Probability of Occurrence of Soil Disturbances during Timber Harvesting

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Abstract – Nacrtak

This paper deals with the probability of occurrence of soil disturbance during timber harvesting operations. Studies were carried out in southern Poland in 26 stands differing in terrain, skidding method, stand age, amount of timber harvested, forest site type, stocking, and soil type. In each stand the occurrence of the following forms of disturbances was measured: soil surface disturbance, soil cover tearing off and soil compaction. Logistic regression models describing the probability of occurrence of respective disturbance forms were constructed. It was found that the probability of occurrence of soil surface disturbance depends on forest site type and stocking. Soil cover tearing off depends mainly on harvesting density, while soil compaction depends both on the harvesting system and on harvesting density.

Keywords: *timber harvesting, soil disturbance, probability, modeling*

1. Introduction – *Uvod*

Each case of human interference in forest environment, especially harvesting timber crops, is associated with disturbances in forest ecosystems. These disturbances may be described in many different ways but their best qualitative impression may be obtained by estimating their size and the chance of their occurrence. The size of disturbances in forest environment caused by timber harvesting, as well as factors affecting their value, are relatively well recognized. Most often the size of disturbance is associated with the configuration of terrain (Suwała and Rzadkowski 2001), stand age (Habert 2003, Rzadkowski 1999), the harvesting system used (Košir and Robek 2000, Suwała 1995), and the skidding method (Messingerova 1997, Porter 1997). On the other hand, the knowledge concerning the probability of occurrence of disturbances is fragmentary (Sowa 1997). We also do not know what factors decide that in a given cutting area we may expect a definite probability of occurrence of disturbances. Studies concerning this problem are complicated by the fact that many features of each cutting area may affect the chance of occurrence of disturbances. Each logging operation is conducted in a defined terrain that includes stands of a given age (thinnings, final cuttings), and involves the use of machines working with a given harvesting system. Hence it is difficult to determine to what extent each of these characteristics makes the occurrence of environmental disturbances probable. In order to fully explain this problem, it would be necessary to carry out a great number of experimental replications, in which all factors are fixed with the exception of a variable factor. In practice, it is impossible to carry out such a study. However, with a larger number of replications, and using statistical methods, it is possible to obtain a certain idea about the effect of individual characteristics of the timber harvesting process on the probability of occurrence of disturbances.

Based on previous studies (Sowa 2002) it was assumed that the occurrence of disturbance in the forest environment during timber harvesting operations is not an unforeseeable random event. Therefore it is possible to develop a mathematical model describing this process.

The aim of this study was to determine the probability of occurrence of soil disturbance during timber harvesting operations. The scope of the study was limited to selected forest stands in southern Poland. Attempts were made to determine characteristics of the stands and features of the timber harvesting process connected with the probability of occurrence of disturbances.

Table 1 Characteristics of research stands
Tablica 1. *Značajke istraživanih sastojina*

Terrain configuration and place of research *Konfiguracija terena i mjesto istraživanja*	Stand number – *Broj sastojine*	Age, years – *Dob, godine*	Forest site type *Tip sastojine*	Dominant species *Glavna vrsta*	Growing stock, m^3/ha *Drvna zaliha, m^3/ha*	Average breast height diameter, cm *Srednji prsni promjer stabala, cm*	Average height, m *Srednja visina, m*	Stand quality class *Bonitetni razred*	Stocking – *Obrast*	Category of utilisation *Vrsta prihoda*	Harvesting system *Metoda izradbe drva*	Skidding means *Sredstvo privlačenja drva*	Terrain slope, ° – *Nagib terena, °*	Harvesting density, m^3/ha *Sječna gustoća, m^3/ha*
Mountain terrains – The forest district Jeleśnia and Forest Experimental Station in Krynica *Planinski tereni – Šumski okrug Jeleśnia i Istraživački centar Krynica*	1	120	Fresh mixed mountain coniferous forests *Svježe planinske mješovite šume četinjača*	Spruce *Smreka*	438	36	29	III	0.8	*Final cut* *Dovršni sijek*	Tree-length *Deblovna*	Horse *Konj*	14	95
	2	120	Fresh mixed mountain coniferous forests *Svježe planinske mješovite šume četinjača*	Spruce *Smreka*	501	37	31	II/III	0.8	*Final cut* *Dovršni sijek*	Tree-length *Deblovna*	Horse *Konj*	15	86
	3	45	Fresh mixed mountain forests *Svježe planinske mješovite šume*	Beech *Bukva*	268	16	17	I	1.1	Late thinning *Kasna proreda*	Tree-length *Deblovna*	Horse *Konj*	17	67
	4	45	Fresh mixed mountain forests *Svježe planinske mješovite šume*	Beech *Bukva*	256	15	15	I	1.0	Late thinning *Kasna proreda*	Tree-length *Deblovna*	Horse *Konj*	13	79
	5	45	Fresh mountain forests *Svježe planinske šume*	Spruce *Smreka*	360	17	18	I	1.2	Late thinning *Kasna proreda*	Half-tree-length *Poludeblovna*	Horse *Konj*	21	87
	6	30	Fresh mountain forests *Svježe planinske šume*	Fir *Jela*	30	8	10	I	0.7	Early thinning *Rana proreda*	Half-tree-length *Poludeblovna*	Horse *Konj*	10	8
	7	110	Fresh mountain forests *Svježe planinske šume*	Beech *Bukva*	252	41	29	I	0.5	*Final cut* *Dovršni sijek*	Cut-to-length *Sortimentna*	Horse *Konj*	24	112
	8	45	Fresh mountain forests *Svježe planinske šume*	Fir *Jela*	240	14	13	I	0.9	Early thinning *Rana proreda*	Cut-to-length *Sortimentna*	Farm tractor *Poljopr. traktor*	19	20
	9	30	Fresh mountain forests *Svježe planinske šume*	Beech *Bukva*	90	17	14	I	0.8	Early thinning *Rana proreda*	Tree-length *Deblovna*	Horse *Konj*	21	21
Upland terrains – The forest district Gromnik *Brdski tereni – Šum. okrug Gromnik*	10	120	Fresh upland forests *Svježe brdske šume*	Fir *Jela*	287	45	32	I/II	0.5	*Final cut* *Dovršni sijek*	Cut-to-length *Sortimentna*	Horse *Konj*	20	24
	11	105	Fresh upland forests *Svježe brdske šume*	Beech *Bukva*	300	43	27	I	0.7	*Final cut* *Dovršni sijek*	Tree-length *Deblovna*	Skidder *Skider*	11	132
	12	80	Fresh upland forests *Svježe brdske šume*	Fir *Jela*	248	36	26	I/II	0.4	*Final cut* *Dovršni sijek*	Tree-length *Deblovna*	Skidder *Skider*	11	192
	13	100	Fresh upland forests *Svježe brdske šume*	Beech *Bukva*	130	42	26	I/II	0.5	Late thinning *Kasna proreda*	Tree-length *Deblovna*	Skidder *Skider*	10	50

Table 1 Characteristics of research stands (continuation)
Tablica 1. *Značajke istraživanih sastojina (nastavak)*

Terrain configuration and place of research *Konfiguracija terena i mjesto istraživanja*	Stand number – *Broj sastojine*	Age, years – *Dob, godine*	Forest site type *Tip sastojine*	Dominant species *Glavna vrsta*	Growing stock, m³/ha *Drvna zaliha, m³/ha*	Average breast height diameter, cm *Srednji prsni promjer stabala, cm*	Average height, m *Srednja visina, m*	Stand quality class *Bonitetni razred*	Stocking – *Obrast*	Category of utilisation *Vrsta prihoda*	Harvesting system *Metoda izradbe drva*	Skidding means *Sredstvo privlačenja drva*	Terrain slope, ° – *Nagib terena, °*	Harvesting density, m³/ha *Sječna gustoća, m³/ha*
Upland terrains – The forest distict Gromnik *Brdski tereni – Šumski okrug Gromnik*	14	60	Fresh upland forests *Svježe brdske šume*	Beech *Bukva*	262	46	29	I/II	0.6	Late thinning *Kasna proreda*	Tree-length *Deblovna*	Skidder *Skider*	10	117
	15	50	Fresh upland forests *Svježe brdske šume*	Fir *Jela*	260	18	16	II	0.8	Early thinning *Rana proreda*	Tree-length *Deblovna*	Horse *Konj*	13	39
	16	60	Fresh upland forests *Svježe brdske šume*	Fir *Jela*	75	13	13	II	0.7	Late thinning *Kasna proreda*	Cut-to-length *Sortimentna*	Farm tractor *Poljopr. traktor*	15	51
	17	40	Fresh upland forests *Svježe brdske šume*	Beech *Bukva*	175	11	16	III	0.9	Early thinning *Rana proreda*	Tree-length *Deblovna*	Horse *Konj*	13	23
	18	35	Fresh upland forests *Svježe brdske šume*	Spruce *Smreka*	150	13	14	I	0.8	Early thinning *Rana proreda*	Tree-length *Deblovna*	Farm tractor *Poljopr. traktor*	9	29
Lowland terrains – The forest distict Krzeszowice *Nizinski tereni – Šumski okrug Krzeszowice*	19	60	Moist mixed coniferous forests *Vlažne mješovite šume četinjača*	Pine *Bor*	200	24	19	I	0.7	Late thinning *Kasna proreda*	Half-tree-length *Poludeblovna*	Farm tractor *Poljopr. traktor*	1	30
	20	30	Fresh mixed coniferous forests *Svježe mješovite šume četinjača*	Pine *Bor*	115	14	12	I	0.8	Early thinning *Rana proreda*	Half-tree-length *Poludeblovna*	Farm tractor *Poljopr. traktor*	1	37
	21	50	Moist mixed coniferous forests *Vlažne mješovite šume četinjača*	Pine *Bor*	230	22	18	I/II	0.8	Late thinning *Kasna proreda*	Half-tree-length *Poludeblovna*	Farm tractor *Poljopr. traktor*	1	22
	22	35	Fresh mixed coniferous forests *Svježe mješovite šume četinjača*	Pine *Bor*	85	12	10	I	0.8	Early thinning *Rana proreda*	Half-tree-length *Poludeblovna*	Farm tractor *Poljopr. traktor*	1	13
	23	95	Fresh mixed coniferous forests *Svježe mješovite šume četinjača*	Pine *Bor*	150	27	20	III	0.5	Final cut *Dovršni sijek*	Half-tree-length *Poludeblovna*	Horse *Konj*	0	91
	24	110	Fresh mixed coniferous forests *Svježe mješovite šume četinjača*	Pine *Bor*	187	29	20	III/IV	0.7	Final cut *Dovršni sijek*	Half-tree-length *Poludeblovna*	Horse *Konj*	2	62
	25	30	Fresh mixed coniferous forests *Svježe mješovite šume četinjača*	Pine *Bor*	165	14	14	I	0.9	Early thinning *Rana proreda*	Half-tree-length *Poludeblovna*	Farm tractor *Poljopr. traktor*	2	26
	26	120	Fresh mixed coniferous forests *Svježe mješovite šume četinjača*	Pine *Bor*	219	30	22	I	0.8	Final cut *Dovršni sijek*	Tree-length *Deblovna*	Skidder *Skider*	3	70

2. Material and methods – *Materijal i metode*

The research was conducted in southern Poland in mountainous (Jeleśnia Forest District and Forest Experimental Station in Krynica), upland (Gromnik Forest District), and lowland (Krzeszowice Forest District) conditions.

Sample plots were established in stands where the following categories of timber utilization were conducted: early thinnings, late thinnings, and final cuttings. The investigated harvesting systems were as follows: tree-length, half-tree-length, cut-to-length system. Skidding was performed by horses, farm tractors and skidders. Chain saws were used for tree felling, delimbing, and bucking.

Three stands were chosen for each category of timber harvesting. Such an arrangement was repeated in three forms of terrain configuration (the exception are sample plots in mature stands in lowlands, represented by 2 stands). Thus, the experiment was carried out in 26 different stands in total. The description of their basic characteristics is presented in Table 1.

Before the beginning of harvesting, on a 2-hectare working area in each stand, 16 circular sample plots of 1-are, set up on a network of rectangles (25 × 50 m), were established. The stands where the present research was located were hardly accessible. Except division roads – 1st class trails – the stands had no lower class trails. The arrangement of sample plots in relation to 1st class trails is presented in Fig. 1.

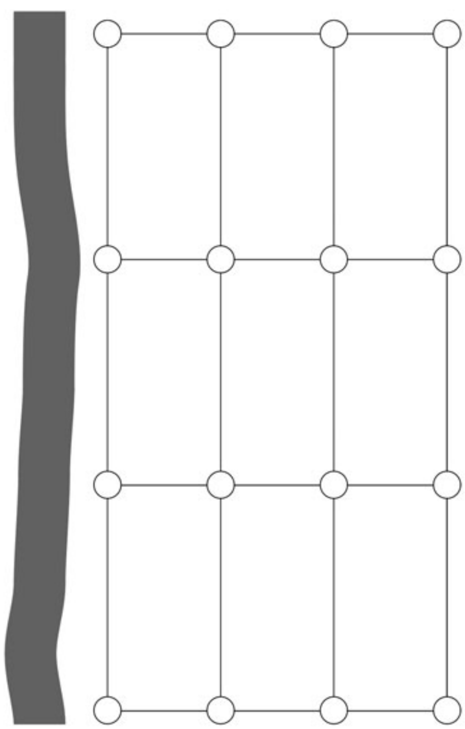

Fig. 1 Study design for single plot
Slika 1. *Postavljanje pokusnih ploha*

The centers of sample plots were marked with PVC poles and the plot number was painted on the nearest tree. Taking into account studies concerning soil disturbances by other authors (Dyrness 1965, Porter 1997, Sowa 2002, Wästerlund 1990, Wästerlund 1992) the following classification was assumed:

⇒ soil surface disturbance, i.e. translocation of litter and humus and exposure of mineral soil without its disturbance, most often caused by uncontrolled shifting or turning of the timber load;

⇒ soil cover tearing off, i.e. exposure of deeper layers and disturbing the mineral soil, most often in the form of furrows made by larger ends of skidded timber;

⇒ soil compaction, i.e. distinct marks of soil compaction made during skidding operation by a vehicle or a timber load.

Directly after felling, the circular sample plots were found and assessment of soil disturbances was performed. If even one soil disturbance of the above-mentioned types was recorded, then – in the course of calculating the probability of occurrence of damage in the analysed stand – a given circular sample plot was classified as disturbed, regardless of the size of this disturbance. Each single disturbance of the soil cover, recorded in field, was ascribed only to one of the above-mentioned forms of soil disturbances. Disturbances of various types were often recorded on a single sample plot – such a sample plot was taken into consideration in the calculation of the probability of all forms of soil disturbances found on it.

The data obtained during this study were analyzed statistically using the computer program STATISTICA 6.0 PL (StatSoft, Inc. 2004). All tests were performed at the significance level $\alpha = 0.05$.

3. Results and discussion – *Rezultati s raspravom*

The probability of occurrence of a random event, and soil disturbance is such an event, is one of its characteristics. To calculate this probability, individual circular sample plots were coded either (1) when a disturbance occurred, or (0) when there was no disturbance. For each working area (stand), the probability of occurrence of soil disturbances was computed by determining the percentage of circular sample

Table 2 The probability of occurrence of soil disturbances in research stands

Tablica 2. *Vjerojatnost pojave oštećenja tla u istraživanim sastojinama*

Stand number *Broj sastojine*	Probability of occurrence of respective soil disturbances, % *Vjerojatnost pojave određenoga oštećenja tla, %*		
	Soil surface disturbance *Površinsko oštećenje tla*	Soil cover tearing off *Premještanje slojeva tla*	Soil compaction *Zbijanje tla*
1	64	14	57
2	33	28	57
3	6	40	26
4	12	43	56
5	90	50	90
6	12	6	25
7	42	71	28
8	18	18	43
9	37	56	18
10	0	25	18
11	0	63	0
12	0	42	68
13	0	31	6
14	15	61	7
15	15	15	0
16	4	46	39
17	0	61	23
18	0	55	22
19	42	42	78
20	8	8	33
21	0	37	50
22	6	25	31
23	12	75	62
24	11	66	77
25	6	12	93
26	12	43	18
Total – *Ukupno*	14	37	37

plots with disturbances (code 1). The results are shown in Table 2.

Analysis of the data in Table 2 showed that the occurrence of soil surface disturbances was statistically least probable. In total, in the entire experiment, surface disturbances were found in about 15% of circular sample plots. The tearing off and compacting of soil was equally probable – about 40%. The results of research by other authors, concerning the probability of occurrence of soil damage in the course of timber harvesting indicate a large differentiation of this index depending on stand conditions in which felling is performed and on the technologies applied. For example, research done in British Columbia shows that the probability of occurrence of deep disturbances and compacting in the soil of the forests of New Zealand is relatively low – depending on the sampling method, the chance of their occurrence was described as 4–7% and 35–50%, respectively. In European conditions (France), during final cutting, much higher probability of soil disturbance was recorded, depending on the skidding means. In skidding by skidder, the probability of disturbance was 87% and by forwarder it raged from 65 to 86% (Gondard et al. 2003). Research on the probability of soil disturbance during harvesting has been conducted in Poland, too. Gil et al. (1987) reported that the probability of occurrence of soil disturbances in a mountain stand designated for final cutting (group cutting method) using mechanical skidding was 59–69%, while that for soil compaction was 19–44%. The results obtained have confirmed the opinion of Giefing (1990) that the chance of occurrence of disturbance caused by timber harvesting increases as the stand age increases. It was found that the probability of occurrence of soil disturbances was on the average 68% during final cuttings, 65% during late thinnings, and 52% during early thinnings.

In order to assess the usefulness of individual characteristics of stands, types of operations, and conditions occurring in circular sample plots for the estimation of the risk of soil disturbance occurrence, the correlation between these features and the occurrence of disturbance (zero-one codes) was calculated and expressed by Spearman's coefficient of correlation *R*. It was assumed that the following characteristics (factors) may affect the probability of occurrence of soil disturbances:

- ⇒ A) configuration of terrain (mountains, uplands, lowlands);
- ⇒ B) category of timber utilization (final cutting, late thinning, early thinning);
- ⇒ C) harvesting system (tree-length, half-tree-length, cut-to-length);
- ⇒ D) skidding means (horse, farm tractor, skidder);
- ⇒ E) harvesting density of circular sample plot (m^3/are);
- ⇒ F) terrain slope in a circular sample plot (°);
- ⇒ G) harvesting density of entire cutting area (m^3/ha);
- ⇒ H) forest site type;

⇒ I) soil type and subtype (typical brown soil, acid brown soil, typical podzolic soil, podzolic gley soil);

⇒ J) soil texture (heavy loam, medium loam, sandy loam, coarse sand, compact sand, loose sand);

⇒ K) stocking;

⇒ L) crown closure (full, moderate, open);

⇒ M) stand age (years);

⇒ N) growing stock (m^3/ha).

The results are presented in Table 3.

It may be observed that the correlation between the probability of occurrence of soil disturbances and the selected characteristics (factors) was not strong. The maximum value of the correlation coefficient *R* was 0.26, and this correlation was considered to be weak (Stanisz 1998). Thus, the correlation did not adequately explain what characteristics affected the probability of occurrence of soil disturbance. The individual characteristics are known, but perhaps their integration into one model would permit to determine which one of them, and to what degree, affects the occurrence of disturbance. The probability of occurrence of soil disturbance ranged from 0 to 1,

Table 3 Strength and significance of correlation between the probability of occurrence of analyzed forms of soil disturbances and the selected characteristics of stands

Tablica 3. *Jakost veze i značajnost korelacije između vjerojatnosti pojave promatranih oblika oštećenja tla i odabranih značajki sastojina*

Correlated characteristics *Korelirane značajke*	Soil surface disturbance *Površinsko oštećenje tla*		Soil cover tearing off *Premještanje slojeva tla*		Soil compaction *Zbijanje tla*		All disturbance forms *Svi oblici oštećenja tla*	
	R	*p*	*R*	*p*	*R*	*p*	*R*	*p*
Terrain configuration *Konfiguracija terena*	**0.24**	**0.00**	0.02	0.65	0.05	0.29	0.02	0.74
Timber utilisation category *Vrsta prihoda*	0.04	0.46	0.02	0.62	0.02	0.62	0.01	0.82
Harvesting system *Metoda izradbe drva*	0.03	0.49	0.08	0.08	**0.24**	**0.00**	0.02	0.61
Skidding means *Sredstvo privlačenja*	**0.23**	**0.00**	0.03	0.55	0.09	0.07	0.05	0.33
Harvesting density of circular plot *Sječna gustoća* pokusne plohe	**0.11**	**0.02**	**0.13**	**0.01**	**0.22**	**0.00**	**0.27**	**0.00**
Terrain slope *Nagib terena*	0.06	0.21	0.06	0.23	**0.15**	**0.00**	0.09	0.08
Harvesting density of cutting area *Sječna gustoća sječine*	**0.13**	**0.01**	**0.14**	**0.00**	**0.10**	**0.04**	**0.21**	**0.00**
Forest site type *Tip sastojine*	**0.26**	**0.00**	0.03	0.56	0.04	0.43	0.02	0.61
Soil type and subtype *Tip i podtip tla*	**0.25**	**0.00**	0.01	0.85	0.03	0.51	0.05	0.29
Soil texture *Tekstura tla*	**0.23**	**0.00**	0.05	0.26	**0.10**	**0.03**	0.04	0.41
Stocking *Obrast*	**0.19**	**0.00**	0.03	0.60	**0.13**	**0.01**	0.07	0.12
Crown closure *Sklop sastojine*	0.00	0.99	0.04	0.36	0.02	0.73	0.03	0.59
Stand age *Dob sastojine*	0.06	0.19	0.06	0.19	0.06	0.22	0.04	0.42
Growing stock *Drvna zaliha*	**0.20**	**0.00**	0.00	0.97	0.07	0.14	**0.13**	**0.01**

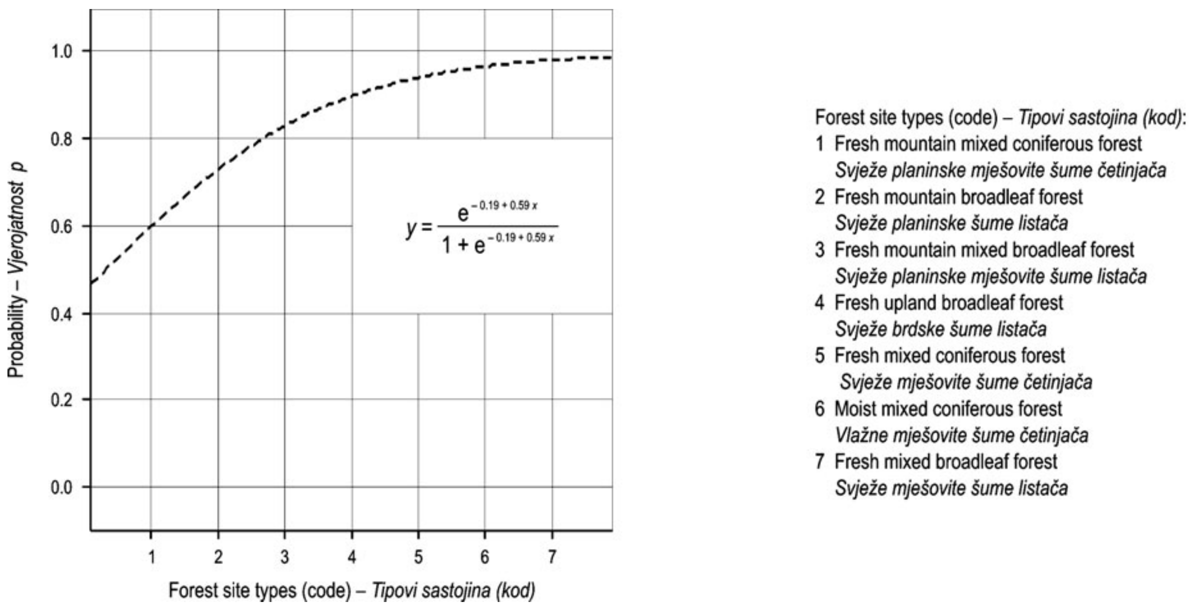

Fig. 2 Regression model of the probability of occurrence of soil surface disturbance depending on forest type

Slika 2. *Regresijski model vjerojatnosti pojave površinskoga oštećenja tla ovisno o tipu sastojine*

and in individual circular sample plots the soil disturbances were dichotomic, they either occurred or not. Therefore, it was assumed that by using a model of logistic regression it would be possible to describe most fully the effect of individual factors on the probability of soil disturbances. Models were elaborated separately for each soil disturbance form, and the consecutive factors were introduced to the model beginning with those characterized by the highest values of Spearman's coefficient of correlation *R*. Currently the effect of characteristics being added on quality of the model were analyzed. The use of this method of model development prevented their basing on random variables mutually correlated with one another e.g. stand age and the category of timber harvesting. At the same time this permitted to choose the variable which would contribute more to the model.

According to the assumption made, attempts were made to build the model determining the relationship between the forest site type and the probability of occurrence of soil surface disturbances. For this purpose a quasi-Newton method of estimation was used (Stanisz 2000). The model obtained and codes of forest site types are shown in Fig. 2.

The chi-squared test showed statistical significance of the model ($\chi^2 = 35.02$, $p = 0.00$). The percentage of circular sample plots for which, by using the model, it was possible to predict correctly the occurrence of damage was computed, assuming that all circular sample plots with the model probability of occurrence of soil damage smaller or equal to 0.5 will be treated as 0 (a lack of damage) and those with the probability greater than 0.5 as 1 (damage occurred). The parameter calculated – and called the odds ratio – replaces the coefficient of the correlation R^2, which is a measure of adjusting the type model that does not occur in logistic regression.

The model presented above had simultaneously three parameters: terrain conditions – forests of mountain, upland, and lowland sites. The probability of occurrence of surface disturbances increased in the same order. It was verified whether basing of a logistic model on terrain conditions only (mountains, uplands, and lowlands) would give the same results as in the case of using forest site types. However, the model obtained, although a significant one, was characterized by only 48% efficiency in estimating the probability of occurrence of soil surface disturbance.

According to the assumed model development method, the following random variables were successively introduced into the model (Fig. 2): soil type and subtype, terrain configuration, skidding means, soil texture, and growing stock. However, these operations did not significantly improve the model, i.e. the test χ^2 did not show differences between new models and the model shown in Fig. 2. Only the use of stand stocking resulted in model improvement ($\chi^2 = 314.06$, $p = 0.00$) (Fig. 3).

This model was statistically significant ($\chi^2 = 52.76$, $p = 0.00$). The model was very efficient because it correctly estimated the probability of occurrence of surface disturbances in 87%. The addition of new vari-

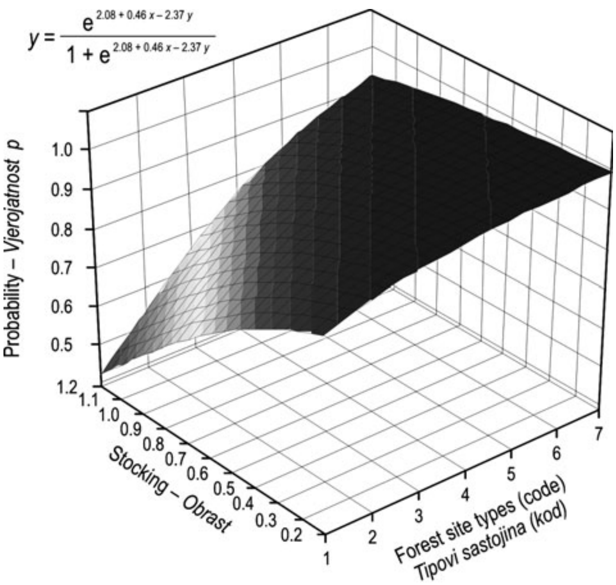

Fig. 3 Regression model of probability of occurrence of soil surface disturbance depending on forest type and stocking

Slika 3. *Regresijski model vjerojatnosti pojave površinskoga oštećenja tla ovisno o tipu i obrastu sastojine*

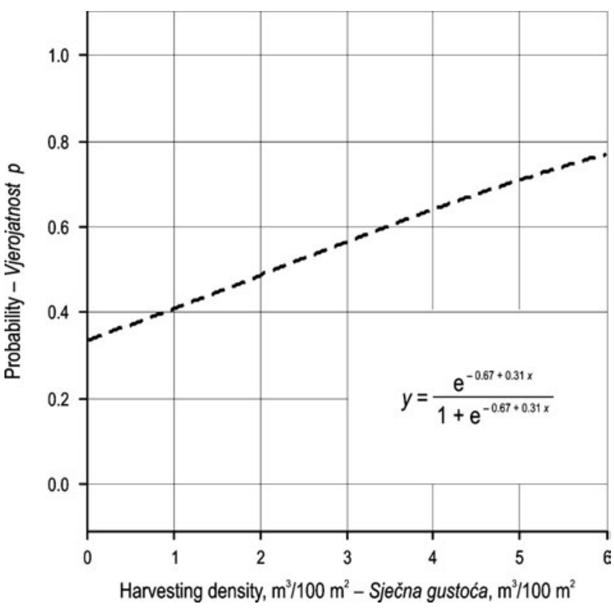

Fig. 4 Regression model of the probability of occurrence of soil cover tearing off depending on harvesting density

Slika 4. *Regresijski model vjerojatnosti pojave premještanja slojeva tla ovisno o sječnoj gustoći*

ables, i.e. growing stock and harvesting density in a circular sample plot, did not result in any statistically significant difference. When analyzing the model in Fig. 3, it may be noticed that the factor of stocking had the greatest effect on the probability of occurrence of soil disturbance in mountain and upland stands. In the case of lowland stands its effect was insignificant. The results of this study showed that the probability of occurrence of soil surface disturbances in nearly 90% depended on stand factors on which man's activities had no direct influence. This, however, does not mean that the forest manager and the firm conducting timber harvesting are free of responsibility for the condition of the forest because the level of disturbances is greatly affected by their size. And this, as shown, is also connected with the harvesting system selected.

The data in Table 3 show that the harvesting density had the greatest effect on the occurrence of soil cover tearing off. However, the model using this random variable turned out to be statistically insignificant ($\chi^2 = 5.75$, $p = 0.09$). On the other hand, the attempt to subject the probability of occurrence of soil cover tearing off to harvesting density in a circular sample plot permitted to obtain a significant model ($\chi^2 = 7.75$, $p = 0.01$) (Fig. 4).

The model estimated correctly the probability of occurrence of soil tearing off in 62% of cases (odds ratio). The graph (Fig. 4) shows that the performance of harvesting operations, even those not too intensive, resulted in over 30% probability of occurrence of disturbances in the form of soil cover tearing off. However, the extrapolation of values of the logistic function for greater volumes of harvested timber

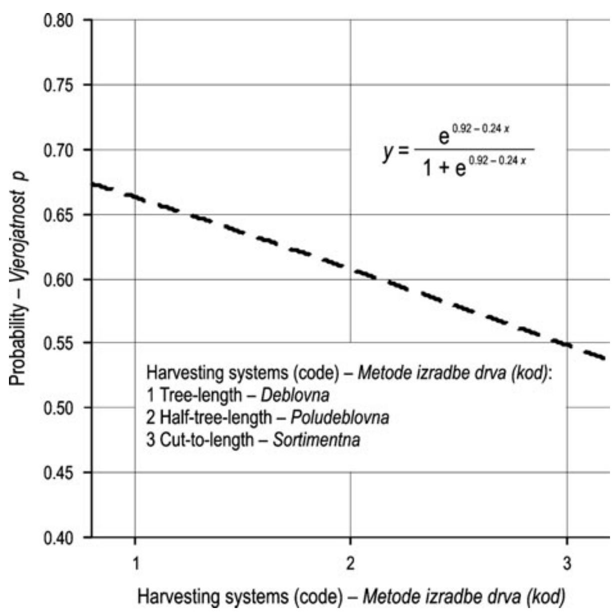

Fig. 5 Regression model of the probability of occurrence of soil compaction depending on harvesting system

Slika 5. *Regresijski model vjerojatnosti pojave zbijanja tla ovisno o metodi izradbe drva* showed that a 100% certainty of the occurrence of soil cover tearing off is attained not sooner than when intensity of harvesting is 15 m^3/ha, and this is unattainable in practice.

The attempt to explain the occurrence of soil compaction caused by the harvesting system used resulted in obtaining a logistic model shown in Fig. 5.

This model was statistically significant ($\chi^2 = 289.62$, $p = 0.04$). It permitted to determine correctly 62% of the probability of occurrence of soil compaction. Its analysis showed that soil compaction most often occurred during timber harvesting in the tree-length system. The occurrence of this kind of soil disturbance was less probable in the half-tree-length system, and the least probable in the cut-to-length system. However, the differences between individual systems in this respect were not large (up to 10%). Development of the model by addition of harvesting density in a circular sample plot (Fig. 6) resulted in a significant ($\chi^2 = 399.24$, $p = 0.00$) increase in the efficiency of forecasting the occurrence of soil compaction to the level of 68%.

This model was significantly different from the model with only free term ($\chi^2 = 17.24$, $p = 0.00$). The graph presenting the logistic function (Fig. 6) shows that in spite of a significant effect of the harvesting system on the probability of occurrence of soil compaction, the harvesting density had a greater effect on the occurrence of this form of disturbance.

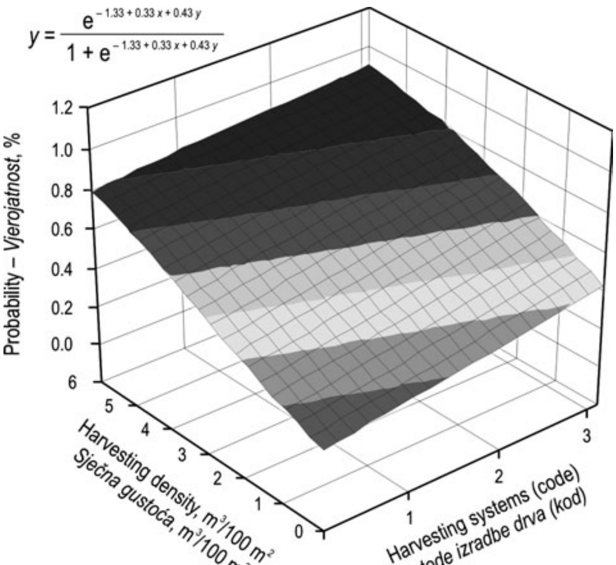

Fig. 6 Regression model of the probability of occurrence of soil compaction depending on harvesting system and harvesting density

Slika 6. *Regresijski model vjerojatnosti pojave zbijanja tla ovisno o metodi izradbe drva i sječnoj gustoći*

4. Conclusions – *Zaključci*

On the basis of research results, the following conclusions should be pointed out:

⇒ The probability of occurrence of soil disturbance during timber harvesting operations is a highly foreseeable characteristic.

⇒ Mathematical models developed during this study permit to determine the probability of occurrence of a definite form of soil disturbance as well as to determine characteristics of stands and operations affecting the value of this probability.

⇒ The probability of occurrence of soil surface disturbances significantly depends on the forest site type and stand stocking. The latter factor is of greater importance, and it is inversely proportional to the value of the probability.

⇒ Soil surface tearing off may be deduced in over 62% from the harvesting density.

⇒ The harvesting system and harvesting density significantly affect the probability of occurrence of soil compaction.

⇒ The probability of occurrence of soil compaction depends on the length of skidded timber. The highest one was found when the tree-length system was used. Under the half-tree-length system the probability was smaller, and under the cut-to-length system its value was the smallest.

⇒ The probability of occurrence of any of the analyzed forms of soil disturbance is directly proportional to the harvesting density.

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Sažetak

Vjerojatnost pojave oštećenja tla pri pridobivanju drva

Cilj je rada određivanje vjerojatnosti pojave oštećenja tla pri pridobivanju drva. Istraživanje je provedeno u 26 šumskih sastojina u planinskom, brdskom i nizinskom području. Šumske su sastojine razvrstane po vrsti prihoda na rane prorede, kasne prorede i dovršni sijek. Na svakom području izabrane su po tri sastojine iste vrste prihoda, osim u nizinskom području gdje je dovršni sijek zastupljen samo u dvije sastojine. Stabla su se sjekla i izrađivala motornim pilama uz primjenu deblovne, poludeblovne i sortimentne metode izradbe. Drvo se privlačilo konjima, poljoprivrednim traktorima ili skiderima. Značajke su istraživanih šumskih sastojina te primijenjenih metoda izradbe drva i privlačenja drva prikazane u tablici 1.

Prije izvođenja radova u svakoj je sastojini na površini od 2 ha postavljeno 16 pokusnih ploha kružnoga oblika površine 1 ar u prostornom rasporedu 25 x 50 m (slika 1). Nakon sječe i izrade stabala te privlačenja drva na pokusnim su plohama zabilježena oštećenja tla koja su razvrstana u 3 oblika:

⇒ *površinsko oštećenje tla – skidanje sloja humusa i listinca zbog pomicanja i okretanja tovara*

⇒ *premještanje slojeva tla – oštećenje tla u obliku brazdi zbog guranja tla debljim krajem drvnih sortimenta pri privitlavanju*

⇒ *zbijenost tla – izrazito oštećenje tla pri privlačenju drva zbog prolaska vozila i tovara.*

Pokusne su plohe razvrstane po vrsti oštećenja tla. Vrlo je često na istoj plohi zabilježeno više oblika oštećenja tla te se ta pokusna ploha razmatrala u proračunu vjerojatnosti svih zabilježenih oblika oštećenja tla.

Podaci su mjerenja statistički obrađeni u računalnom programu STATISTICA 6.0 PL.

U proračunu vjerojatnosti pokusna ploha s pojavom oštećenja tla označena je s 1, a pokusna ploha bez oštećenja tla s 0. Za svaku šumsku sastojinu određena je vjerojatnost pojave određenoga oblika oštećenja tla temeljem postotnoga odnosa oštećenja tla u pokusnim plohama (tablica 2).

Pretpostavka je da ove značajke mogu utjecati na pojavu oštećenja tla: konfigurcija terena, vrsta prihoda, metoda izradbe drva, sredstvo privlačenja drva, obujam posječenoga drva na pokusnoj plohi, nagib terena na pokusnoj plohi, sječna gustoća, tip sastojine, vrsta tla, tekstura tla, obrast, dob sastojine i drvna zaliha. Rezultati korelacija između navedenih značajki i pojave oštećenja tla pokazuju slabu povezanost podataka (tablica 3).

U daljnjoj analizi podataka korištena je logistička regresija s obzirom na to da se pojavnost oštećenja tla na pokusnim plohama vrednovala s 0 (bez oštećenja) i 1 (s oštećenjem). Logističkom regresijom određeni su modeli za svaki oblik oštećenja tla te χ^2 *testom utvrdila statistička značajnost modela.*

Na slici 2 prikazan je model vjerojatnosti pojave oštećenja tla u ovisnosti o tipu sastojine te su opisani kodovi tipova sastojine. Prikazani model prikazuje da je vjerojatnost pojave oštećenja najmanja u planinskim uvjetima, a najveća u nizinskim uvjetima. Uvrštavanjem ostalih varijabli u model nije dobiveno statistički značajno poboljšanje modela. Obrast je sastojine jedina nezavisna varijabla koja je utjecala na poboljšanje modela. Obrast sastojine ima najveći utjecaj na povećanje vjerojatnosti pojave oštećenja tla u planinskim i brdskim uvjetima, dok je njegov utjecaj neznačajan u nizinskim uvjetima (slika 3). Rezultati istraživanja pokazuju da vjerojatnost pojave oštećenja tla značajno ovisi o stanišnim uvjetima, ponajprije o tipu sastojine i obrastu.

Statistički značajnim pokazao se model procjene vjerojatnosti pojave premještanja slojeva i tla u ovisnosti o obujmu posječenoga drva na pokusnoj plohi (slika 4). Model u 62 % slučajeva ispravno procjenjuje vjerojatnost pojave premještanja slojeva i tla. Logistički model procjene pojave zbijanja tla izrađen je u ovisnosti o metodi izradbe drva (slika 5) te je uočeno da je pri primjeni deblovne metode najčešća pojava zbijanja tla. Vjerojatnost je pojave zbijanja tla najmanja pri primjeni sortimentne metode. No, razlike u vjerojatnosti pojave zbijanja tla između tri promatrane metode izradbe drva nisu velike (do 10 %). Logistički model prikazan na slici 6 pokazuje da unatoč značajnu utjecaju primjene određene metode izradbe drva najveći utjecaj na vjerojatnost pojave zbijanja tla ima obujam posječenoga drva. Općenito, obujam posječenoga drva ima najveću utjecaj na sve oblike oštećenja tla.

Ključne riječi: *pridobivanje drva, oštećenje tla, vjerojatnost, modeliranje*

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