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Characterization of soil erosion and its implication to forest management

Nuray Misir*, Mehmet Misir, Uzay Karahalil and Hakki Yavuz

Faculty of Forestry, Karadeniz Technical University, Trabzon-610 80, Turkey

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Abstract: *Forests have traditionally been managed to maximize timber production or economic profit, completely neglecting other forest values. Nowadays, however, forests are being managed for multiple uses. The basic requirement of multiple use forestry is to identify and quantify forest values and to determine management objectives. The priorities of management objectives, however, must be decided. In this study, a model predicting the soil loss for multi objective forest management was developed. The model was based on data from remeasurement of permanent sample plots. The data were gathered from 132 sample plots. Approximately 80% of the observations were used for model development and 20% for validation. The model was designed for even aged and uneven aged forests, as well as for forests with mixed and pure species composition. The explicatory variables in the model were mean diameter and number of trees. All parameter estimates were found highly significant (p<0.001) in predicting soil loss. The model fit and validation tests were fairly good. The soil loss model presented in this paper was considered to have an appropriate level of reliability. It can be used in the overall multi-objective forest management planning, but, it should be limited to the conditions for which the data were gathered.*

Key words: *Forest values, Soil loss, Regression analysis, Multiobjective planning*

Introduction

Nowadays, multiobjective planning is necessary in forestry because of increased and varied demand for forest products and services. Management objective such as production of quality potable water, aesthetic, recreation and community health in forest especially adjacent to big cities are of great importance. Forests have managed to produce wood products at various diameters and quality classes as the society demanded overtime. Afterwards, the importance of these objectives has gradually diminished and overwhelmed by other management objectives such as conservation of water resources, prevention of soil erosion, creation of landscape aesthetic, camouflaging military facilities and allocation of land for recreation (Asan, 1992).

Erosion, the detachment of soil particles, occurs by the action of water, wind or glacial ice. Such background soil erosion has been occurring for some 450 million years, since the first land plants formed the first soil. Only erosion caused by water will be considered here. Water related erosion occurs when raindrops, spring runoff or floodwaters wear away and transport soil particles.

Soil erosion by water and wind affects both agriculture and the natural environment, and is one of the most important of today's environmental problems. It isn't easy to find comprehensive information about erosion, as the subject is multidisciplinary involving geomorphologists, agricultural engineers, soil scientists, hydrologists and others and is of interest to policy-makers, farmers, environmentalists and many other groups.

Soil loss estimation: Given the importance of soil erosion, characterization of soil loss is equally important. In erosion control planning, soil loss estimates for a particular site are determined using a prediction model and compared with a T-value for that site (Schmit *et al.*, 1982). The Universal Soil Loss Equation (USLE) is an example of a model used extensively to predict erosion from croplands and rangelands (Wischmeier and Smith, 1978).

Until recently, prediction of soil loss rates on National Forest lands involved using the USLE(Wischmeier and Smith, 1978; Dismeyer and Foster, 1981). Soil losses were evaluated in the context of potential soil losses, natural soil losses, current soil losses and tolerable soil losses. Potential losses were those that would occur after complete removal of the vegetation and litter. Natural losses were associated with the potential natural vegetation community. Current losses were those occurring with current management. Tolerable loss was assumed to be the rate that can occur while sustaining inherent site productivity (Megahan, 1992).

Soil loss rates have been generally estimated in agricultural areas up to now. Various USLE and GIS combinations have been used to estimate soil loss in forest land. But in these studies, soil loss was determined quantitatively.

Forest values including soil protection function need to be determined quantitatively in multiobjective forest management planning. Relationships between soil loss and stand structure on a particular site must be determined before incorporation of soil

Corresponding author: E-Mail: nuray@ktu.edu.tr, Tel.: + 90 462 377 34 98, Fax: + 90 462 377 28 75

protection values into multiobjective forest management plans. So far, very little information has been found about the characterization of soil loss with respect to stand structure on various sites.

The aim of the present study was to develop soil loss model applicable for multi objective forest management planning. The model should include regular soil loss estimation (not floods). It should be applicable to both even aged forest as well as forest with mixed and pure dominated spruce species. Since the soil loss model also should be applicable to large scale forestry scenario analysis in practical management planning, the modeling was restricted to include only explicatory variables that directly and indirectly are available from practical forest inventory data (including soil data).

Materials and Methods

This study was conducted in Blacksea region in Trabzon, Turkey. Altitude of this area ranges from 400 m to 2300 m. High productive forest study area is 3105.25 ha of which 171 ha is unproductive high forest, 8 ha is coppice forest and 506.25 ha is unproductive coppice.

Data were collected from 132 permanent sample plots, distributed to study area with 300 m x 300 m intervals. Sample plots were taken from pure and mixed spruce stands in Karadeniz Technical University, Faculty of Forestry. Plots were taken from thinned stands and located on five different sites. Areas of rectangular plots varied from 400 m^2 to 800 m^2. For each plots, all trees were measured for diameter at breast height (dbh), diameter at stump level, total height, age and crown diameter in 1997. For each plots slope, altitude and aspect were also measured.

In sample plots in forested area, dbh and heights of all commercial trees over 8 cm dbh were measured. Number of trees per hectares, basal area, stand volume, quadratic mean diameter, and mean height were calculated for each sample plots. These values were calculated to be 0 (zero) for 40 sample plots taken from bare land.

Stand characteristics were computed from individual tree measurements in the plots. Volume per hectare (*V*), basal area (*BA*), basal area mean diameter ($\overline{d}_q$), mean height weighted by basal area ($\overline{h}_q$), stand density indexes (Curtis *et al.*, 1981; Reineke, 1933; Drew and Flewelling, 1977), Tree Area Ratio Density Index (Chisman and Schumacher, 1940) and number of trees per hectare (*N*), some soil and physiographic properties and observed soil loss amounts are given in Table 1.

Table - 1: Statistical evaluation of stands in the study area

Stand parameters/ Characteristics	Min	Max	Mean	S.D.*
Soil loss (ton/ha/year) (*A*)	0.07	5.909	0.865	1.070
Mean diameter ($d_{\overline{q}}$ (cm))	0.00	43.70	27.01	6.824
Mean height ($\overline{h}_q$ (m))	0.00	25.62	18.63	4.797
Age (*t* (year))	3	118	69	10.310
Volume (*V* (m^3/ha))	0.00	704.05	371.05	131.929
Basal area (*BA* (m^2/ha))	0.00	58.61	35.89	11.373
Number of trees (*N*)	0	1100	607	221.674
Relative density (Curtis *et al.*,1981)	2.84	10.16	7.07	1.643
Relative stand density (Drew and Flewelling, 1977)	0.26	1.01	0.68	0.162
Relative stand density (Reineke, 1933)	0.00	0.70	0.17	0.055
Tree area ratio density Index	0.00	93.58	46.284	19.377
Sand %	51.2	89.2	69.45	9.691
Silt %	6	36	20.10	7.586
Clay %	2.4	23.8	10.45	5.003
Crown closure	0.10	0.90	0.65	0.180
Organic matter	6.06	18.80	10.95	3.199
Permeability	2	4	2.88	0.773
Altitude	400	2300	980	110.245
Slope (°)	10	70	38.19	14.003

* Standart deviation

In this study, the soil loss expressed as ton ha^{-1} $year^{-1}$ for the study area was determined using the Universal Soil Loss Equation (USLE).

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

Soil samples were collected from 132 plots (92 of which were located in forested area and 40 in bare land) and analyzed in a laboratory for soil properties including; silt %, sand %, clay %, organic matter %, and classes for structure and permeability (Altun, 1995).

The soil erodibility factor *K* values of soil samples were calculated using the following equation (Wischmeier and Smith, 1978):

$$K = \frac{2.1 \times M^{1.14} \times 10^{-4} \times (12 - OM) + 3.25 \times (S - 2) + 2.5 \times (P - 3)}{100} \quad (2)$$

where *OM* is soil organic matter content, *M* is (%silt + %very fine sand)x(100-%clay), *S* is soil structure code and *P* is permeability class. If soil organic matter content was greater or equal to 4%, *OM* was considered constant at 4%. The rainfall erosivity obtained from average annual rainfall erosivity map (There are no long term meteorological data or another study for the country to calculate the R factor. So, erosivity maps of 1976 have been used) for Turkey is 74.3 (Dogan and Gucer, 1976).

The slope length factor *L*, accounts for increases in runoff volume as downslope runoff lengths increase. The slope stepness factor *S* accounts for increased runoff velocity as stepness increases. These factors were obtained from digitized topographic maps of study area.

For direct application of the USLE a combined slope length and slope stepness (*LS*) factor was evaluated for each sample plots as (Arnoldus, 1977):

$$LS = l^{0.5} \times (0.0138 + 0.00965 \times S + 0.00138 \times S^2) \quad (3)$$

where *l* is runoff length (meter), *S* is slope (percent)

Crop and management factor (*C*) is the soil loss from an area with specified cover. Assigning a proper value to cover management factor (*C*) in the USLE is a problem, however. Tree categories of woodland are considered separately: 1) undisturbed forest land, 2) woodland that is grazed, burned, or selectively harvested and 3) forest lands which have had site preparation treatments for reestablishment after harvest. Factor *C* for undisturbed forest land may be obtained from Table 2 (Wischmeier and Smith, 1978).

In this study, the values of C factor were considered as 0.001, 0.003, 0.006, and 0.009 for 71-100%, 41-70%, 11-40% and 0-10% crown closure, respectively.

Table - 2: Factor *C* for undisturbed forest land

Percent of area covered by canopy of trees	Factor *C*
100 – 75	0.0001 – 0.001
70 – 45	0.002 – 0.004
40 – 20	0.003 – 0.009

The conservation practice factor *P*, is determined by the extend of conservation practices such as strip, cropping, contouring, and terracing practices, which tend to decrease the erosive capabilities of rainfall and runoff. Values of *P* range from zero to one. Since such methods are not used in study area, the value of *P* was assumed to be 1. The conservation practice factor (P); describes the reduction in soil erosion from conservation techniques. (P) also can be described as incorporating the erosion control management practices. When there isn't any protective measures P factor can be determined as 1 (Schwab *et al.*, 1993). In the study area, no erosion control practice is specifically adopted so in this analysis (P) factor equal to 1.0 was used.

Data analysis: The candidate variables for the soil loss models were numerous and diverse. Hartanto *et al.* (2003), classified such variables in four groups: Soil characteristics, physiographic properties, climatic properties and stand characteristics. The candidate variables of present study were divided in to two groups: (i) measures of physiographic structure and (ii) measures of the stand level of structure and density. Altitude, exposition, aspect, slope and exposure length were used as measures of physiographic structure. Mean height, mean diameter, crown closure and stand density indexes were used as measures of the stand level of structure in the present study.

Several possibilities exist to describe stand density. Hamilton (1986); Ojansuu *et al.* (1991); Vanclay (1991) and Tuhus (1997), all used *BA*, and Burgman *et al.* (1994) have used *N*, to provid examples of models with stand density parameters as explicatory variables in modeling. Since *N* and *BA* were directly determined, and did not rely on functional relationships, as opposed to volume (*V*), not only these two variables were selected for testing in the present study, but also the others (Curtis *et al.*, 1981; Reineke, 1933; Drew and Fleweling, 1977; Chisman and Schumacher, 1940) were tested.

The soil loss model should be applicable to different stand structures. Therefore, all variables were tested. Based on the discussion above, the following soil loss model was hypothesized:

$$\hat{A} = \beta_0 + \beta_1 S_1 + \beta_2 S_2 + \beta_3 S_3 \quad (4)$$

where S_1 is the physiographic structure (altitude, exposition, aspect, slope and exposure length), S_2 is the stand structure ($\bar{d}_q$, $\bar{h}_q$ and crown closure) and S_3 is the stand density (Curtis *et al.* (1981); Drew and Flewelling (1977); Reineke (1933) and Chisman and Schumacher (1940).

Relationship between magnitude of soil loss obtained from sample plots and stand characteristics have been used to model soil protection value, using stepwise procedure in Regression Analysis Method the significance of parameter estimates was tested by means of *t=b/ASE*, where b is the parameter estimate and *ASE* is the asymptotic standard error. The parameters of the model for the data were determined using Stepwise Regression Analysis in SAS software (SAS Institute Inc., 1999). Only were variables which were significant (p<0.001) included in the equation. The assumption of homoscedasticity was tested using the Durbin Whatson test.

A soil loss model was constructed based on some site and stand characteristics as a predictor and possible insignificant predictor were excluded. The predicted variable in the soil loss model was annual soil loss amount, which resulted in a linear relationship between the dependent and independent variables. The predictors of a soil loss model were chosen from stand level characteristics. All of them had to be significant at the p<0.05 level without any systematic errors in residuals.

Model validation: The soil loss model was evaluated quantitatively by examining the magnitude and distribution of residuals to detect any obvious patterns and systematic discrepancies, and by testing for bias and precision to determine the accuracy at model predictions (Vanclay, 1994; Soares *et al.*, 1995; Gadow and Hui, 1998; Mabvurira and Miina, 2002). Reltive bias and root mean square error were calculated as follows:

$$Bias = \frac{\sum_{i=1}^{n}\left(A_i - \hat{A}_i\right)}{n} \qquad (5)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(A_i - \hat{A}_i\right)^2}{n-p}} \qquad (6)$$

where n is the number of observations, p is the number of parameters in the model, A_i and $\hat{A}_i$ are observed and predicted values, respectively

In addition, the models were further validated by an independent control data set. The validation of a model should involve independent data. The data were partitioned in two independent groups, one for model development of soil loss estimation and the other set for validation. The data set used for model development of soil loss estimation comprised approximately 80% of the plots (102), while the remaining 20% of the plots (30) were used for validation. Although the number of sample plots determined for development of soil loss estimation was made relatively large in order to provide sufficient data for model development phase, the number of sample plots in the test data still should be large enough for validation and appropriate statistical test. The deviations between predicted and observed values were tested by Student's Paired *t* test.

Results and Discussion

Parameter estimates of the soil loss model are logical and significant at the 0.001 level (Table 3). The adjusted R^2 value was 0.62. The number of trees and quadratic mean diameter are the strongest predictors of the soil loss model, explaining 62% of the relationships while quadratic mean diameter and number of trees were able to explain only 42% and 24%of the relationship, respectively. The mean soil loss for the total material was 0.865 ton/ha/year. All descriptive factors for soil loss were evaluated through a linear regression analyses. The results of the regression analyses are therefore shown in Table 3.

Table - 3: Estimates of the parameters and variance components of the soil loss model (Eq.4)

Variable	Estimate	Standard error	Beta	*t*-value	*p*-value
Intercept	4.728	0.361		13.109	0.000
	-0.0021	0.000	-0.433	-6.022	0.000
N	-0.096	0.011	-0.612	-8.509	0.000
Adjusted R^2	0.62				

Multiple correlation analysis showed that $\overline{d}_q$ and N are the true key factors which explain soil loss estimation. In a multiple regression analyses between soil loss and the number of trees, mean diameter, tree-area ratio, basal area, volume, different stand density indexes performed using a stepwise procedure (Haan, 1986), the quadratic mean diameter and the number of trees were the only parameters chosen as statistically significant. The best regression equation is:

$$\hat{A} = 4.728 - 0.096 \times \overline{d}_q - 0.0021 \times N \qquad (7)$$

In the analyses, the number of trees and quadratic mean diameter were the variables with most significant effect, in spite of the rather small coefficients of -0.096 and –0.0021. Other stand density indicators did not show any significant effect.

The assumption of homoscedasticity was tested using the Durbin Whatson test. The test indicated homogenous variances over the full range of predicted values at p<0.05 level.

Soil loss equation has the flexibility to assume various shapes with different parameter values and produce satisfactory relationships under most circumstances. The relationship is biologically reasonable in such that unrealistic soil loss predictions do not occur beyond the range of the empirical observations.

The bias of the fixed part of the soil loss model was examined by plotting the residuals as a function of the predicted values and predictors of the model (Fig. 1). The residuals of the fixed model part are correlated within each site and stand hampering the direct use of Fig. 1 for model evaluation (part of the residual variation is explained by the random site and stand factors). However, it is evident that there is no noticeable trend between the residuals of the soil loss model and independent variables (Fig. 1). On the other hand, the residuals of the soil loss model do not have a heterogeneous variance as a function of predicted soil loss.

Fig. 2 and 3 show predicted and observed soil loss [model data set (a), control data set (b)] plotted over $\overline{d}_q$ and N, respectively. The predicted mean values of the figures were calculated using actual values of the explicatory variables for each observation. In general, the soil loss fitted well over the explicatory variables in the model data set. For the test data set, when all variables were not included in the model, the deviations between predicted and observed soil loss were somewhat larger.

Model validation: The refitted model including only quadratic mean diameter and number of trees showed small RMSE and approximately homogenous variances over the full range of

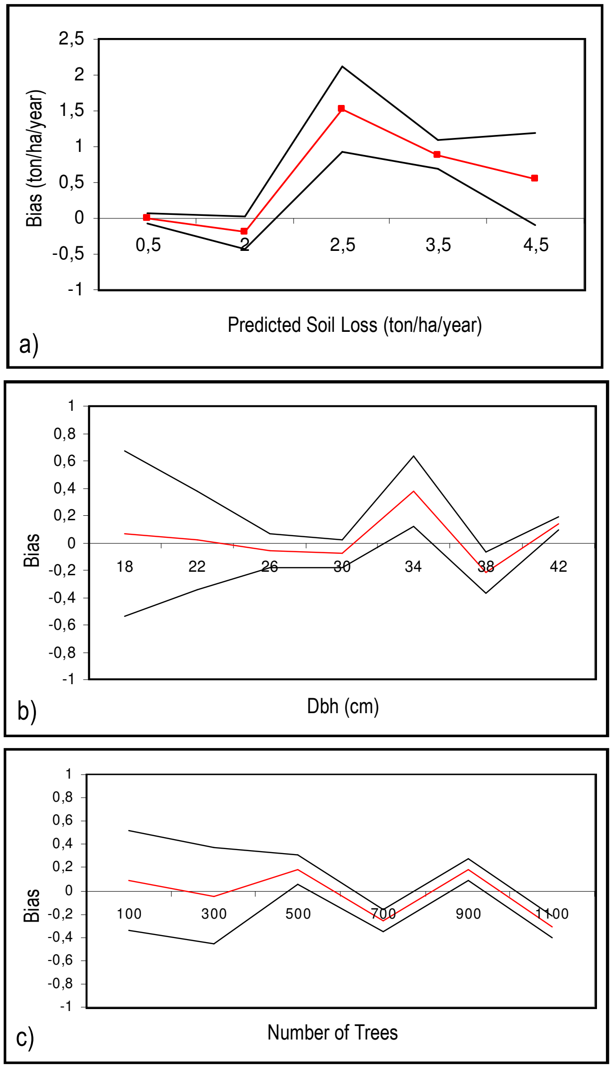

Fig. 1: Mean bias of the soil loss model as a function of predicted soil loss (a), mean diameter (b) and number of trees (c) bold lines indicate the standard error

predicted variables (Table 4, Fig. 1), indicating equal variances and reasonable model specification. The residual plots also indicated that soil loss was well predicted across $\overline{d}_q$ and *N*. The residual plots against the predicted soil loss clearly show that the function appropriately fits the data.

The soil loss model was tested using Student's Paired *t* test by an independent control data set (30 sample plots). The

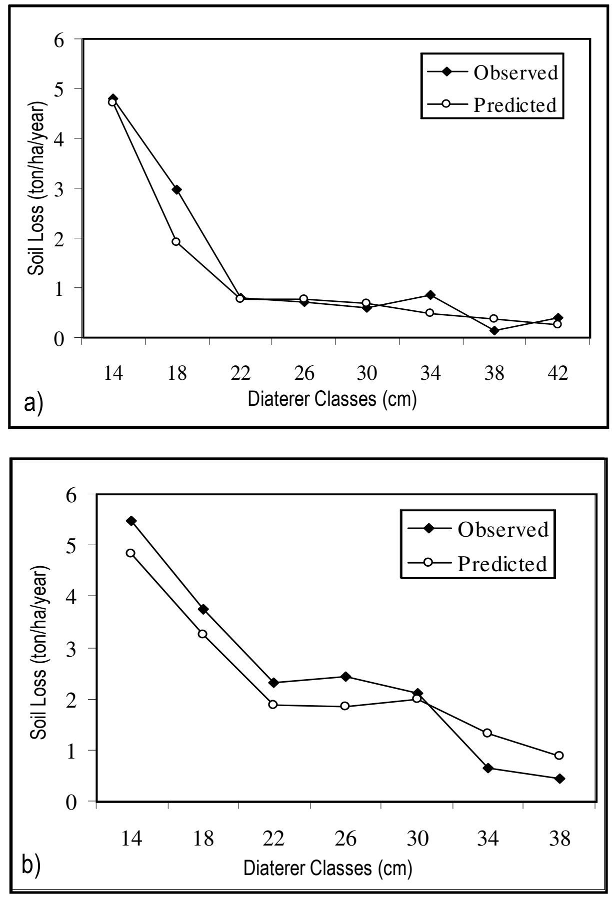

Fig. 2: Predicted and observed soil loss (ton/ha/year) over diameter classes for both model data set (a) and control data set (b)

model presented in this study was considered to have an appropriate level ($p<0.05$) of reliability (Table 5).

While very few soil loss models were developed so far (Misir and Misir, 2004; Karahalil, 2003), none of them were statistically examined for the applicability of the model to estimate the soil loss in real scenario.

Table - 4: Bias and RMSE values of the soil loss models

Criteria	The soil loss model (mm ton/ha/year)	Soil loss model including all variables
Bias	0.00	0.00 ton/ha/year
RMSE	0.59	0.66 ton/ha/year

Our results indicated that $\overline{d}_q$ and *N* were significant variables in predicting soil loss. The transformations seemed to behave bad over mean diameter, *i.e.* from a relatively fast decline of soil loss for the smallest diameters to a more moderate decline for larger diameters (Fig. 3a).

The model gave decreased soil loss with increased diameter and was accepted because of the expected logical behavior. As expected, the deviations between predicted and observed soil loss over diameter classes were generally larger for the control data compared to the model data. Some of the largest deviations for the control data, however, are probably coincidencial because of few observations in some diameter classes (Fig. 2b). Therefore, large data set covering enough number of trees for each dbh class would be needed for better assessments of soil loss. Physiographic characteristics (soil and physiographic) shown no signs of significant effects in the present data.

Stand density index *N*, *i.e.* number of trees, was highly significant ($p<0.001$) in predicting soil loss (Table 3) as would be expected. The parameter estimate of *N* was negative. This means that as the soil loss decreases *N* increases. The model behavior over *N* (Fig. 3a) seemed good. A similar pattern was not detected in the control data, though (Fig. 3b).

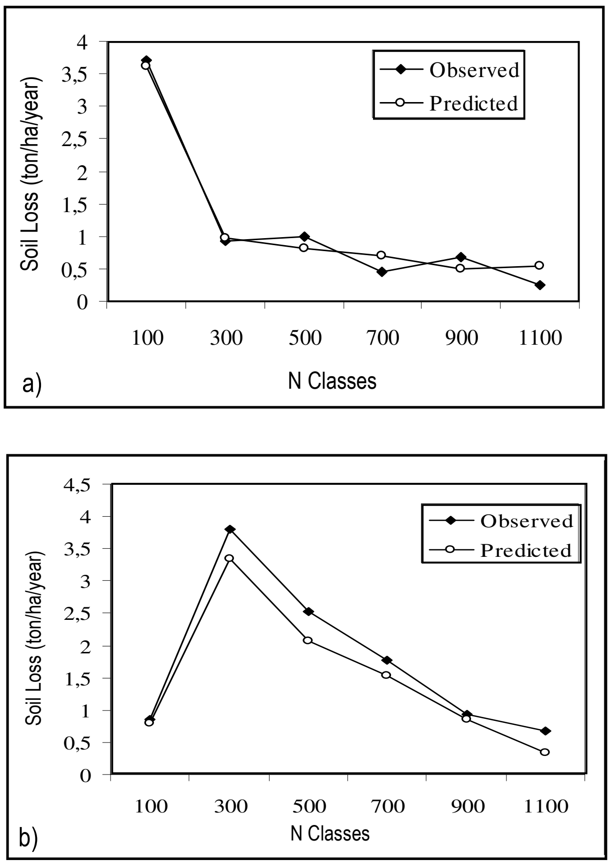

Fig. 3: Predicted and observed soil loss (ton/ha/year) over the number of trees classes for both model data set (a) and control data set (b)

Table - 5: Results of Student's Paired-t test

			Bias
Paired differences		**Mean**	-0.186
		S.D.	0.693
		S.E.mean	0.097
	%95 Conf. Int. of the difference	**Lover**	-0.381
		Upper	0.0089
		***t*-value**	-1.917
		Df	29
		***p*-value**	0.061

N, *BA*, volume, relative density (Curtis *et al.*, 1981), relative stand density (Reineke, 1933; Drew and Flewelling, 1977) and Tree Area Ratio Density Index (Chisman and Schumacher, 1940) were tested as measures for stand density and the only one of them was found significant. The parameter estimate was negative, *i.e.* soil loss amount decreases as the *N* increases. This is consistent with the fact that soil loss changes according to the number of trees.

In the present data the density seemed too much correlated with *N*, to be included in the models. When the predicted and observed soil loss of the test data set were tested Student's Paired t-test, no evidence of lack of fit was found (Table 5).

Mean height, mean diameter and crown closure were tested as measures for stand structure, but only one of them, mean diameter, was highly significant in predicting soil loss because the parameter estimate was significant and negative, *i.e.* soil loss amount decreases as $\overline{d}_q$ increases. This is in correspondence with the nature and, it was possible to detect in the data.

The data used in the present study was in general substantial. The number of observations was relatively large (Table 1). The dispersion of practical forest treatments under different conditions was also included.

The large sample plot size was an advantage in the analysis. A plot size of 800 m^2 means that a relatively large number of the trees are not affected by the forest conditions outside the plot. In other words, a relatively few number of trees are affected by the forest conditions inside the plot.

Plots that were subjected to any harvesting operations between the measurement periods were excluded from the data material because of insufficient information about the treatments. If the harvest on these plots were a result of regular management practices, there would be no problems related to the exclusion. However, if the harvest were a result of an extraordinary situation (*i.e.* floods), exclusion of the plots would lead to an underestimated soil loss amount.

The aim of the present work has been to create models applicable for forest management scenarios. Although stands or sample plots are commonly used as the basic calculation units in such analyses, the target levels with respect to accuracy of the predictions are usually dependent on purpose. Detailed studies of forest structures at the stand level are seldom an important part of such analyses. The uncertainties related to the soil loss models should be seen in this perspective.

Soil loss is an important variable used in forest management planning with the sustainability of multiple values in focus. Measuring soil loss is costly, however. Foresters usually welcome an opportunity to estimate the soil loss with an acceptable accuracy. Missing soil losses may be estimated using a suitable soil loss equation. Based on a comprehensive data set which includes very different stands, such soil loss equation was fitted for a major tree species in complex stands of Turkey. The fit statistics indicated that the soil loss model is most suitable for predicting soil losses. The parameter estimates will provide reasonable precision and therefore the model can be recommended for thinned spruce stands in Turkey. Due to the data kind of the used, the suggested soil loss equation (Eq. 7) should not be used in un-thinned stands and in model predictions which do not contain any of these treatments.

The stand location and stand density measures used in this study and variables entered into the soil loss model can easily be obtained from and are available in current forest inventories. Where possible, the use of the soil loss model with these attributes is suggested. In summary, the suggested model improves the accuracy of soil loss prediction, ensures compatibility among the various estimates in a forest management scenario, and maintains projections with reasonable biological limits.

Linear models for prediction of soil loss for stand level, designed for use in large scale forestry scenario models and analyses have also been developed. The model was developed from a substantial data set representing the entire dispersion of conditions and treatments of the Black Sea Region Spruce productive and nonproductive forest area. Although soil loss a phenomenon is complicated to model, the model fit and the validation tests turned out satisfactory, in spite of several uncertain topics revealed from the work.

Given the uncertainties of large scale forestry scenarios, the presented soil loss model seems to hold an appropriate level of reliability, and we feel that it can be applied in forest management scenarios, including soil loss estimation and control. The model can be revised or calibrated when new measurements from the forest permanent sample plots of the research area obtained in next period.

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