plots (n=11) were established (20x 10 or 25 x 15 m) in the study area. The plots were chosen in presently undisturbed by man forest areas containing large trees. Two live and two dead Taurus fir trees within each of the 11 sample plots (n=44) were selected in early October 2007 for tree-ring analysis (Table 1). All sample trees were in the dominant or co-dominant crown class. The living trees were selected that had similar diameter at breast height (dbh), competition and microsite conditions as the dead trees. Two cores were taken at breast height from each tree. Annual ring widths were measured to the nearest 0.01 mm using a streomicroscope. The computer program COFECHA (Holmes, 1983) was used to detect measurement and cross- dating errors. Develop a mean chronologies based on 44 radii from 22 dead Taurus fir and 44 radii from 22 Taurus fir.

The dead-tree and live-tree ring-width measurements for each tree were converted to basal area increment (BAI), the cross-sectional area (cm^2) of annual xylem produced per tree. BAI is preferable to ring width as an indicator of growth primarily because ring width often decreases strongly with tree growth, as wood is added to a larger circumference, whereas BAI is roughly related linearly to crown area (Antos *et al*., 2008).

We plotted BAI for the last 110 years before death for the 22 and for the last 110 years before the study for the 22 live (control)

trees. To evaluate growth rate before mortality, which could relate to slow growth over a long period, we divided the last 110 years of growth into 10 segments each 10 years long and calculated mean BAI for each period. We compared growth rate for these 10-year periods directly between the dead and control trees. Trees in the same stand could die for different reasons, and have different rates and patterns of growth prior to mortality. Thus, we aggregated these patterns into there basic groups: chronically slow growth (BAI never exceeded 10 cm^2 year^{-1} for any 10 year period during the last 100 years of life); abrupt decline (some from of pronounced decrease in growth during the last 50 years); good growth (had no abrupt decline and fairly good growth rates up to the time of death). However, differences in basal area increment growth dead and living groups for all years from 1897-2007 and from 1957-2007 were tested using ANOVA model.

Derivation of mortality models: Twelve deterministic, empirical mortality models were selected based on the analyses by Bigler and Bugmann (2004a). The parameters were fitted using logistic regression to predict the survival probability Pr ($Y_{i,t}$ = 1/$X_{i,t}$) of tree i at a given time t (Hosmer and Lemeshow, 1989):

$$\Pr(Y_{i,t} = 1/X_{i,t}) = \frac{\exp(X_{i,t}\beta)}{1 + \exp(X_{i,t}\beta)} \quad (1)$$

where $Y_{i,t}$ = status of tree i at time t (Y= 1 means the tree is living, Y= 0 means the tree is dead). Pr ($Y_{i,t}$= 1/$X_{i,t}$) is a survival probability in the interval [0,1] and $X_{i,t}$.b is a linear combination of the independent variables (X) and the regression coefficients (b).

The independent variables were calculated using time series of bai or rw of individual trees. Two growth level variables over a period of three years were considered, since preliminary analyses showed that growth level variables over this period had a higher statistical significance than variables calculated over five or more years (Bigler and Bugmann, 2003); bai$_3$ (cm^2) is the three year average of bai and rw$_3$ (mm) is the three year average of tree-ring width. Based on an extensive statistical screening procedure, we decided to consider a short-term growth trend variable and a long-term growth trend variable. The slopes of local linear regressions (locreg) over 5 years (locreg$_5$) and 25 years (locreg$_{25}$) of bai were used. Finally, the relative growth variable relbai was calculated as the ratio of bai and ba (basal area increment divided by basal area), in order to take the size of the tree into account. Combinations of the independent variables were used to fit logistic regression models (Eq. 1) to the data set, including 1230 to 1758 repeated measurements from the 22 dead and 22 living trees (Table 2).

Assessing model performance: Model performance was assessed two classification accuracy criteria (Fielding and Bell, 1997) and three prediction error criteria (Bigler and Bugmann, 2003) were used. The first classification accuracy criterion was defined as the percentage of dead trees that were correctly predicted to be dead (CC$_d$; correctly classified dead trees). The second

classification accuracy criterion was defined as the percentage of living trees that were correctly predicted to be alive (CC_l; correctly classified living trees). We denoted the first prediction error criterion as the percentage of actually dead trees that were predicted to die no more than 15 years prior to actual death ($PE_{d,15}$). The second and third criteria were defined as the percentages of actually dead or living trees that were predicted to die >60 years prior to death or prior to the last measured year, respectively ($PE_{d,60}$, $PE_{l,60}$).

Statistical analysis: The AIC (Akaike Information Criterion) was used during the model selection procedure to assess the goodness-of-fit of the models. In these previous studies, low growth levels, negative growth trends or low relative growth generally indicated an increased mortality risk (Wycoff and Clark, 2000). The distributions of these growth patterns, based on the last measurement of each tree, were compared in the present study between classes dead and live. To test differences between classes, the exact Wilcoxon rank sum test (Zar, 1999) was applied, a non-parametric test that takes into account tied observations. Analyses were performed with the SPSS Ver. 15.0 statistical package.

Results and Discussion

Growth rate: On average over the site, the BAI of control trees increased gradually with time, whereas for trees that died, BAI increased until about 60 years before death (Fig. 1). Basal area increment growth started to diverge at about 60 years before death growth differences between dead and control trees are most effectively portrayed when adjusted for time of death. This analysis reinforces the results presented above (Fig. 2). Moreover, Antos *et al.* (2008) found that basal area increment averaged substantially less during the last 10 years before death than for live Subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) growing on in the British Columbia (Canada). Trees that died started diverging in growth, on average, 20-40 years before death. Similar results were reported by studies in Norway spruce (*Picea abies* L. Karst.) stands at northwestern Finland (Lannenpaa *et al.*, 2008).

Variation among individuals : We can summarize growth before mortality as follows. About 18% of the trees that died had chronically slow BAI: never exceed 10 cm^2 year^{-1} for any 10-year period during the last 100 years of life and generally below 8 cm^{2}year^{-1}. Chronic slow growth was 18% at stand (Fig. 3). Abrupt declines in growth within their last 50 years occurred in 46% of trees that died. The timing of declines varied and was not concentrated in the last few years of life. Thirty six percent of trees had good growth in at least one period and had no abrupt decline in the last 50 years before death. Thus, slow growth or abrupt declines in growth are typical, but not invariably related to mortality; some of the trees that died were among the fastest growing (Fig. 3). Moreover, Antos *et al.* (2008) found that about 50% of trees that died had chronically slow growth, 30% had pronounced declines in growth, whereas 20% had good growth up to death for Subalpine fir.

At the eleven sample plots comprising, the averaged growth curves of dead and living trees started deviating from each other
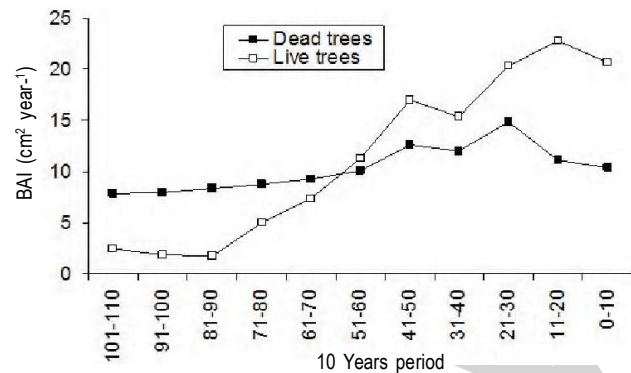

Fig. 1: Mean growth rate (basal area increment, BAI) for 10-year periods for dead and surviving canopy Taurus fir
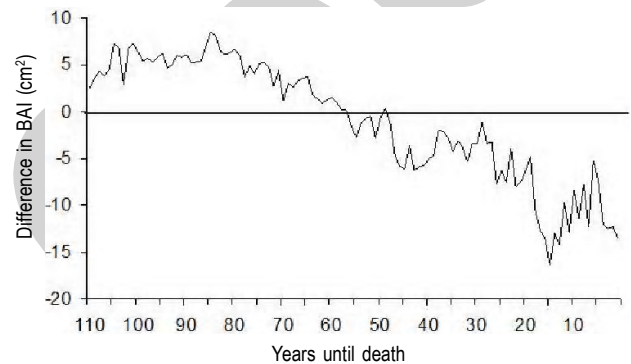

Fig. 2: Difference in growth rates basal area increment (BAI) between canopy Taurus fir that died and that were live in a given year
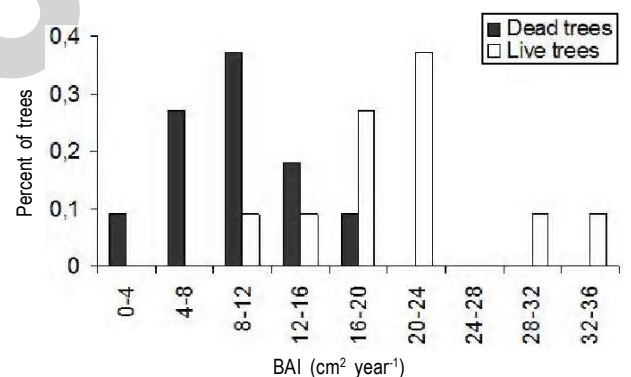

Fig. 3: Distribution of the growth trend and increment among Taurus fir. The mean annual basal area increment (BAI) is during the last 10-year period

after 1950 (Fig. 2). Dead trees showed a higher growth increase than the living trees between 1897 and 1957. The average basal area growth of the living trees decreased from 4.59 cm^2 year^{-1} in 1957 to 19.07 cm^2 year^{-1} in 2007, while in the same period the growth of the dead trees was reduced from 8.53 to 12.20 cm^2 year^{-1} (Fig. 2). This finding indicated that events that resulted in wide or narrow growth rings were generally reflected in the growth patterns of both live and dead (at time of sampling) Taurus fir trees in the

Table - 1: Summary of sample trees used in annual basal area increment for dead and live Taurus fir group

Group	Number of trees	Average diameter (cm)	Average height (m)	Average volume (m³)
Dead	22	43.5	16.3	1.015
Live	22	45.9	18.8	1.359

Table - 2: Independent variables used in mortality models

Model	Linear combination of independent variables	Number of measurements
Model 1	$\log(bai_3)$	1714
Model 2	$locreg_5$	1668
Model 3	$locreg_{25}$	1230
Model 4	rw_3	1714
Model 5	$\log(relbai)$	1758
Model 6	$\log(bai_3) + locreg_5$	1668
Model 7	$\log(bai_3) + locreg_{25}$	1230
Model 8	$\log(bai_3) + \log(relbai)$	1714
Model 9	$locreg_5 + \log(relbai)$	1668
Model 10	$locreg_{25} + \log(relbai)$	1230
Model 11	$\log(bai_3) + locreg_5 + \log(relbai)$	1668
Model 12	$\log(bai_3) + locreg_{25} + \log(relbai)$	1230

bai_3= three-year average of basal area increment (cm²); $locreg_5$ = slope of local linear regressions over five years of basal area increments; $locreg_{25}$= slope of local linear regressions over 25 years of basal area increments; rw_3 = three -year average of tree-ring widths (0.01 mm); relbai= ratio of basal area increment to basal area. Linear combinations of two growth level variables [$\log(bai_3)$, rw_3], two growth trend variables [$locrec_5$, $locreg_{25}$], and one relative growth variable [$\log(relbai)$] were included

study area. Similar growth declines have previously been noticed in other *Abies* species prior to tree death (Bigler *et al*., 2004; Antos *et al*., 2008).

Analysis of variance was used to examine the differences between basal area increments within dead and live groups. F value of ANOVA was 1.454 (df=1.218; p= 0.229), indicating that for the dead-live groups, there was no statistically significant difference between the basal area increments. However, F value for from 1957 to 2007 was (df=1.98; p<0.001). This result indicated that for the dead-live group, there was a statistically significant difference between basal area increments during 1957-2007.

Patterns of growth prior to mortality: Among trees that showed evidence of impending mortality, ring patterns varied greatly. Trees with chronically slow growth often decreased gradually to very low levels of growth before death; however, others continued at slow rates for long periods and showed no notable declines near the time of death. Taurus fir is shade tolerant and able to persist for long periods in the shade (Bozkus, 1987). Thus, it is not surprising that slow growth alone is not a strong predictor of impending mortality. However, very few of the live trees were growing as slowly as those that died. Although very slow growth (<8cm² year⁻¹ in BAI) does not directly indicate imminent mortality, and could be a long-persistent condition, very slow growth does imply a substantially

elevated probability of mortality. If growth is already slow, any factor causing a further decrease or a sudden stress may be much more likely to contribute to mortality than in a rapidly growing tree. For example, drought is much more likely to lead to mortality in slow-growing trees (Ogle *et al*., 2000).

Declines in growth before mortality varied in form. Some individuals slowly declined in growth, indicating gradually deteriorating conditions for a tree. Others showed abrupt declines, but these varied in timing from just before mortality to many years earlier. Following an abrupt decline some trees vulnerable. Both the trend in growth and the magnitude of growth immediately before death can contribute to predicting mortality (Bigler and Bugmann, 2003, 2004a; Bigler *et al*., 2004). We found that the trend in growth during the last 10 years was a poor predictor of mortality whereas the actual rate of growth provided better separation between trees that died and surviving trees. Over the longer term, trends in growth (overall declines) are clearly related to subsequent mortality, but during the last few years growth may even stabilize. This is consistent with the proposition that mortality is typically the culmination of a long series of events, and that once reduced to very slow growth some trees can still persist until an event, which might be minor for a better growing individual, actually causes death (Wycoff and Clark, 2000, 2002).

Model performance: The mortality models that were fitted using data set are shown in Table 3. The lowest AIC values were found for model 3, 7, 10 and 12 with values ranging between 363 (model 12) and 418 (model 3). However, models 3, 7, 10 and 12 showed the highest overall performance, as indicated by the low average ranks (Table 4). According to these results, the logistic mortality model (model 3, 7, 10 and 12) based on the independent variables $locreg_{25}$ (growth trend) and relbai (relative growth) achieved relatively precise mortality predictions for dead and living trees.

All models that contain only one independent variable (models 1 to 5 in Table 3) have p values smaller than 0.001. However, in combination with additional variables (models 6 to 12), some of the former variables turned out to be less significant. Among the variables that were used in combination with one or two other variables, *i.e*., all variables except for rw_3, only the variables $locreg_5$, and relbai proved always to have p<0.001. The relative growth variable (relbai) and particularly the long-term growth trend variable ($locreg_5$), which takes into account the current growth rate as well as the size of the tree, seem to have a high predictive power in this longitudinal approach of modeling tree mortality. If the model is to be evaluated with respect to inference, only models with significant variables (p<0.05) should be considered, which are satisfied all models.

The observed Taurus fir decline in stand may be considered as a natural, cyclic phenomenon. However, from a forest manager's perspective, death of a large number of trees may rather be classified as a complex disease. The early

Table - 3: Estimates of fitted mortality models using logistic regression (n=44 trees)[1]

Model	Independent variables	Estimated regression coefficient	Standard error	p values	AIC
Model 1	intercept	1.500	0.080	<0.001	699
	$\log(bai_3)$	-0.545	0.198	<0.001	
Model 2	intercept	0.214	0.050	<0.000	728
	$locreg_5$	0.107	0.038	0.004	
Model 3	intercept	0.524	0.066	<0.001	418
	$locreg_{25}$	2.175	0.236	<0.001	
Model 4	intercept	1.313	0.120	<0.001	639
	rw_3	-0.339	0.334	<0.001	
Model 5	intercept	-1.530	0.238	<0.001	721
	$\log(relbai)$	-0.466	0.063	<0.001	
Model 6	intercept	1.555	0.206	<0.001	673
	$\log(bai_3)$	-0.562	0.083	<0.001	
	$locreg_5$	0.070	0.038	0.006	
Model 7	intercept	2.224	0.302	<0.001	385
	$\log(bai_3)$	-0.714	0.122	<0.001	
	$locreg_{25}$	1.608	0.244	<0.001	
Model 8	intercept	-0.479	0.335	0.015	646
	$\log(bai_3)$	-0.469	0.082	<0.001	
	$\log(relbai)$	-0.483	0.068	<0.001	
Model 9	intercept	-2.022	0.279	<0.001	663
	$locreg_5$	0.006	0.039	0.048	
	$\log(relbai)$	-0.593	0.073	<0.001	
Model 10	intercept	-2.467	0.479	<0.001	390
	$locreg_{25}$	1.320	0.262	<0.001	
	$\log(relbai)$	-0.730	0.117	<0.001	
Model 11	intercept	-0.675	0.366	0.035	618
	$\log(bai_3)$	-0.476	0.085	<0.001	
	$locreg_5$	-0.015	0.040	0.046	
	$\log(relbai)$	-0.539	0.075	<0.001	
Model 12	intercept	-0.589	0.652	0.036	363
	$\log(bai_3)$	-0.536	0.127	<0.001	
	$locreg_{25}$	1.084	0.262	<0.001	
	$\log(relbai)$	-0.586	0.122	<0.001	

AIC (Akaike Information Criterion) values

Table - 4: Verification of the models fitted to the data (n=44 trees). Values are percentages followed by ranks for each performance criterion (1-12) in parentheses

Model	CC_d	CC_l	$PE_{d,15}$	$PE_{d,60}$	$PE_{l,60}$	Average rank
Model 1	43.8 (7.5)	81.3 (5)	31.3 (7.5)	18.8 (10.5)	6.3 (4)	6.9
Model 2	12.5 (12)	93.8 (1)	12.5 (10)	18.8 (10.5)	6.3 (4)	7.5
Model 3	43.8 (7.5)	87.5 (2)	43.8 (1.5)	12.5 (6.5)	12.5 (8.5)	5.2
Model 4	43.8 (7.5)	81.3 (5)	6.3 (11.5)	25.0 (12)	6.3 (4)	8.0
Model 5	37.5 (11)	75.0 (9.5)	37.5 (4.5)	6.3 (2)	6.3 (4)	6.2
Model 6	43.8 (7.5)	81.3 (5)	6.3 (11.5)	12.5 (6.5)	18.8 (11)	8.3
Model 7	43.8 (7.5)	81.3 (5)	25.0 (9)	6.3 (2)	6.3 (4)	5.5
Model 8	50.0 (3.5)	75.0 (9.5)	31.3 (7.5)	12.5 (6.5)	18.8 (11)	7.6
Model 9	43.8 (7.5)	68.8 (12)	43.8 (1.5)	6.3 (2)	18.8 (11)	6.8
Model 10	56.3 (1.5)	75.0 (9.5)	37.5 (4.5)	12.5 (6.5)	6.3 (4)	5.2
Model 11	50.0 (3.5)	75.0 (9.5)	37.5 (4.5)	12.5 (6.5)	6.3 (4)	5.6
Model 12	56.3 (1.5)	81.3 (5)	37.5 (4.5)	12.5 (6.5)	12.5 (8.5)	5.2

CC_d = Percentage of correct classification of dead trees, CC_l = Percentage of correct classification of living trees, $PE_{d,15}$ = Percentage of actually dead trees with prediction error ≤ 15 years, $PE_{d,60}$ = Percentage of dead trees with prediction error > 60 years, $PE_{l,60}$ = Percentage of living trees with prediction error > 60 years. The values of the performance criteria were computed using a threshold of 0.975; highest performances have the lowest ranks (1) and lowest performances have the highest ranks (12)

detection of an increased mortality risk on the individual tree level, preferentially prior to crown damage, may be useful in evaluating and controlling future mortality in Taurus fir stands of Turkey. As demonstrated in this study, assessment of a tree's current mortality risk based on growth patterns and a derived statistical mortality model clearly identifies trees at high risk of dying. Forest management might take advantage of these procedures to identify and selectively cut low-vitality trees, so as to release the remaining healthy trees. However, predicting mortality and understanding the causes of mortality are essential to the effective management of forests both for timber production and ecosystem protection.

We recommend that further studies should be conducted to investigate the sensitivity of forest succession models in general and the behavior of the tree mortality submodels in particular, with a focus on changing and changed climatic conditions. However, validity of the mortality models with independent data sets from geologically and climatologically different areas should be supported the reliability of our models for predicting tree death. The generality of the models gives us confidence that they can be applied to Taurus fir trees growing at a wide range of ecologically different sites.

The results of this study indicate that basal area increment averaged substantially less during the last 10 years before death than for control trees. Trees that died started diverging in growth, on average, 50-60 years before death. The rate of change in growth indicated a decline relative to the living group of trees but overlap was extensive between the two groups. Although some trees die abruptly without evidence in their ring patterns of impending mortality, overall our results indicate that mortality of canopy Taurus fir in these old forests is a gradual process related to long periods of low growth or long-term declines growth. Mortality models including a long-term growth trend (locreg$_{25}$) and the relative growth rate (relbai) as explanatory variables were most reliable with respect to inference and prediction. We conclude that the methods presented improve our understanding of how tree growth and mortality are related, which results in more accurate mortality models that can ultimately be used to increase the reliability of predictions from models of forest dynamics. However, the early detection of trees with increased mortality risk may help evaluate and control future mortality in Taurus fir stands.

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