

## A new method for early prediction of Turkish red pine (*Pinus brutia* Ten.) germination percentage

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### Abstract

This study was carried out to find a method to determine the seed germination ability (percentage) in the Turkish red pine (*Pinus brutia* Ten.) quickly and with high reliability. For this purpose, 82 seed lots of Turkish red pine were used, collected from different seed stands and orchards in different years. Since none of the seeds were folded, the germination ability was evaluated in a period between the 7th to 28th days. The seeds were divided into 4 groups (20–39.9%, 40–59.9%, 60–79.9%, 80–100%). Germination Percentage Index (GPI) are expressed with the mid-value of the related interval (e.g. GPI<sub>30</sub>: germination ability between 20–39.9%). Four different germination percentage intervals describing the germination percentage was fitted with 11 different regression models. The best fit of these models was determined by 7 fitness measures. As a result, the current germination percentage increment reached the highest values on the 13<sup>th</sup>, 13<sup>th</sup>, 14<sup>th</sup>, and 13<sup>th</sup> day for the indexes of 90, 70, 50, and 30, respectively. Within this study, it has been revealed that germination percentages in Turkish red pine seed lots can be predicted 7 to 10 days in advance.

**Key words:** seed; germination percentage index; germination percentage intervals; growth model; regression

Editor: Bohdan Konôpka

### 1. Introduction

Germination tests are the most basic method used to determine the seed's ability to germinate. This ability is defined as the germinability or its capacity of any seed lot, which is expressed by converting a qualifying feature (germinated/non-germinated) into a quantitative parameter (%) (Ranal & Santana 2006). This parameter, which expresses the germination ability quantitatively and which is determined in varied conditions and times according to plant species, is called the germination percentage (Thompson & El-Kassaby 1993; Ranal et al. 2009). Plant growers take this parameter, amongst other things (the number of individuals desired per unit area, thousand grain weight of the seed lot, percentage of cleaning, etc.) into account when determining the number of seeds to be planted in the production area (Stoeckeler & Slabaugh 1965).

Since Turkish red pine (*Pinus brutia* Ten.) has a wide distribution, especially at the wildfire-sensitive parts of Turkey, its seedlings are the most produced species in Turkish forestry. As of 2013, 13% of the total number of seedlings produced in forest nurseries consists of Turkish red pine. In recent years, forest enterprises have started to stockpile large amounts of seeds as a precaution in case

of major fires. In cases like this, it would be very useful to be able to determine quickly and with high reliability what is the ability to germinate in case of a sudden use. The percentage of seed germination in Turkish red pine was determined by a 28-day test, similarly to the international standard test period of Aleppo seed (ISTA 1996). Nurseries that grow seedlings of this species apply every year to research institutes to determine the germination capabilities of seed lots of different origins. The 28-day test period may be too long for practitioners in some cases, especially in times of urgent need.

The course of germination ability during the test period is expressed by the percentage of cumulative germination forming a time-dependent S curve (Sigmoid) (Lehle & Putnam 1982). The shape and steepness of the sigmoid curve reveals the germination energy of the seed lots tested (Joosen et al. 2010). In general, S curves of seed lots with low germination ability are flat or oblique, and those with high germination ability are steep. However, the S curves of two seed lots with approximately the same germination ability may also differ in flatness or steepness. This means that there is a difference between the germination energies of the two seed lots (Tilki & Çalikoğlu 1998).

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It is called the germination index, which takes into account both germination ability and germination energy (Czabator 1962; Diavanshir & Pourbeik 1976). Essentially, the germination index is the rate of healthy seedlings that a seed lot can yield in nursery or land conditions, and it can also be specified as the yield or yield rate of that seed lot. In addition, besides the yield rate of a seed lot, there are also indices (Strength Indices) that demonstrate the health and quality of the seedlings that it gives. In this case, the germination ability, germination index, and power index are three important parameters indicating the quality of a seed lot (Hussain et al. 2015).

Seed germination ability is influenced by many internal and external factors. (Bewley & Black 1994). The germination percentage of a seed lot can be regarded as a composition formed by the effect of all these factors. In forestry, the yield strengths of stands that develop under different environmental and genetic conditions of a tree species can also be determined or compared according to the growth environment or site index, which reveals the effects of all these conditions within a standard age (Pretzsch 2009).

Similarly, it may be possible to compare the germination capability of current seed lots with a similar standard index, regardless of which different factors (genetic characteristics, date of harvest, storage period and conditions, etc.) have come to date. In this paper, the concept of “Germination Percentage Index (GPI)” is used in this direction and meaning. In this context, this index shows the germination ability class for each interval that includes the germination percentage obtained at the end of a germination test performed in standard conditions and time. Germination percentage intervals can be characterized as High, Medium, or Low or quantified as a germination percentage range.

Çalikoğlu (2013) revealed a significant ( $p < 0.05$ ) but not very strong ( $r = 0.56$ ,  $r^2 = 0.31$ ) correlation in the attempt to estimate the germination percentage by measuring the conductivity of seed leakage in Turkish red pine. Çalışkan and Makineci (2015) also found a low coefficient of determination ( $r^2 = 0.11$ ), although correlation between the carbon and nitrogen content of seeds and germination percentage was significant. The authors also determined that these relationships are stronger in cold stratified Turkish red pine seeds ( $R^2 > 0.60$ ). The result of both studies showed that the need for cold pre-treatment in Turkish red pine seeds limits the possibility of predicting the germination percentage more accurately.

This situation encourages estimating efforts of the germination ability of unfolded Turkish red pine seeds. Another point that intensifies these efforts is that in practice Turkish red pine seeds are widely used without cold wet pre-treatment.

In this study, germination test data of 82 different seed lots were used. Based on these data, germination curves were created for defined intervals of germination percentage and the most accurate and reliable one of these indices was chosen for its germination range. The

early estimation possibilities of index classes were also investigated for the Turkish red pine seed lots.

## 2. Materials and methods

In this study, 82 germination test results obtained at different times were analyzed. Each test was performed on a seed lot of different seed stand or orchard. The germination percentages on the 28th day had very wide variation. Although all germination tests were performed in different laboratories, they were all carried out as  $4 \times 50$  samples in petri dishes (110 mm) in the same type of germination cabinet under the same temperature ( $20 \pm 1^\circ\text{C}$ ) and humidity (65–70%). The seeds were not subjected to pre-treatment.

No germination occurred before the 7<sup>th</sup> day for the unfolded seeds. Therefore, our analysis covered the test period between the 7<sup>th</sup> and 28<sup>th</sup> day. 82 seed lots were divided into 4 different germination percentage intervals according to the germination percentages at the end of the test period.

There were no seed lots with a lower germination percentage than 20%. Therefore, the germination percentage intervals were divided by germination percentages as 20–39.9%, 40–59.9%, 60–79.9%, and 80–100%. The GPI were named after the middle values of these ranges as GPI\_30, GPI\_50, GPI\_70, and GPI\_90. The number of seed lots and data used for each GPI were 8 and 109, 20 and 318, 18 and 241 and 36 and 511, respectively. The progress of germination percentages as function of time was fitted to sigmoid regression curves and their improved versions (Brown & Mayer 1988; Torres & Frutos 1989; Torres & Frutos 1990; Shafii et al. 1991; Galan et al. 2015). In this study, 11 different regression models (Table 1) (selected from Sigmaplot Regression wizard equation) were tested to select the best fitting model for GPI's to represent each germination percentage intervals.

The best fit model for each GPI was selected with a total of seven different evaluation criteria shown in Table 2, adjusted  $R^2$  ( $R^2_{adj}$ ), average error ( $\bar{D}$ ), total error percentage (TEP), Mean Absolute Percentage Error (MAPE), Akaike Information Criterion (AIC), Schwarz Bayesian criterion (SBC) and Root Mean Squared Error (RMSE) (Yavuz 1999; Beal 2005; Weisberg 2005; Ercanlı & Kahraman 2015; Aydın 2016; Özçelik & Karaer 2016). Sigmaplot 10.0 was used in the statistical analysis and calculations described in this section (Sigmaplot 2006).

Among the criteria, the coefficient of determination should be maximized because it shows the proportion of variability that can be explained with the tested models. The other criteria should be minimized because they show the amounts of error related to the models. However, a model that gives good results according to one or more of these criteria may give unsuccessful results according to other criteria. Because of this, it is suggested to list the regression models according to each evalua-

**Table 1.** Regression models used in this study.

| Model name                   | Model formula                                                                 | Model number |
|------------------------------|-------------------------------------------------------------------------------|--------------|
| Sigmoid –with 3 parameters   | $y = \frac{a}{1 + e^{-\left(\frac{x-x_0}{b}\right)}}$                         | 1            |
| Sigmoid – with 4 parameters  | $y = y_0 + \frac{a}{1 + e^{-\left(\frac{x-x_0}{b}\right)}}$                   | 2            |
| Sigmoid – with 5 parameters  | $y = y_0 + \frac{a}{\left[1 + e^{-\left(\frac{x-x_0}{b}\right)}\right]^c}$    | 3            |
| Logistic – with 3 parameters | $y = \frac{a}{1 + \left(\frac{x}{x_0}\right)^b}$                              | 4            |
| Logistic – with 4 parameters | $y = y_0 + \frac{a}{1 + \left(\frac{x}{x_0}\right)^b}$                        | 5            |
| Weibull – with 4 parameters  | $y = a \left[ 1 - e^{-\left(\frac{x-x_0+b \ln 2c}{b}\right)^c} \right]$       | 6            |
| Weibull – with 5 parameters  | $y = y_0 + a \left[ 1 - e^{-\left(\frac{x-x_0+b \ln 2c}{b}\right)^c} \right]$ | 7            |
| Gompertz – with 3 parameters | $y = ae^{-e^{-\left(\frac{x-x_0}{b}\right)}}$                                 | 8            |
| Gompertz – with 4 parameters | $y = y_0 + ae^{-e^{-\left(\frac{x-x_0}{b}\right)}}$                           | 9            |
| Chapman – with 3 parameters  | $y = a(1 - e^{-bx})^c$                                                        | 10           |
| Chapman – with 4 parameters  | $y = y_0 + a(1 - e^{-bx})^c$                                                  | 11           |

e = Euler's coefficient (2.71828182),  $X_0$  – is the inflection point of the GPI curve, a: variable indicating the highest germination-lowest germination percentage,  $Y_0$  – the maximum value that germination percentage can take, b and c are other coefficients.

**Table 2.** Evaluation criteria for best model fit.

|                                                                                                   |     |
|---------------------------------------------------------------------------------------------------|-----|
| $R_{adj}^2 = 1 - \frac{\sum (GP_i^t - GP_i)^2 / (n - k)}{\sum (GP_i^t - GP_{avg}^t)^2 / (n - 1)}$ | [1] |
| $\bar{D} = \frac{1}{n} \sum (GP_i^t - GP_i)$                                                      | [2] |
| $TEP = \frac{\sum GP_i^t - GP_i}{\sum GP_i} 100$                                                  | [3] |
| $MAPE = \frac{\sum  GP_i^t  - \sum  GP_i }{\sum GP_i} 100$                                        | [4] |
| $AIC = n \cdot \ln \left( \frac{\sum (GP_i^t - GP_i)^2}{n} \right) + 2k$                          | [5] |
| $SBC = n \cdot \ln \left( \frac{\sum (GP_i^t - GP_i)^2}{n} \right) + k \cdot \ln(n)$              | [6] |
| $RMSE = \sqrt{\frac{(GP_i^t - GP_i)^2}{n - k}}$                                                   | [7] |

$GP_i$  – measured values of the dependent variable,  $GP_i^t$  – the values of the dependent variable estimated by the regression model,  $GP_{avg}^t$  – the average of the values estimated by the regression model of the dependent variable, n – number of data, k – number of parameters.

tion criterion and determine the most appropriate model based on the sum of the rank numbers (rank value) (Reed & Green 1984; Yavuz 1999; Aydın 2016). This approach was used in this study as well; rank numbers were given starting from the largest values of the coefficient of determination and the smallest values of the other success criteria, then the sum of the rank numbers was considered as the degree of success for the corresponding regression model. In this case, the model with the smallest total rank number was chosen as the best fitted GPI model. In case of the coefficients in the selected model are not significant, the next model with the lowest total rank was chosen (Yavuz 1999).

The presentation of the best fitting regression models was carried out with two different graphics. In the first graph, the observed values of the sample seed lots and the estimated values of the best fitting regression model are shown in the form of a scatter plot. The observed germination percentage values corresponding to the observation days were shown as a scatter plot, and the prediction of the best fitting model was overlaid on them.

In the second graph, the residual errors of the best fitting model were plotted. These errors should show a random distribution with no particular trend. (Ercanlı 2010).

### 3. Results

#### 3.1. Findings for GPI\_30

The coefficients and significance levels of the parameters for the tested models are shown in Table 3.

Thus, 11 regression models were scored in terms of seven different evaluation criteria, and their total scores were ranked from the lowest score to the highest. Values of the seven evaluation criteria and the rank of the models (written in *italic*) for each evaluation criterion are shown in Table 4. The models that take the first three places in terms of each evaluation criterion are specified using a bold font.

As a result of the scoring, model number 10 took first place. However, since the *c* coefficient in the model was not significant, it could not be chosen as the best fitted model (Table 3). Instead, the model number 8, in the 2nd rank was chosen as best fitting for GPI\_30. Coefficients of this model were found statistically significant. The regression curve of the selected model and the error amounts of the values estimated by the model are shown in Fig. 1.

When the graphs in Figure 1 are examined, it is seen that the model selected for GPI\_30 is predicts germination rate around 26.5% for the 28th day. The residual errors are randomly distributed and do not have an increasing or

**Table 3.** Coefficients of the models fitted to GPI\_30 data.

| Model No | a          | b          | c        | $x_0$      | $y_0$   |
|----------|------------|------------|----------|------------|---------|
| 1        | 25.7736*** | 2.0701***  |          | 14.0962*** |         |
| 2        | 29.1478*** | 2.6102***  |          | 13.6987*** | -2.6301 |
| 3        | 27.0796*** | 3.3983***  | 5070.10  | -16.0639   | -0.0060 |
| 4        | 26.9707*** | -6.0939*** |          | 14.1984*** |         |
| 5        | 28.1071*** | -5.6387*** |          | 14.1094*** | -0.7612 |
| 6        | 28.2070*** | 6.4196***  | 1.1985** | 14.2705*** |         |
| 7        | 27.5064*** | 6.3059***  | 1.1788** | 14.4223*** | 0.7313  |
| 8        | 27.0719*** | 3.3971***  |          | 12.9287*** |         |
| 9        | 27.0798*** | 3.3987***  |          | 12.9274*** | -0.0058 |
| 10       | 27.1266*** | 0.2899***  | 41.9170  |            |         |
| 11       | 27.0891*** | 0.2906***  | 42.3778  |            | 0.0274  |

a, b, c,  $x_0$ ,  $y_0$  – the coefficients of the models, F; F value obtained by regression analysis of the related model, significance levels are shown as asterisks for illustration. (\*, \*\* and \*\*\*) indicate significant differences at  $p \leq 0.05$ ,  $p \leq 0.01$  and  $p \leq 0.001$ , respectively. The above explanations are also valid for charts prepared for other germination classes.

**Table 4.** Rank of the models and values of the evaluation criteria for GPI\_30.

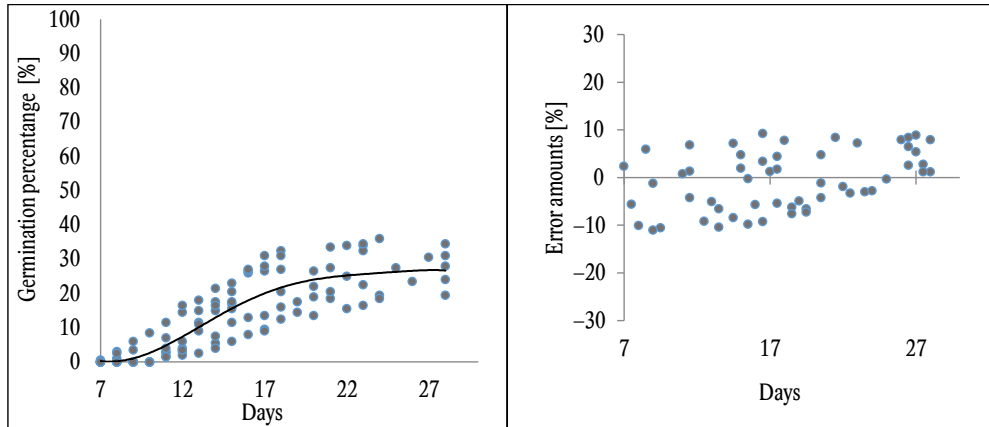
| Model number | $R^2_{adj}$         | $\overline{D}$                      | TEP                 | MAPE                | AIC                  | SBC                  | RMSE               | Sum of points | Rank |
|--------------|---------------------|-------------------------------------|---------------------|---------------------|----------------------|----------------------|--------------------|---------------|------|
| 1            | 0.7431<br><i>11</i> | -0.159<br><i>11</i>                 | 1.194<br><i>11</i>  | 34.899<br><i>11</i> | 383.851<br><i>7</i>  | 391.925<br><i>4</i>  | 5.739<br><i>11</i> | 66            | 11   |
| 2            | 0.7435<br><i>9</i>  | -1.73×10 <sup>-05</sup><br><i>1</i> | 0.00013<br><i>1</i> | 34.495<br><i>10</i> | 384.696<br><i>9</i>  | 395.462<br><i>9</i>  | 5.735<br><i>9</i>  | 48            | 8.5  |
| 3            | 0.7433<br><i>10</i> | -3.15×10 <sup>-05</sup><br><i>6</i> | 0.00024<br><i>6</i> | 33.746<br><i>6</i>  | 385.707<br><i>11</i> | 399.163<br><i>11</i> | 5.737<br><i>10</i> | 60            | 10   |
| 4            | 0.747<br><i>3</i>   | -0.082<br><i>9</i>                  | 0.618<br><i>9</i>   | 34.169<br><i>9</i>  | 382.082<br><i>3</i>  | 390.156<br><i>3</i>  | 5.692<br><i>3</i>  | 39            | 6    |
| 5            | 0.745<br><i>7</i>   | 2.72×10 <sup>-05</sup><br><i>5</i>  | -0.0002<br><i>5</i> | 33.984<br><i>8</i>  | 383.876<br><i>8</i>  | 394.641<br><i>8</i>  | 5.714<br><i>7</i>  | 48            | 8.5  |
| 6            | 0.746<br><i>4</i>   | 0.153<br><i>10</i>                  | -1.155<br><i>10</i> | 32.798<br><i>1</i>  | 383.631<br><i>4</i>  | 394.396<br><i>5</i>  | 5.707<br><i>4</i>  | 38            | 5    |
| 7            | 0.744<br><i>8</i>   | -2.54×10 <sup>-05</sup><br><i>4</i> | 0.00019<br><i>4</i> | 33.379<br><i>2</i>  | 385.241<br><i>10</i> | 398.697<br><i>10</i> | 5.725<br><i>8</i>  | 46            | 7    |
| 8            | 0.748<br><i>2</i>   | -0.00071<br><i>7</i>                | 0.005<br><i>7</i>   | 33.749<br><i>7</i>  | 381.706<br><i>2</i>  | 389.781<br><i>2</i>  | 5.682<br><i>2</i>  | 29            | 2    |
| 9            | 0.746<br><i>6</i>   | -2.06×10 <sup>-05</sup><br><i>2</i> | 0.00016<br><i>2</i> | 33.746<br><i>5</i>  | 383.706<br><i>6</i>  | 394.472<br><i>7</i>  | 5.709<br><i>6</i>  | 34            | 4    |
| 10           | 0.748<br><i>1</i>   | 0.003<br><i>8</i>                   | -0.026<br><i>8</i>  | 33.724<br><i>3</i>  | 381.682<br><i>1</i>  | 389.756<br><i>1</i>  | 5.682<br><i>1</i>  | 23            | 1    |
| 11           | 0.746<br><i>5</i>   | -2.48×10 <sup>-05</sup><br><i>3</i> | 0.00019<br><i>3</i> | 33.739<br><i>4</i>  | 383.681<br><i>5</i>  | 394.447<br><i>6</i>  | 5.709<br><i>5</i>  | 31            | 3    |

decreasing trend, so model errors do not have significant problems in providing statistical assumptions.

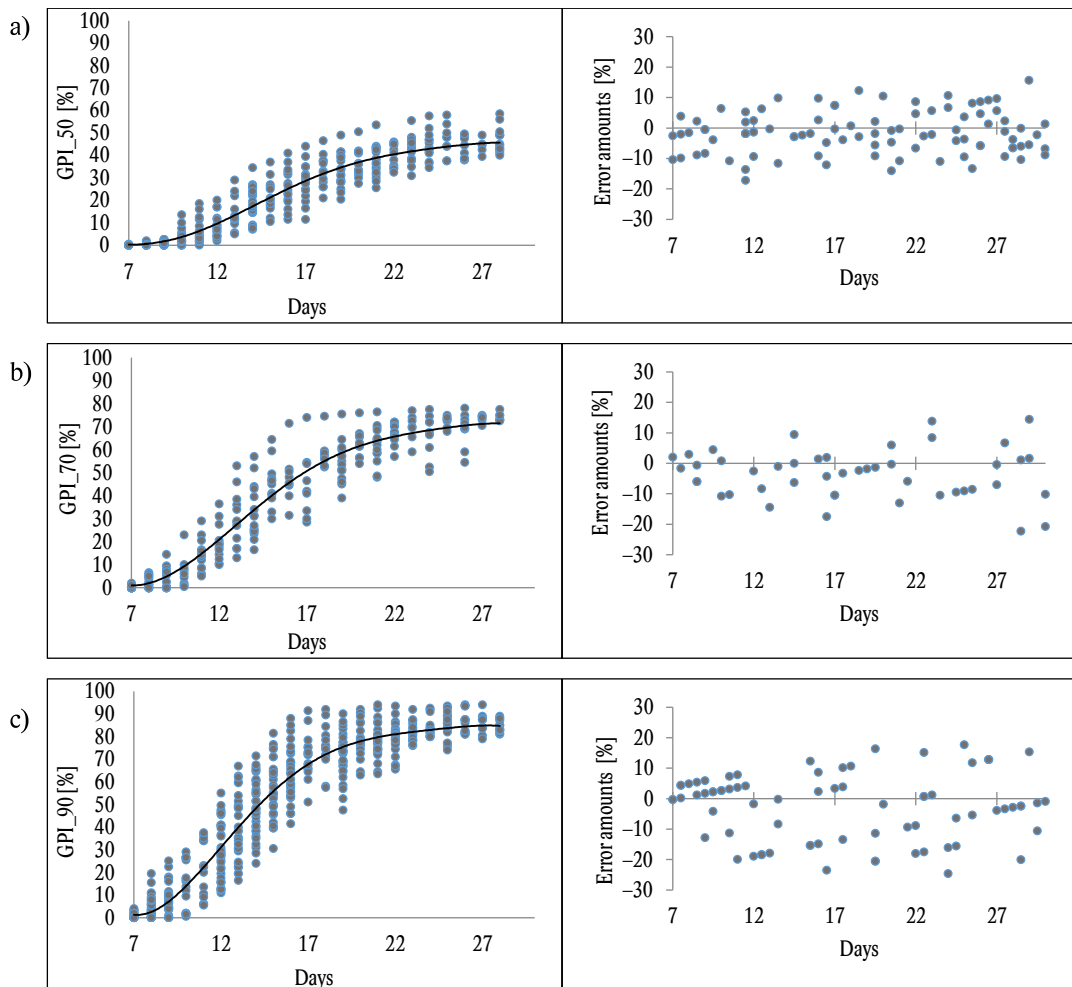
The regression curves of the selected models and the error amounts of the values estimated by the models for GPI\_50, GPI\_70, GPI\_90 are shown collectively in Fig. 2 (a, b and c).

### 3.2. General evaluation for all germination indices

Same approach was used to determine the best fitted regression models for Germination Percentage Indexes of GPI\_50, 70, and 90. Coefficients, total points, and



**Fig. 1.** Scatter and residual plots of chosen regression model for GPI\_30.



**Fig. 2.** Scatter and residual plots of chosen model for GPI\_50 (a), GPI\_70 (b) and GPI\_90 (c).

success ranks for all evaluated models are shown in the Appendix A Tables A1–A6, while ranks for the best fitting models for each class are shown in Table 5.

The 1<sup>st</sup> ranked models were disqualified due to insignificant coefficient for GPI\_30, GPI\_70 and GPI\_90. Therefore, the 2<sup>nd</sup>-best ranked models which have significant coefficients were chosen.

The  $R^2_{adj}$  values of the selected regression equations for germination indexes ranged from 0.748 to 0.916. In cases of the  $\bar{D}$  and TEP criteria, the selected models had a low success (7<sup>th</sup> and 8<sup>th</sup> ranks)  $\bar{D}$ , but they were more successful in terms of other evaluation criteria and thus

cies. Especially for fast growing species and good sites, optimal rotation periods are very short, while for poor sites and slow growing tree species these rotation periods are quite long. To obtain the highest wood yield from the forest areas, it is necessary to regenerate the forests at the specified ages, otherwise, the current annual increment of wood yield will start to decrease. In other words, after this period, every part of the forest that is not regenerated begins to reduce the mean annual increment for wood production.

Similarly to annual increment for wood production, we calculated the Current Germination Percentage

**Table 5.** The evaluation scores and rank of the best fitting models for all GPI's.

| Germination Indexes | Model No | $R^2_{adj}$ | $\bar{D}$     | TEP         | MAPE        | AIC           | SBC           | RMSE       | Sum of points | Rank |
|---------------------|----------|-------------|---------------|-------------|-------------|---------------|---------------|------------|---------------|------|
| GPI_30              | 8        | 0.748<br>2  | -0.00071<br>7 | 0.005<br>7  | 33.749<br>7 | 381.706<br>2  | 389.781<br>2  | 5.682<br>2 | 29            | 2    |
| GPI_50              | 10       | 0.887<br>1  | -0.085<br>8   | 0.363<br>8  | 18.811<br>3 | 1132.315<br>1 | 1143.601<br>1 | 5.904<br>1 | 23            | 1    |
| GPI_70              | 10       | 0.914<br>1  | -0.100<br>7   | 0.258<br>7  | 14.515<br>5 | 1003.439<br>1 | 1013.894<br>1 | 7.970<br>1 | 23            | 2    |
| GPI_90              | 8        | 0.916<br>3  | 0.044<br>7    | -0.086<br>7 | 13.419<br>3 | 2271.308<br>2 | 2284.018<br>2 | 9.203<br>3 | 27            | 2    |

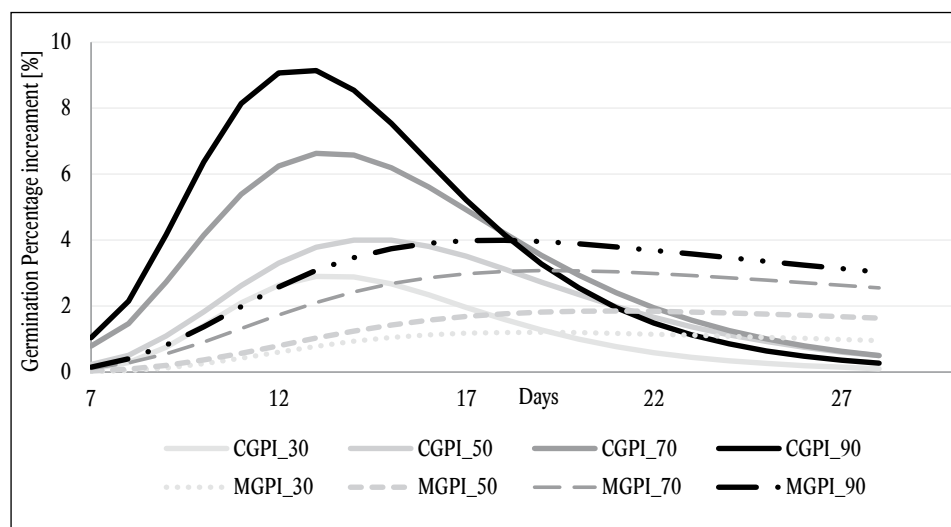
obtained better total rank numbers. Among the evaluation criteria, TEP values are recommended to be between -1% and +1% and MAPE values should be less than 10% (Kalipsız 1999).

In our study, for the selected models, the recommendations for the TEP values of the selected models were met. However, recommendation for MAPE was not fulfilled.

In forestry the “rotation period of the highest wood yield” is defined as the year in which mean annual increment curve intersects the current annual increment. In Turkey, this rotation period is still used in the forests which have the production function. The optimal rotation period for a particular site differs for each tree spe-

Increment (CGPI) and Mean Germination Percentage Increment (MGPI) for each germination interval were calculated and presented the days at which both curves cross (Fig. 3).

As seen on Figure 3, CGPI's reached their highest values on the 13<sup>th</sup>, 13<sup>th</sup>, 14<sup>th</sup>, and 13<sup>th</sup> days for the indexes 90, 70, 50, and 30, respectively, and took the values of 9.14, 6.63, 4, and 2.9 respectively. MGPI's reached the highest values on the 18<sup>th</sup>, 19<sup>th</sup>, 21<sup>st</sup> and 19<sup>th</sup> days for the same indices, respectively, and these values were listed as 3.99, 3.08, 1.85, and 1.21. According to the graph, the days when these two increments of each index intersected each other were the days 18, 20, 21, and 19 in the same order.



**Fig. 3.** Germination indices curves for unfolded seeds in Turkish red pine.

These intersections can be considered points of maximal gain for seed germination similarly to rotation periods mentioned on the example above. In other words, at these dates, there has been a significant germination percentage increase, while after them, the increase in germination percentages has slowed down. Therefore, to estimate germination percentages most accurately, waiting for 18–21 days would be appropriate.

#### 4. Discussion

In our study, a modeling application was carried out to explain the germination ability of Turkish red pine seeds. To reduce the variation in the germination percentages on the 28th day of different seed lots, they were classified into intervals based on their final germination percentages, similarly to the creation of Site classes, and the most appropriate model for each interval was selected.

Seed lots were classified from the worst germination percentage to the best and named after middle of this range as GPI\_30 (20–39.9%), GPI\_50 (40–59.9%), GPI\_70 (60–79.9%), and GPI\_90 (80–100%) respectively. Similar classifications were made for the germination ability of pine species in the USA and European spruce in Denmark (High 85–100%, Medium 65–85%, Low 40–65%, Weak <40%) (Bonner 1991; Sorensen et al. 1996). In our study, for these germination intervals, model numbers 8, 10, 10, and 8 (Table 1), respectively, were chosen as the best fitted models.  $R_{adj}^2$  values of the selected models were 0.748, 0.887, 0.914, and 0.916, respectively, and these values can be said to be quite high coefficient values.

It is suggested that the Total Error Percentage (TEP), which is one of the evaluation criteria used in our study, should take a value between –1% and +1% (Kalipsız 1999). When the selected models for germination rate are examined according to this criterion, it is seen that it has been met by the selected models. However, according to the same study, MAPE values were suggested to be less than 10% and this criterion was not met by any of the selected models. It is known that MAPE is quite difficult to stay within the recommended limits in forestry studies, especially in single-entry interactions (Ercanlı et al. 2008). Since the models used in our study were single entry (time dependent) models, this may be the reason why it was not possible to meet the recommended conditions for MAPE. In the literature, there are also models developed based on humidity, temperature, and time to reflect different ecological conditions (Dahal & Bradford, 1994; Meyer et al. 2000; Alvarado & Bradford, 2002). To ensure the condition of MAPE, the models that will explain the germination rate more accurately may have to include additional independent variables. However, within the scope of our study, germination rate developments were observed at a fixed humidity and temperature in laboratory conditions. Therefore, there was no need to add more different variables.

In our study, it is seen that the increase of germination percentage is maximal at the 13<sup>th</sup> and 14<sup>th</sup> day for Turkish red pine seed lots. After the germination percentage increment has reached its maximum, especially from the 18<sup>th</sup> and 21<sup>st</sup> day, a linear trend is evident in the curves, as has been seen in many studies in which the germination curve followed a horizontal or near-horizontal trend until the end of the germination test (Shafii et al. 1991; Ochudho & Modi 2006; Galan et al. 2015; Andersen et al. 2016). In other words, these days are the earliest days that we can predict the germination index of unfolded Turkish red pine seed parties with a good degree of accuracy. This will allow us to spend 7–10 days (i.e., 25–36%) less time compared to a standard germination test for Turkish red pine.

#### 5. Conclusions

With the effect of changing climatic conditions due to global warming, forest areas on a very large scale are under fire threat. Especially in the Mediterranean basin, after the wildfires in recent years, it is necessary to determine the germinability of large amounts of seed lots in a limited time. For this, it is very important to quickly determine the germination capabilities of the seed lots stored in the nurseries. In this study, a method is proposed to reveal the germination percentages of Turkish red pine seed lots in a reliable and faster way. It is thought that the approach introduced by this study can be applied to other tree species, especially in forest areas sensitive to fire.

#### Acknowledgments

*This manuscript was created from the database of a research project numbered 19.1712/2017 funded by the Southwest Anatolia Forestry Research Institute, which is an R&D unit of the General Directorate of Forestry. Comments of two anonymous reviewers helped significantly improve the manuscript. Authors thank to Servet Çalışkan and Bilal Çetin for sharing the germination test data. Authors also thank to Matúš Hrivnák for their valuable contribution.*

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## Appendix A

**Table A1.** Coefficients of the models fitted to GPI\_50 data.

| Model No | a          | b          | c           | $x_0$       | $y_0$      |
|----------|------------|------------|-------------|-------------|------------|
| 1        | 44.6794*** | 2.6231***  |             | 15.4974***  |            |
| 2        | 53.3447*** | 3.4948***  |             | 14.7581***  | −6.6210**  |
| 3        | 49.1962*** | 4.5507***  | 4195.229 NS | −24.0770 NS | −1.1017 NS |
| 4        | 47.7803*** | −5.1808*** |             | 15.7113 NS  |            |
| 5        | 51.4814*** | −4.5659*** |             | 15.5841***  | −2.1779 NS |
| 6        | 48.0390*** | 9.2120***  | 1.5563***   | 15.6669***  |            |
| 7        | 47.9327*** | 9.1502***  | 1.5433***   | 15.6917***  | 0.1490 NS  |
| 8        | 47.5530*** | 4.3203***  |             | 14.0495***  |            |
| 9        | 49.1964*** | 4.5512***  |             | 13.8830***  | −1.1008 NS |
| 10       | 47.8143*** | 0.2244***  | 22.9253***  |             |            |
| 11       | 49.1839*** | 0.2143***  | 19.2471***  |             | −0.8986 NS |

**Table A2.** The values and success rank of the models according to the evaluation criteria for GPI\_50.

| Model No | $R_{adj}^2$  | $\overline{D}$               | TEP                          | MAPE          | AIC            | SBC            | RMSE        | Sum of points | Rank |
|----------|--------------|------------------------------|------------------------------|---------------|----------------|----------------|-------------|---------------|------|
| 1        | 0.8866<br>9  | −0.319<br>11                 | 1.361<br>11                  | 19.199<br>9.5 | 1135.851<br>8  | 1147.137<br>4  | 5.937<br>9  | 61.5          | 11   |
| 2        | 0.8872<br>6  | −1.19E <sup>−05</sup><br>4   | 5.06×10 <sup>05</sup><br>4   | 18.835<br>5   | 1134.512<br>6  | 1149.561<br>7  | 5.915<br>6  | 38            | 5    |
| 3        | 0.885<br>11  | −8.48×10 <sup>−06</sup><br>1 | 3.62×10 <sup>−05</sup><br>1  | 19.254<br>11  | 1140.706<br>11 | 1159.516<br>11 | 5.964<br>11 | 57            | 9    |
| 4        | 0.887<br>5   | −0.191<br>10                 | 0.813<br>10                  | 18.969<br>8   | 1133.238<br>3  | 1144.524<br>3  | 5.913<br>5  | 44            | 6    |
| 5        | 0.8873<br>5  | −1.07×10 <sup>−05</sup><br>3 | 4.59×10 <sup>−05</sup><br>3  | 18.628<br>1   | 1133.661<br>5  | 1148.709<br>6  | 5.908<br>4  | 26            | 2    |
| 6        | 0.8875<br>3  | 0.018<br>7                   | −0.078<br>7                  | 18.684<br>2   | 1133.636<br>4  | 1148.684<br>5  | 5.907<br>3  | 31            | 4    |
| 7        | 0.8868<br>8  | 1.027×10 <sup>−05</sup><br>2 | −4.38×10 <sup>−05</sup><br>2 | 18.888<br>7   | 1137.401<br>9  | 1156.211<br>10 | 5.933<br>8  | 46            | 8    |
| 8        | 0.8877<br>2  | −0.094<br>9                  | 0.401<br>9                   | 18.835<br>4   | 1132.512<br>2  | 1143.798<br>2  | 5.906<br>2  | 30            | 3    |
| 9        | 0.8879<br>7  | −1.43×10 <sup>−05</sup><br>5 | 6.1×10 <sup>−05</sup><br>5   | 18.852<br>6   | 1134.986<br>7  | 1150.034<br>8  | 5.920<br>7  | 45            | 7    |
| 10       | 0.8871<br>1  | −0.085<br>8                  | 0.363<br>8                   | 18.811<br>3   | 1132.315<br>1  | 1143.601<br>1  | 5.904<br>1  | 23            | 1    |
| 11       | 0.8864<br>10 | 1.82×10 <sup>−05</sup><br>6  | −7.75×10 <sup>−05</sup><br>6 | 19.199<br>9.5 | 1137.851<br>10 | 1152.899<br>9  | 5.947<br>10 | 60.5          | 10   |

**Table A3.** Coefficients of the models fitted to GPI\_70 data.

| Model No | a          | b          | c          | $x_0$      | $y_0$      |
|----------|------------|------------|------------|------------|------------|
| 1        | 69.1672*** | 2.4655***  |            | 14.2981*** |            |
| 2        | 86.0722*** | 3.4892***  |            | 13.3571*** | −13.4287** |
| 3        | 75.6448*** | 4.2412***  | 3848.3945  | −22.2534   | −1.8277    |
| 4        | 73.4983*** | −5.1230*** |            | 14.4741*** |            |
| 5        | 79.6761*** | −4.4559*** |            | 14.3146*** | 3.8358     |
| 6        | 77.3207*** | 7.6109***  | 1.1668***  | 14.6280*** |            |
| 7        | 75.2855*** | 7.5143***  | 1.1540***  | 14.8212*** | 2.1007     |
| 8        | 73.0359*** | 4.0120***  |            | 12.9341*** |            |
| 9        | 75.6447*** | 4.2417***  |            | 12.7589*** | −1.8260    |
| 10       | 73.3982*** | 0.2415***  | 22.2549*** |            |            |
| 11       | 75.4526*** | 0.2305***  | 18.6213*** |            | −1.4056    |

**Table A4.** The values and success rank of the models according to the evaluation criteria for GPI\_70.

| Model No | $R_{adj}^2$  | $\overline{D}$                | TEP                           | MAPE         | AIC            | SBC            | RMSE        | Sum of points | Rank |
|----------|--------------|-------------------------------|-------------------------------|--------------|----------------|----------------|-------------|---------------|------|
| 1        | 0.906<br>11  | -0.472<br>11                  | 1.213<br>11                   | 15.822<br>11 | 1022.907<br>11 | 1033.362<br>11 | 8.298<br>11 | 77            | 11   |
| 2        | 0.9123<br>10 | $1.96 \times 10^{-05}$<br>2   | $-5.032 \times 10^{-05}$<br>2 | 14.846<br>10 | 1009.088<br>10 | 1023.027<br>8  | 8.047<br>10 | 52            | 8    |
| 3        | 0.9134<br>7  | $-8.54 \times 10^{-05}$<br>6  | 0.00022<br>6                  | 14.459<br>4  | 1007.199<br>8  | 1024.623<br>10 | 7.999<br>7  | 48            | 7    |
| 4        | 0.9125<br>9  | -0.270<br>9                   | 0.694<br>9                    | 14.822<br>9  | 1006.991<br>7  | 1017.446<br>3  | 8.029<br>9  | 55            | 10   |
| 5        | 0.9135<br>6  | $2.656 \times 10^{-05}$<br>4  | $-6.82 \times 10^{-05}$<br>4  | 14.541<br>6  | 1005.460<br>5  | 1019.399<br>6  | 7.987<br>6  | 37            | 5    |
| 6        | 0.9127<br>8  | 0.427<br>10                   | -1.095<br>10                  | 14.353<br>1  | 1007.772<br>9  | 1021.711<br>7  | 8.025<br>8  | 53            | 9    |
| 7        | 0.9136<br>5  | $-2.494 \times 10^{-05}$<br>3 | $6.4 \times 10^{-05}$<br>3    | 14.596<br>8  | 1006.337<br>6  | 1023.761<br>9  | 7.985<br>5  | 39            | 6    |
| 8        | 0.9145<br>2  | -0.115<br>8                   | 0.295<br>8                    | 14.552<br>7  | 1003.936<br>2  | 1014.391<br>2  | 7.978<br>2  | 31            | 4    |
| 9        | 0.9138<br>4  | $-1.856 \times 10^{-05}$<br>1 | $4.76 \times 10^{-05}$<br>1   | 14.459<br>3  | 1005.198<br>4  | 1019.137<br>5  | 7.982<br>4  | 22            | 1    |
| 10       | 0.9147<br>1  | -0.100<br>7                   | 0.258<br>7                    | 14.515<br>5  | 1003.439<br>1  | 1013.894<br>1  | 7.970<br>1  | 23            | 2    |
| 11       | 0.9143<br>3  | $2.757 \times 10^{-05}$<br>5  | $-7.075 \times 10^{-05}$<br>5 | 14.432<br>2  | 1004.928<br>3  | 1018.867<br>4  | 7.978<br>3  | 25            | 3    |

**Table A5.** Coefficients of the models fitted to GPI\_90 data.

| Model No | a          | b          | c          | $x_0$      | $y_0$      |
|----------|------------|------------|------------|------------|------------|
| 1        | 82.2787*** | 2.0972***  |            | 13.3092*** |            |
| 2        | 92.8240*** | 2.6040***  |            | 12.7997*** | -8.8791*** |
| 3        | 85.2105*** | 3.2391***  | 11.5200    | 4.3058     | 0.0515     |
| 4        | 85.7043*** | -5.7321*** |            | 13.3633*** |            |
| 5        | 87.7468*** | -5.4743*** |            | 13.2953*** | -1.4484    |
| 6        | 84.0233*** | 8.1164***  | 1.9506***  | 13.2537*** |            |
| 7        | 82.7947*** | 7.6389***  | 1.8430***  | 13.3359*** | 1.3677     |
| 8        | 85.7344*** | 3.4124***  |            | 12.0663*** |            |
| 9        | 84.7843*** | 3.3471***  |            | 12.1266*** | 0.7300     |
| 10       | 85.8957*** | 0.2878***  | 31.7013*** |            |            |
| 11       | 84.6505*** | 0.2956***  | 35.6776*** |            | 0.9467     |

**Table A6.** The values and success rank of the models according to the evaluation criteria for GPI\_90.

| Model No | $R_{adj}^2$  | $\overline{D}$                | TEP                           | MAPE         | AIC            | SBC            | RMSE        | Sum of points | Rank |
|----------|--------------|-------------------------------|-------------------------------|--------------|----------------|----------------|-------------|---------------|------|
| 1        | 0.913<br>11  | -0.316<br>11                  | 0.626<br>11                   | 13.986<br>11 | 2287.314<br>11 | 2300.023<br>10 | 9.348<br>11 | 76            | 11   |
| 2        | 0.9154<br>8  | $2.33 \times 10^{-05}$<br>3   | $-4.619 \times 10^{-05}$<br>3 | 13.423<br>4  | 2276.113<br>8  | 2293.058<br>7  | 9.237<br>8  | 41            | 7    |
| 3        | 0.9155<br>7  | $1.355 \times 10^{-05}$<br>1  | $-2.685 \times 10^{-05}$<br>1 | 13.447<br>6  | 2275.028<br>7  | 2296.210<br>9  | 9.218<br>7  | 38            | 6    |
| 4        | 0.9169<br>1  | -0.095<br>10                  | 0.189<br>10                   | 13.505<br>10 | 2270.440<br>1  | 2283.150<br>1  | 9.195<br>1  | 34            | 3-4  |
| 5        | 0.9167<br>2  | $2.514 \times 10^{-05}$<br>4  | $-4.983 \times 10^{-05}$<br>4 | 13.407<br>1  | 2271.633<br>4  | 2288.578<br>4  | 9.197<br>2  | 21            | 1    |
| 6        | 0.9152<br>9  | 0.059<br>8                    | -0.117<br>8                   | 13.436<br>5  | 2277.795<br>9  | 2294.740<br>8  | 9.252<br>9  | 56            | 10   |
| 7        | 0.9151<br>10 | $-2.156 \times 10^{-05}$<br>2 | $4.275 \times 10^{-05}$<br>2  | 13.500<br>9  | 2279.173<br>10 | 2300.355<br>11 | 9.256<br>10 | 54            | 9    |
| 8        | 0.9164<br>3  | 0.044<br>7                    | -0.086<br>7                   | 13.419<br>3  | 2271.308<br>2  | 2284.018<br>2  | 9.203<br>3  | 27            | 2    |
| 9        | 0.9163<br>5  | $-2.692 \times 10^{-05}$<br>5 | $5.336 \times 10^{-05}$<br>5  | 13.460<br>7  | 2273.110<br>5  | 2290.055<br>5  | 9.210<br>5  | 37            | 5    |
| 10       | 0.9164<br>4  | 0.062<br>9                    | -0.122<br>9                   | 13.412<br>2  | 2271.544<br>3  | 2284.253<br>3  | 9.205<br>4  | 34            | 3-4  |
| 11       | 0.9161<br>6  | $-3.96 \times 10^{-05}$<br>6  | $7.85 \times 10^{-05}$<br>6   | 13.465<br>8  | 2273.177<br>6  | 2290.123<br>6  | 9.211<br>6  | 44            | 8    |