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A Practical Linear Model for Estimation of Tree Falling Direction Error in Mountainous Forests of Northern Iran

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ABSTRACT Directional felling of trees plays a key role in reducing of damages to forest residual trees and can also facilitate skidding. The aim of this study was to present a practical linear model for estimation of tree falling direction error in an uneven-aged mixed stand in northern forests of Iran. To conduct the study a number of 95 trees of four species *Fagus orientalis lipsky*, *Carpinus betulus L.*, *Alnus subcordata* and *Acer platanoides* were randomly selected,and assumed felling direction were marked on the trunk of these trees. The trees were felled by experienced chainsaw operators, and the differences between the assumed and actual direction were measured as the felling error. The results showed that among the 12 effective factors, the elements of foot slope, diameter at the breast height (DBH), horizontal and vertical angles and area of the backcut surface (HABS, VABS, BA), vertical angle and area of undercut surface (VAUS, UA) were significantly correlated with the felling error; the determination coefficient (R^2) of the presented linear model was 52.0 % ($P< 0.01$). Among the model factors, DBH, VABS, and HABS had the three most pronounced impacts on felling error.

Key words: *Directional felling, Felling error, Harvesting operation, Linear regression*

1 INTRODUCTION

Harvesting operations have many negative impacts on the forest ecosystem as reported by several researchers (Agherkakli, *et al.*, 2011; Naghdi *et al.*, 2015). Felling operation is a forest management activity that has negative effects on stand and soil as well as it is harmful for the forest workers. The aims of directional felling are: (i) safety for chainsaw operators, (ii) reducing logging waste, (iii) reducing logging damages to residual stand and soil, and (iv) facilitating the next stages of logging operation. Controlled and safe felling includes various procedures; checking saw and other equipment, assessing environmental conditions, selection and assessment of marked trees, designating an escape route/clearing around tree, performance of undercut and backcut, and finally, moving to a safe area to avoid the felling tree and its parts, as well as to avoid butt kick or bounce (Bentley *et al.*, 2005). Undercut is a V-shaped notch cut into the side of the tree in the assumed fall direction. Backcut is made about 5 centimeter higher than the hinge part of undercut and on the opposite side. This backcut releases the stresses on the back of the tree allowing the tree

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to fall. Felling is one of the harvesting components that can result in serious damages to residual stand if it is not accomplished properly. Using the correct working techniques that include proper elements of felling can prevent damage to humans, soil and residual stand. A correct undercut along with a right backcut, maintaining hinge wood, helps the cut tree to fall in a desired direction, whereas deviation of these elements from their correct structure can result the tree to fall in an improper direction (FAO, 2004). One of the most important objectives in directional felling is to cut trees in form that logs are situated in a suitable direction to skid trails; however effort must be made to select a direction in which felling operation imposes less damage than the other ones, although the damage resulted from felling is unavoidable (Cedergren *et al.*, 2002). The sustainable production of wood in forest management requires logging/operation methods with minimum harm and damage to the soil and residual stand. Shormag (2009) showed that in felling operation as the first step in wood production, damaged residual trees was about 17 to 20% (on average) and in that 33% of these trees were of 50 to 70 cm of diameter. In addition, the severity of damage was to the extent that 13% of those trees with damaged crown finally destroyed.

Skid trails in the forest are spaces between the trees, which are used to move wood from the stump area to the side of the skid roads (Sessions, 2007). The design of skid trails prior to felling is one of the most important prerequisites of harvesting operation in selection-cutting managing forests. The investigation of felling trees toward skid trails showed that, the time required for skidding was decreased when logs were located in the correct direction, and also log rotation and damage to residual stand and regeneration was considerably avoided (Naghdi *et al.,* 2007). Undoubtedly, trees must be cut in all harvesting systems. Although decreasing harvest intensity lowers damage, but ignoring the fact that marked trees should fall in a predetermined direction may have irreparable subsequent damage (Appanah and Weinland, 1990). Skill in directed felling associated with skid trail planning is proven to decrease damage to the stand after felling (Pinard, 1994). The skill of the felling group in accomplishing directed felling could be investigated by whether trees fall in the proper predetermined route.

A number of studies, specifying valuable residual trees, provided the required guidelines for the felling group to maintain those trees (Krueger, 2004). Some researchers determined the most suitable falling direction for the chain saw operator through specifying the falling direction of trees on their trunks after designing the skid trails (Pinard, 1994; Nikooy, 2007; Shormag, 2009). In order to find out whether trees fall on the proper trail according to predetermined planning, it is necessary to estimate the difference between this route and the actual direction (felling error, FE). Krueger (2004) studied the ability of felling group in directed felling in Bolivia. Results of his study showed that, on average, there was a 35.2° difference between the intended and the actual direction of the trees' fall. According to the obtained results from this research, increasing the diameter of the log enhanced the FE and this increase was different for various species. It was also observed that the FE varied between work groups (Krueger, 2004). Multiplicity of effective factors in directional falling operation may cause the chain saw operator to doubt in specifying falling direction and even, sometimes, the time of this step of a single working cycle is more increased than a normal status (Shormag, 2009). Specifying felling direction on the trunk of the tree can provide chain saw operator with a proper guideline in

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order to select a direction so that the tree falls with least damage to residual stand and also to speed up the skidding operation (Conway, 1982).

Many tools have been developed to fell trees in the desired direction (Lindroos *et al.*, 2007). Although using these tools can effectively facilitate directed felling, identifying the most important components of an exact felling operation can help felling groups to perform the operation more accurately and in safe and controlled conditions.

Apart from the ability of felling groups in performing a directed felling, there are also other effective factors on FE. The purpose of this research was to study and modeling the factors influencing FE and to identify their impact on the amount of FE. The factors such as trees' height and diameter, foot slope at the harvesting site, undercut and backcut angles and the spout of undercut were considered as possible independent variables influencing FE. By identifying the effective factors on the FE, the felling groups could perform the operation more accurately with less damage to the vegetation and soil.

2 MATERIALS AND METHODS

2.1 Study area

The study was conducted in the compartment 207 of district 2 of Nav watershed of Asalem forest in the northern Iran. The longitude was between 48° 44' 36" and 48° 49' 58" and the latitude was between 37° 37' 23" and 37° 42' 31". The whole area of the compartment was 54 hectares, with harvestable area of 41 hectares and protected area of 13 hectares. The altitude ranged between 450 to 750 m a.s.l. The general aspect of the compartment was northern. Around 22 hectares of this compartment had a slope of 0to 31%, 18 hectares had a slope of 61 to 80%, 10 hectares had a slope of 81 to 100%, and about 3 hectares had slope of higher than 100%. The number per hectare of tree were 232 with volume of 273 (m^3) per hectare.

2.2 Research methodology

To conduct the research, 95 marked trees were randomly selected out of the whole unevenly distributed marked trees in the study compartment. The most proper felling direction for marked trees was determined before felling operation by consulting the supervisor of forest management plan and chain saw operators, and then the related azimuth was recorded. In order to guide the felling groups, the assumed felling direction was marked by staining the stump of trees in blue color, and assumed felling direction was measured by a compass. No additional forces were applied to guide the trees to fall in the desired direction. After felling operation, the actual azimuth of the trees' fall was also measured and recorded. The azimuth of a straight line from the center of the stump to the center of the trunk at a distance of 5 meter from the backcut was measured as actual falling direction. All selected trees were numbered on the stump and log to minimize the probability of error. The difference between the azimuth of assumed and actual direction of felling were considered as felling error (Figure 1 and Figure 2).

The possible effective factors on occurrence of FE including foot slope (Cedergren et al., 2002; Conway, 1982), tree's deviation (Conway, 1982), diameter at the breast height (DBH) (Nikooy, 2007; Sobhani and Naeij-Nouri, 2006), tree's height, tree's volume, spout angle of undercut, the surface area of undercut and backcut (Sarikhani, 2001; Siadati, 1997; Conway, 1982; Stenzel et al.,1985) were measured and the obtained data was recorded in respective forms (Table 1). Figure 3 illustrates the measured angles on the stump after felling operation.

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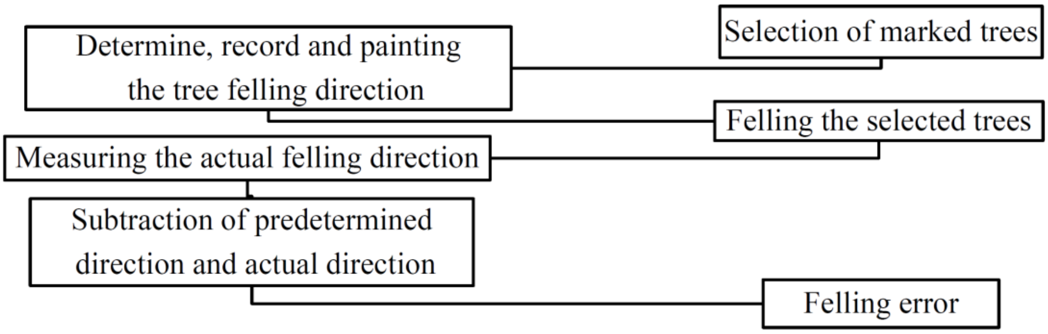

Figure 1 Diagram of data collection during study

Figure 2 Marking felling direction on trunk of remarked tree (a) and difference

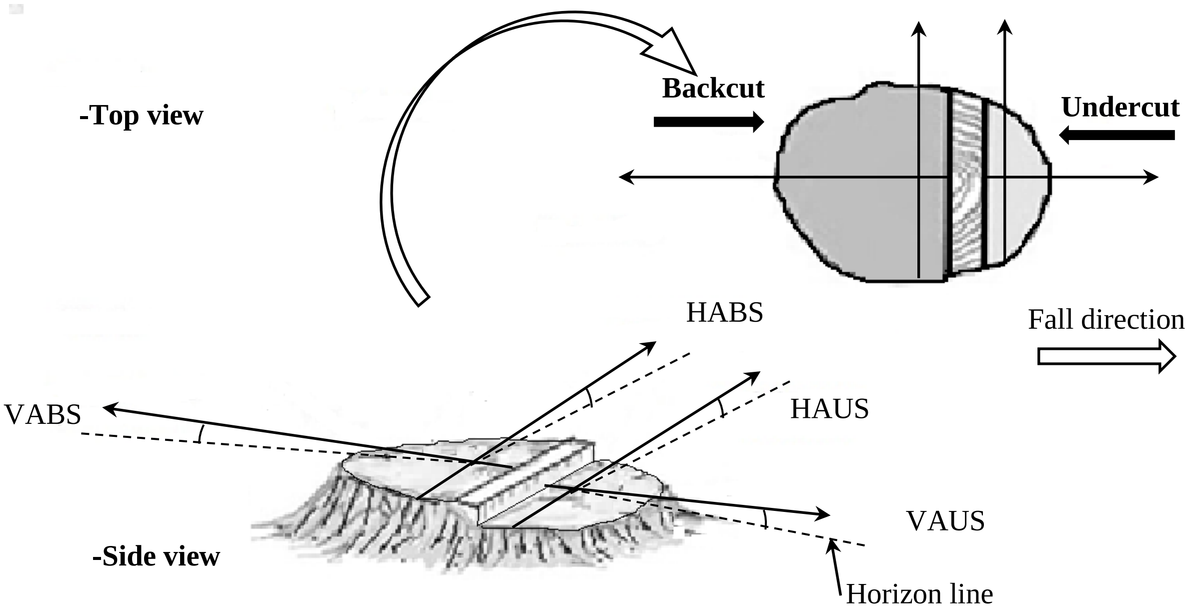

Figure 3 Measured angles of stump after felling operation, vertical angle of backcut surface (VABS), horizontal angle of backcut surface (HABS), horizontal angle of undercut surface (HAUS), and vertical angle of undercut surface (VAUS)

Multiple linear regression (MLR) methods (Enter, Backward, Forward, and Bidirectional eliminations) were selected to develop the linear model of FE estimation. Four assumptions of normality, linearity, heteroscedasticity, and multi collinearity of data should be checked before building of a MLR model. The normality of all variables could be seen via histogram graph, plot P-P, plot Q-Q, or kurtosis and skewness (Johnson *et al*., 1994). In the present research, the normality of data was tested by Kolmogorov-Smirnov test because the sample size was greater than 50. The relationship between response and controlled variables should be linear (i.e. based on a straight line). In this case, the prior knowledge of the nature of linearity is required to apply MLR method. After examination of the independent variables for collinearity (Kumar, 1975) and recognizing the multivariate outliers (unusual value for dependent variable), four multiple regression methods were adopted to develop a linear model for FE. The normality of residuals, and Cook's distance (should be less than 1) (Cook and Weisberg, 1982) and Mahalanobis statistic (should be less than the critical chi-square for degree of freedom equal to the number of independent variables and $\alpha = 0.001$) (Schinka *et al.,* 2003) were checked in each model. To evaluate explanation of the model for various species, the sensitivity analysis was performed by plotting the FE against the independent variables.

3 RESULTS

Table 1 shows the descriptive statistics of measured parameters for selected trees. When the FE occurs, factors such as diameter, edge slope of the log, height, deviation, undercut and backcut surface size, and decay level may have some effects on it.

Table 1 The estimated parameters and their descriptive statistics in the study region

Measured Parameters	Number	Mean	Standard deviation	Min	Max
FE (Degree)	95	31.66	21.35	1	100
Tree Height (m)	95	10.20	4.77	10.2	29.10
Leaning (degree)	95	18.83	19.18	0	39
DBH* (cm)	95	61.04	19.04	28	102
Foot slope (percent)	95	50.04	14.98	15	73
Undercut spout angle (degree)	95	24.70	7.23	11	45
Horizontalangle of undercut surface (degree)	95	7.48	7.07	1	34
Vertical angle of undercut surface (degree)	95	13.67	12	0	36
Horizontal angle of backcut surface (degree)	95	7.04	6.46	0	25
Vertical angle of backcut surface (degree)	95	16.09	13.53	1	54
Undercut area (cm^2)	95	505.56	281.48	85	1187
Backcut area (cm^2)	95	988.20	520.01	277	2175
Decayed area (cm^2)	95	57.71	120.70	0	724

* Diameter at breast height

Among four applied MLR methods, Enter method had the highest determination coefficient (R^2 = 53.7 %). After that, result of the Backward method had the highest performance with the R2 of 52.0 %. The Stepwise and Forward methods had the same R2 of 46.5 %. The Enter method considered all variables in the model, so provided a long equation. Regarding the difference in R2 of the four developed models, the one fitted by

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Backward model was selected as the most efficient model with the least influencing factors (Eq. 1).

$$Y = 28.235 - 0.469 \times s + 0.586 \times \alpha - 0.173 \times \beta + 0.139 \times \gamma - 0.017 \times ua + 75.52 \times d + 0.016 \times ba \quad R^2 = 52.0\ \% \qquad (1)$$

Where, Y is FE in degree, s is foot slope (%), α is horizontal angle of backcut surface (%), β is vertical angle of backcut surface (%), γ is vertical angle of undercut surface (%), ua is undercut surface area (cm^2), d is the trees' diameter (cm), and ba is the backcut surface area (cm^2). The value of R^2 showed that 52 % of variability of FE in this research could be explained by the variability of independent variables.

The coefficient of each independent variable in the regression model represents the average change in FE given one unit change in that independent variable by holding other variables constant. The standardized coefficients indicate which variable is stronger or more important in the explanation of FE. Table 2 shows the standardized coefficients for each effective factor of the model.

Table 2 Standardized coefficients of the factors in the model

Factors	s	α	β	γ	ua	d	ba
Standardized coefficient	-0.329	0.586	-0.264	0.188	0.224	0.674	0.401

The results of variance analysis of the model were presented in Table 3. The *p*-value in this table shows that at least one factor among the independent factors has a non-zero coefficient and has a relationship with the dependent factor, which is FE, and the regression model is statistically significant at the level of 0.01 % error. The tolerance and VIF values of all included independent variables were> 0.1 and ≤ 10, respectively. These results ensured that there was no multicollinearity between independent variables.

Table 3 The variance analysis of the models

Source	**Square Sum**	**Degree of freedom**	**Mean Squares**	**F=** $\frac{MSregression}{MSerror}$	**Sig.**
Regression	22285.292	7	3183.618	13.460	P = 0.00
Error	20577.929	87	236.528		
Total	42863.221	94			

3.1 Sensitivity analysis

The effects of modifications in the value of independent variables on the trend of changes in FE were studied by the sensitivity analysis. The results of sensitivity analysis for investigated species against each of significant factors of the model are illustrated in Figures 4-10.

3.2 Foot slope

The foot slope sensitivity analysis illustrated in Figure 4 shows that FE of all species decreases with slope of the ground. *Carpinus betulus* showed the highest sensitivity. *Acer platanoides* and *Fagus orientalis* were approximately the same and were followed by

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Alnus subcordata with the least sensitivity to foot slope. As could be seen in the Figure 4 the order of species in the amount of FE point of view was reversed on the slope higher than about 40 %.

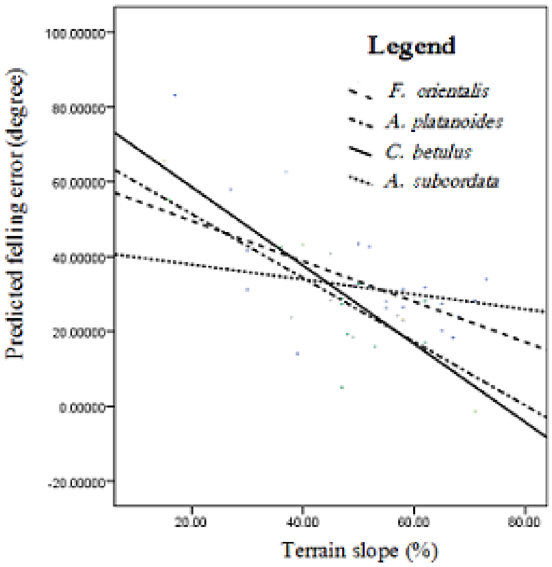

Figure 4 Sensitivity analysis of foot slope

3.3 Vertical angle of undercut surface (VAUS)

Results showed that *F. orientalis* is the most sensitive species associated with change in VAUS. Other species had no remarkable change in FE by changes of VAUS (Figure 5).

3.4 Horizontal angle of backcut surface (HABS)

Results of sensitivity of species to the amount of horizontal angle of backcut surface (HABS) showed that increase in HABS enhances the FE (Figure 6). Among the species, *C.betulus* was the most sensitive species in that FE strictly increased once the HABS increased. Other species had various sensitivities against changes in HABS. However, *A. platanoides* and *F. orientalis* were approximately the same and *A. subcordata* was the least sensitive species.

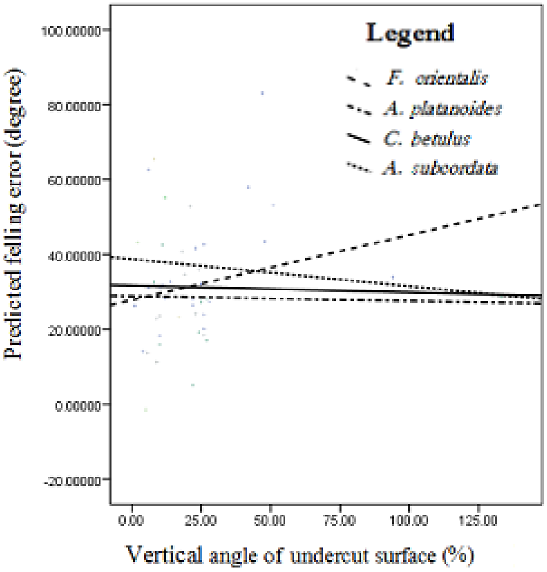

Figure 5 Sensitivity analysis of vertical angle of undercut surface

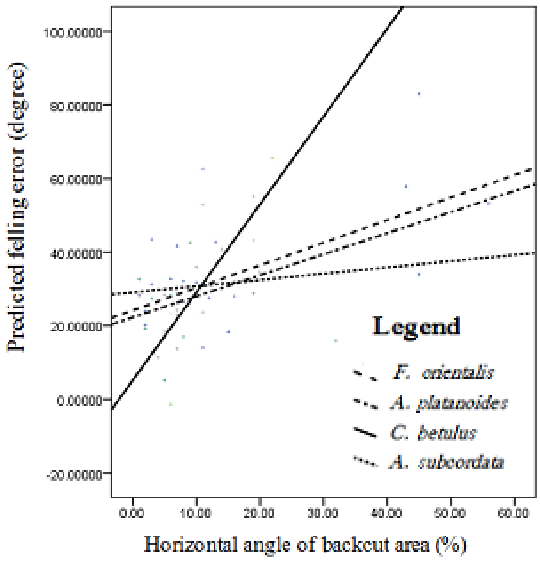

Figure 6 Sensitivity analysis of horizontal angle of backcut surface

3.5 Vertical angle of backcut surface (VABS)

Results of sensitivity analysis of FE against the changes in VABS showed that *C. betulus* was the most sensitive species from this point of view (Figure 7). *A. platanoides* was the next sensitive species. *A. subcordata* showed the least sensitivity and finally FE in the samples of *F. orientalis* showed a little sensitivity to the changes of VABS. Since VABS was not more than 20 % at worst, the order of species over this angle was not notable.

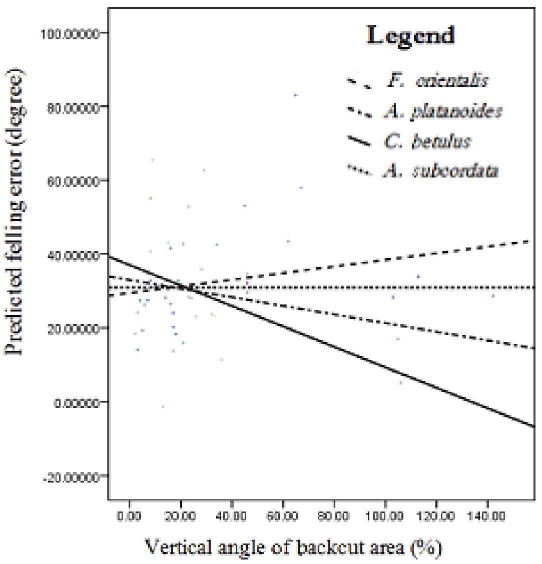

Figure 7 Sensitivity analysis of vertical angle of backcut area

3.6 Diameter (DBH)

Figure 8 illustrates that FE increased once DBH increased in *A. platanoides*, *F. orientalis*, and *C. betulus*. Inversely, FE decreased in *A. subcordata* once DBH increased. The most sensitive species to the change of DBH was *A. subcordata* and the least one was *F. orientalis*.

3.7 Undercut area (UA)

As it was shown in Figure 9, *C. betulus* was the most sensitive species to the changes of undercut area. *F. orientalis*, *A. platanoides* and *A. subcordata* were the later sensitive species, respectively (Figure 9).

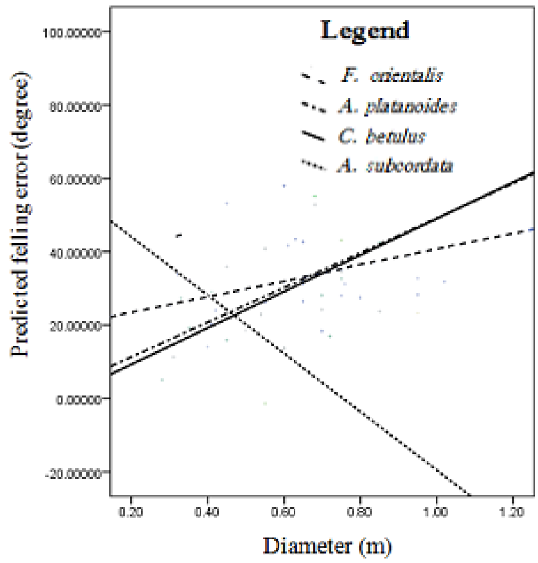

Figure 8 Sensitivity analysis of trees' DBH

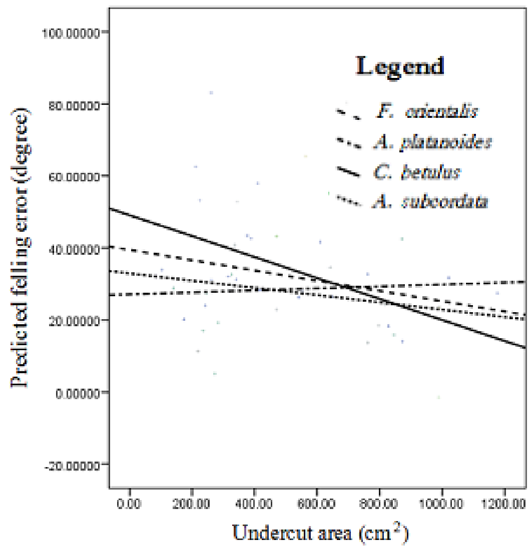

Figure 9 Sensitivity analysis of undercut area

3.8 Backcut area

Result of sensitivity to the change of backcut area in Figure 10 shows that FE in *A. subcordata* increased in high rate with changes of the backcut area. Amount of FE changes was not remarkable in other species.

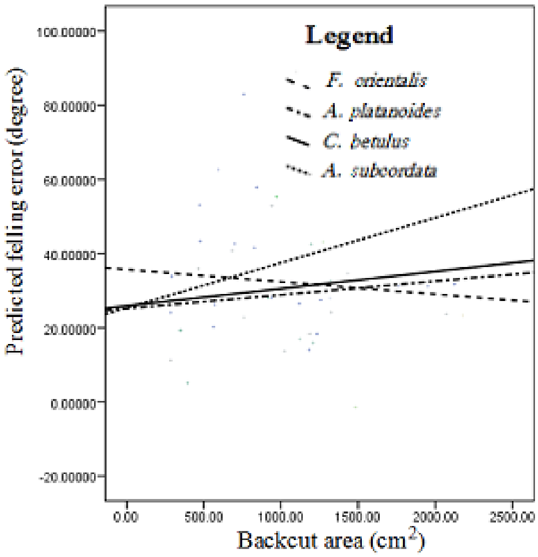

Figure 10 Sensitivity analysis of backcut area

4 DISCUSSION AND CONCLUSION

Results showed that factors such as foot slope, diameter of the tree, vertical and horizontal angles of backcut, vertical angle of undercut and the areas of backcut and undercut had the more pronounce effects on FE occurrence, so that about 52 % of the changes in the model were resulted from the mentioned variables (Table 3). However, other factors could be also significant, among which weather conditions, secondary devices used for felling, land conditions in terms of being slippery, etc. are notable. However, their qualitative nature incapacitated us from further analysis. Results of foot slope sensitivity analysis showed that FE decreased with increase of ground slope (Figure 4). This represents that felling group could predict felling direction more appropriately on steep terrain. In other words, physiographic severity limited falling direction by a considerable degree. The standardized coefficient of foot slope in the Table 3 approves that slope was the most effective factor on FE *C. betulus* and *A. platanoides* showed more sensitivity to the change in foot slope (Figure 4). Reviewing the data made it clear that FE in these species was high on gentle slopes either in which trees had high DBH or HABS/VABS had not been observed by the operator. However, *F. orientalis* and *A. subcordata* showed less sensitivity to HABS and VABS in all slope conditions. Table 3 indicates that DBH, VABS, and HABS are the three most effective factors on FE. Figure 5 illustrates that almost all species showed no remarkable sensitivity to the changes of VAUS except *F. orientalis* that showed an increase in FE with the increase of VAUS. The high FE in felling with higher VAUS was concurrent with violating the HABS and VABS.

Figure 6 illustrates high sensitivity of FE of *C. betulus* to the changes of HABS. Reversely, FE was decreased by increase of VABS (Figure 7). Surveying the sample data proved that DBH had a key role in the current variations, as FE increased whenever changes in HABS or VABS were accompanied by increasing DBH. This fact was more evident in *C. betulus* samples. *C. betulus* also showed the most sensitivity to the change in undercut area (Figure 9). The probable reason for higher FE in lower undercut areas was that the operator had not increased this area enough. This small undercut area led to larger backcut area and higher FE in low diameter trees (Figure 10). Undercut prepares the tree for falling and determines the falling direction. This happens when the undercut spout angle is about 30-40 degrees and has a completely flat surface. Any shift or change in undercut angle deforms the cut and prevents proper forming of the hinge wood. Lack of hinge wood forces tree to go toward one of two incomplete sides of undercut. Even this lack may result in immediate separation of the tree from log (while falling) and cause the tree to be thrown toward falling direction, which in many cases leads to the severe crash of the tree on the

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ground. The existence of slope and decay in the cut tree accentuates the crash. Thus, being aware of correct felling method and considering cutting angles related to felling components can be very helpful. In the present study, the general trend of FE was increasing with an increase in backcut area and with a decrease in undercut area. High FE in the cases with low undercut was due to large tree diameters. In fact, the operator had not increased the depth of undercut although he should, due to the increased diameter. Instead, the operator preferred to assign more area of the cross section of trees to backcut operation (Figure 9 and Figure 10).

Under normal conditions, each undercut or backcut surface has a particular and specified area with the 1:3 proportions (Sarikhani, 2001). If the size of the surface is higher or lower than this value, the tree is deviated from its main direction and FE happens. Conway (1982) has stated that the increase in undercut area and depth causes the tree to fell in a direction other than the considered one or it falls quickly and breaks. On the other hand, a limited undercut area results in an increased backcut area. The first and most important effect of which is that the joint axis leaves its main position and loses its effect, thus FE occurs and the possibility of a split in the trunk and emergence of “barber chair” increases. Increase of tree diameter intensified this problem. The investigation of relationship between diameter and FE approved that “the big size of the crown, along with mass dimensions of these trees, can even intensify the process of estimating the proper falling direction because of the unsuitable distribution of weight in the tree” (Conway, 1982). Slope is one of the main effecting factors on felling direction and the steeper the slope it is, trees must inevitably be cut in that direction; and when the marked tree is not leaning towards that direction, the issue becomes more complex (Sarikhani, 2001). Results of foot slope sensitivity approved that FE increased with foot slope and no factor could change falling direction. As a solution, it is necessary to use tools such as mechanical or hydrolic winches to control felling direction when it is probable for the tree to be damaged while hitting the ground (Siadati, 1997).

Forest operators generally are unfamiliar with proper felling methods. Being aware of new tree felling methods with chain saw, and accomplishing felling under mountainous and steep conditions with thick and broad-leaved trees requires educated felling groups that are familiar with correct felling techniques. Although at the first look, doing this undertaking has some expenditure to which forestry managers resist, however its cost is eventually justified by the outcomes of harvesting operation. At the present status of the studied region, it is better to make workers familiar with correct felling methods theoretically and practically through training courses before starting the felling operation, because training is not only connected to better work performance but ergonomic and health improvement as well (Tsioras, 2015).

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چکیده قطع و انداختن درختان در جهت مناسب نقش مهمی در کاهش صدمات وارده به درختان باقیمانده و تسریع چوبکشی ایفا می کند. هدف از این مطالعه ارایه یک مدل خطی کاربردی برای برآورد خطای قطع در جنگل‌های ناو اسالم بود. برای انجام مطالعه ۹۵ اصله درخت از گونه های راش، ممرز و توسکا و افرا در اندازه های مختلف قطری و ارتفاعی انتخاب و جهت افت مورد نظر بر روی تنه درختان با استفاده از رنگ مشخص و آزیموت آن اندازه گیری شد. پس از عملیات قطع درختان با اره موتوری توسط کارگران با تجربه و آموزش دیده در فصل زمستان ، آزیموت جهت افت واقعی نیز اندازه گیری و تفاوت بین جهت افت مورد نظر و واقعی به عنوان خطای قطع در نظر گرفته شد. قطر برابر سینه، ارتفاع و تمایل درختان، شیب زمین، ابعاد اجزای قطع شامل اندازه زوایای افقی و عمودی صفحه بن زنی و پشت بری وسطوح آنها و زاویه دهانه بن زنی به عنوان متغیرهای مستقل تأثیرگذار بر خطای قطع اندازه گیری شد. رابطه بین هر یک از متغیرهای مستقل و خطای قطع با استفاده از آزمون همبستگی تعیین و مدل خطی بین انها به دست آمد. نتایج نشان داد که شیب زمین، قطر برابر سینه، زاویه افقی و عمودی سطح پشت بری، زاویه عمودی و سطح بن زنی نقش مهمی در خطای قطع دارند. ضریب تبیین معادله ارائه شده ۵۲ درصد بود. دربین عوامل بررسی شده، قطر برابر سینه، زاویه عمودی پشت بری و سطح افقی سطح پشت بری بیشترین تاثیر را در بروز خطای قطع داشتند.

کلمات کلیدی: خطای قطع، بهره برداری جنگل، قطع هدایت شده، رگرسیون خطی