Original scientific paper

Soil compaction in timber skidding in winter conditions

Marijan Šušnjar, Dubravko Horvat, Josip Šešelj

Abstract – Nacrtak

The research of soil compaction in timber skidding was carried out on two skid trails of uniform slope –15 % and 30 %. The degree of soil compaction is shown by changes of water-air soil characteristics of the skid trail after a certain number of passes of a loaded skidder and by comparison between these values and the characteristics of untreaded soil during research. The research was carried out in winter conditions at low air and soil temperatures and with the research site covered with snow.

Multiple passes of a loaded skidder affect the degree of soil compaction. The result of soil compaction is the decrease of momentary moisture content, porosity and soil water capacity, as well as the increase of native bulk density. Soil compaction is higher if the soil is not frozen.

Due to low air temperatures and disappearance of snow from wheel ruts during skidding, the rut soil gets frozen more easily during the night than the untreaded soil. Soil compaction during the day does not cause squeezing out of water from soil micropores and consequently its freezing enlarges the volume of micropores and increases soil porosity and soil water capacity and decreases its native bulk density.

Keywords: *soil compaction, multipass, skid trail, timber skidding, water-air soil characteristics*

1. Introduction – *Uvod*

Wheel skidders equipped with winch are mostly used for skidding in hilly and mountainous regions of Croatia. Timber skidding is carried out with one end of the load elevated from the ground and set on the back of the vehicle, while the other end of the load is dragged on the soil. Forest soil on which timber skidding is carried out has a serious impact on the vehicle's manoeuvrability. As a rule, skidders travel on prepared and marked skid trails, without entering into the stand. In this way soil compaction and damage to trees are lowered. The skidder's travel on skid trails causes damage to forest soil. The level of damages depends on the mass of vehicles and loads as well as on forest soil characteristics.

The soil bearing strength is a mechanical feature which represents the capacity of the soil to resist external forces, and it is determined by settling of soil under external load. Along with shear strength, the bearing strength is one of the most important characteristics for the quality of ground usability from the technical and exploitation point of view, and it affects the level of production efficiency of the means of work as well as the level of damages caused by timber skidding.

Direct damages to forest soil are caused by compaction of soil particles made by vehicle passes and penetration of wheels into the soil because of low soil bearing strength, which results in the transfer of soil horizon and damage to root system. Consequently, the damage to forest soil caused by vehicle passes can be divided into three components: soil compaction, rut formation and soil transfer.

Generally, soil compaction represents a volume soil deformation (Gameda et al. 1987) and increase of bulk density, as a result of compaction of soil particles under the effect of an external force (Arnup 1998).

2. Main issues – *Problematika*

In timber skidding, soil compaction occurs as a result of wheel load exerted on the soil, load of the end of wood hauled on the ground and vibrations of the vehicle during travel (Hogervorst and Adams 1994).

Arnup (1998) defines the following vehicle and soil factors, which have a decisive effect on soil compaction: wheel load exerted on the soil, soil texture, momentary soil moisture content during works, native bulk density and soil porosity, thickness of humus layer and thickness of root system layer.

Under wheel load, stress occurs in the soil resulting in the decrease of soil porosity, increase of soil density, decrease of undefined physical states with an adverse effect on the soil temperature regime and porosity. The increase of soil density affects the root system of plants, because the reduction of pores and soil moisture content cause inaccessibility to nutrients, which is the main cause of poor growth of plants.

Soil compaction causes changes of the basic indicators of its state, and hence the degree of its compaction is measured through these changes. Soil compaction is measured in a different way by different authors: Abebe et al. (1989) by change of soil volume, the so-called compaction index; Carman (1994) and Mathies et al. (2003) by change of soil native bulk density, Hassan (1990) by change of dry soil density, and Bolling (1989) and Hata and Tateyama (1991) by change of porosity.

By the analysis of a soil sample taken from the skid trail in skidding of adapted farm tractors, Vranković and Pernar (1993) observed the increase of momentary moisture content, volume density and soil water capacity, as well as the decrease of soil porosity of wheel rut and skid trail, and higher soil damages were recorded under the tractor wheels.

The sensibility of soil to compaction depends on the soil structure and moisture content. The bearing strength of soil decreases with the increase of soil moisture. Due to unfavourable physical and mechanical features of the soil with high moisture content, higher soil compaction and rut formation occur. Along with momentary moisture content, soil texture also plays an important role in the capability of soil to stand the weight of the vehicle and load without damage, as soil moisture has a different impact on different types of soil. Mechanical properties of the soil are determined by the share of size of its individual particles (granulometric distribution of particles), and also by the content and size of soil pores. Due to the decrease of soil volume, air pressure is increased in closed pores, and the open ones are filled with soil particles. The higher the porosity, the higher the soil compaction caused by wheel and mass load. Froelich (1989) states the proposal of the USDA Forest Service for the quantification of limit values of soil damage, according to which it is considered that the limit value of soil compaction is achieved if the total pore area is lowered by 10 %.

The annual, seasonal and momentary climate effects (precipitations, air temperature, underground water level) cause change of the momentary soil moisture, and consequently directly affect the conditions of the soil bearing strength.

Timber skidding in unfavourable, wet conditions often causes irremediable damage to soil on which wood is hauled (plastic soil deformation) and formation of undesirable large and deep ruts, which makes such work inefficient and unfeasible. (Sever and Horvat 1981). On soils of poor bearing strength, skidding operations are usually distributed in the period of their highest bearing strength (dry or winter period).

The soil moisture content affects directly its bearing strength, as it influences the soil temperature. The soil temperature is affected by soil moisture, quantities of precipitation, air temperature, vegetation cover, soil texture and soil density. The soil gets frozen at low air temperatures in winter. The debth of the frozen soil primarily depends on the number of days with temperatures below 0 °C, and on the depth of the snow cover, and also on soil water content and depth of individual soil layers (Saarilahti 2002).

Soil freezing always means better bearing strength. Skidders working in winter conditions on frozen soil are more efficient and cause less damage to the soil. The vehicles load exerted on the soil results in soil thawing, but it depends on the duration of the exerted load. Short periods of soil load cannot cause thawing of the frozen soil layers.

Soil damage occurs when soil freezing only involves the superficial layers or when the soil temperature changes during the day causing thawing. In case when the superficial layers are not frozen, deeper frozen soil layers prevent the penetration of water into the depth and cause water saturation of superficial layers. At the same time, if there is a snow cover, snow is melted and the soil water content is increased. Such soil has a low bearing strength and serious soil damage occurs to the depth of the frozen soil layers. Therefore, in the thawing period restrictions should be determined in the production process in order to reduce or avoid higher soil damage (Saarilahti 2002).

The weight of the vehicle and load, type and size of tyres, air pressure in the tyres, travel speeds and number of passes are the factors affecting the degree of load on the soil and the degree of soil compaction, depending on soil characteristics.

The degree and depth of soil compaction are closely related to the number of skidder's passes. Most researches show that soil compaction is the highest during the first several passes, after which soil density acquires a certain value, which increases slowly in terms of quantity and depth with the following passes. By measuring soil compaction with penetrometer after multiple skidder passes Seixas et al. (2003) established that soil compaction after the fifth pass accounted for approximately 75 % of the total compaction measured after 20 passes.

It is not possible to avoid completely soil damage in timber skidding. However, such damage can be limited to an ecologically acceptable and economically tolerable level by the application of the most favourable technical and technological solutions and choice of the right time for carrying out these operations with respect to the soil bearing strength. The actions preceding the skidding operations, which can lower soil compaction, are proper designing of skid trails and foreseeing of the number of passes of a vehicle on the same road (Sever and Horvat 1990). For the growth of plants, the pass of an extremely loaded wheel is equally damaging as multiple pass with lower wheel load. Arnup (1998) took into consideration the above stated contradictory demands for higher efficiency and low range of soil damage in timber skidding. Forest tractors of low mass, due to their low load capacity, make a larger number of passes during their work and they repeatedly compact the soil, while heavy tractors make a lower number of passes, with higher load on the soil. When wood must be skidded even in unfavourable soil conditions, from the point of view of lower soil compaction, smaller loads should be skidded, trying to distribute the load evenly on the tractor axles.

Each ecosystem, as well as forest soil, has the capability of stabilization and adaptation. If there are self-regeneration forces in the ecosystem, as called by Hofle 1994, then natural soil regeneration occurs without human interference (Horvat 1995). Such forces also involve physical processes in the soil caused by wetting and drying (swelling and shrinking), and freezing and thawing, as well as by the impact of biological factors – forest soil fauna, impact of seedlings and root system growth (Vranković and Pernar 1993). The soil regeneration process implemented by wetting and drying differs depending on the soil type, and by freezing and thawing depending on the depth of impact of frost activity. Freezing and thawing are considered good for the formation of macropores in the soil. Freezing increases soil porosity, and decreases soil density due to water freezing in the soil into ice crystals. The formed macropores in the soil are unstable and they collapse during thawing, thus quickening the restoration of soil into its natural state.

Natural soil regeneration can be a long process, and it is primarily limited to a 15 cm depth, while the regeneration of deeper compacted soil layers is even slower (Hogervorst and Adams 1994). According to Vranković and Pernar (1993), the soil compacted in timber skidding has not shown any significant changes of characteristics, which implies regeneration after 18 months. Arnup (1998) considers that it takes 5 to 10 years for a well aired clay soil to regenerate after the operations of forest exploitation carried out by machinery. Based on the soil penetration characteristic, Horvat (1995) established natural regeneration only 10 years after timber forwarding.

3. Research methods – *Metode istraživanja*

Soil investigations involved digging of pedological profiles, soil sampling in disturbed and undisturbed (natural) conditions.

The analysis of the pedological profile showed the kind and type of soil and its horizons. Apart from establishing the kind and type of soil and depth extent of individual horizons, Kopecki cylinders were used for getting the information on soil density and porosity structure of each individual horizon.

Based on the sample mass, water and physical soil characteristics can be measured and calculated by laboratory analyses of disturbed soil sample, and granulometric soil content can be determined.

The purpose of soil sampling in its natural state is the determination of water and physical soil characteristics, based on the sample volume. Sampling of disturbed soil was carried out by use of Kopecki cylinders. During sampling, the cylinders were pressed parallel to the surface at a 15 cm depth. The degree of forest soil compaction caused by skidding was established by soil sampling on untreaded soil and skid trail soil depending on the number of skidder passes. After the skidder pass, several cylinders were taken out from the left and right skidder rut. In every cycle, several cylinders were also taken out from untreaded soil in order to establish daily changes of water and physical soil characteristics.

The analyses of soil samples were carried out in the Pedology Laboratory of the Institute for Forest Silviculture of the Faculty of Forestry, Zagreb University, in accordance with the Pedological Research Manual (Škorić 1982). Based on samples taken from undisturbed soil, the following water and physical characteristics were determined by laboratory analyses:

Momentary moisture content (θ_{V0}) – represents the difference in the mass between naturally wet soil (m_W) and soil dried at 105 °C until constant mass

(m_S), which is reduced to the sample volume – cylinder (V).

$$\theta_{V0} = [(m_W - m_S) / V)] \cdot 100, \text{ vol. } \%$$

Native bulk density (ρ_b) – it is determined by dividing the mass of dry soil with the volume of the soil in its natural condition, i.e. the soil from Kopecki cylinder is dried in the drying unit at 105 °C until constant mass. The ratio is established between the mass of dried soil (m_S) and the cylinder volume (V).

$$\rho_b = (m_S / V), \text{ g/cm}^3$$

Soil porosity (ϕ) – represents the sum of all cavities filled with water and air, and it is calculated by use of soil native bulk density (ρ_b) and solid density (ρ_p). Solid density is determined by dividing the mass of completely dry soil with the volume acquired by non-porous mass of solid soil particles, determined on the principle of liquid squeezed out by solid soil particles from a completely filled calibrated glass flask (picnometer). Based on the volume share of pores, Škorić (1991) classified soils into the following four classes: very porous (ϕ > 60 %), porous (46 % > ϕ > 60 %), poorly porous (30 % > ϕ > 45 %) and very poorly porous (ϕ < 30 %) soils.

$$\phi = [1 - (\rho_b / \rho_p)], \text{ vol. } \%$$

Soil water capacity (θ_{VS}) – represents the soil capacity to retain water by molecular adhesion, hydratation and capillary forces, and surface tension. The determination of the water capacity is carried out by putting Kopecki cylinder into a vessel on stand, covered with filter paper whose edges are dipped into water. In this way the soil sample in the cylinder absorbs water through filter paper. When the soil on the surface is covered with dew, it means that it is saturated with water until retention capacity. The cylinder is removed from the stand, and it is left on filter paper for 10 minutes so as to eliminate the superfluous moist, and then it is wiped and weighed. The cylinder is then placed into a drying unit and it is dried at 105 °C until constant mass. The soil water capacity is calculated by determining the difference between the wet soil mass until retention capacity ($\Delta m_W + m_W$) and the mass of dry soil (m_S) reduced to the cylinder volume (V). Based on water volume share in the soil, Škorić (1991) classified the soils with respect to water capacity into five classes: very low capacity (θ_{VS} < 25 %), low capacity (25 % < θ_{VS} < 35 %), medium capacity (35 % < θ_{VS} < 45 %), high capacity (45 % < θ_{VS} < 65 %) and y very high capacity (θ_{VS} > 60 %).

$$\theta_{VS} = [(\Delta m_W + m_W - m_S) / V] \cdot 100, \text{ vol. } \%$$

4. Research site – *Mjesto istraživanja*

Researches were carried out in »Dotršćina« Management Unit of the Educational and Experimental Forest Facility of the Faculty of Forestry, University Zagreb. The directions of two skid trails on which measurements were to be carried out were chosen in the subcompartment 11a. Skid trails are created by multiple skidder passes in timber skidding. At its first pass, the loaded skidder was to move on untreaded soil on marked direction of skid trails.

In choosing the direction of skid trails, we tried to satisfy two conditions:

- Longitudinal slopes of skid trails should be in the range of constructed strip roads and the existing skid trails in the mountainous region of Croatia so as to determine precisely the effects of timber skidding on soil damage under actual conditions of timber skidding.
- The direction of skid trails should be straight and have a uniform slope so as to eliminate frequent changes of inclination in order to achieve the necessary number of measurements under the same skidding conditions.

There is a very wide range of sizes of longitudinal slopes of skid trails, which can be controlled by the tractor, depending on moisture and precipitation conditions, type of tractor, use of chains on driving wheels, up-hill and down-hill skidding, tractor load and degree of soil erosion. For skidders, MacDonald (1999) established the limit value of down-hill slope of 35%, and Inoue and Tsuji (2003) established the limit value of down-hill slope of 45 % and up-hill slope of 30 %.

The slopes of the investigated skid trails are determined by the levelling method and the measuring data are processed by use of »CESTA« software application. The angle of the field slope is determined as the vertical profile of a specific field cross section, and it is quite common to express it as the slope percentage (100 tg α). The values of longitudinal slopes of skid trails are 15 % and 30 %.

5. Research results – *Rezultati istraživanja*

The research of soil compaction was carried out in timber skidding by Ecotrac 120 V. The skidder ECOTRAC 120 V is equipped with a hydraulic forest winch Hittner 2 x 80, of the nominal tractive force of 80 kN. The unloaded skidder mass is 7 257 kg (59 % at the front axle and 41 % at the rear axle). It is driven by a 6 cylinder diesel DEUTZ engine with the nominal power of 84 kW at 2300 min^{-1} and maximum torque of 400 Nm at 1500 min^{-1}. The tyre dimensions are 16.9–30, ply rating 14 PR, and the tyre air pressure during research was 2.5 bars.

By each pass, skidding was carried out both down the slope and up the slope. The load volumes were determined by measuring the length and mean diameter of each wood assortment. At the skid trail with a slope of 15 %, a total of 14.98 m^3 was skidded and 23.23 m^3 at the skid trail with a slope of 30 %, respectively (Table 1).

The degree of soil compaction is shown by changes of water-air soil characteristics of the forest skid trail after a certain number of passes of a loaded skidder, and comparison between these values and the values with the same characteristics of untreaded soil during the research.

The values of water-air soil characteristics are shown as mean values of the results obtained by laboratory analyses of soil samples of each individual skidder pass.

Within the research of soil damage in timber skidding on a skid trail with a slope of 15 %, soil measurements were carried out for two days. On the first day the soil characteristics were measured after the first and second pass. After a day break in the research due to snowing, measuring continued, and the measurements of soil characteristics were carried out after the third, fourth and sixth pass of the loaded skidder. The measurements on untreaded soil were performed under the snow cover and during these two days no changes of soil characteristics were recorded.

Measurements on a skid trail with a slope of 30 % were carried out during two consecutive days. The air and soil temperature were lower than in the previous days. The difference was observed of the characteristics of untreaded soil under the snow cover with respect to the research on a skid trail with a lower slope. On the first day, the measurements were carried out after the first, second, third and fourth pass of the loaded skidder, and on the second day after the sixth and tenth pass.

Table 1 Skidded wood by number of passes

Tablica 1. *Ukupno privučeno drvo po broju prolaza skidera*

Slope *Nagib*	Date of research *Datum istraživanja*	Number of passes *Broj prolaska*	Load volume *Obujam tovara* V m^3	Skidded wood *Privučeno drvo* Σ V m^3
15 %	2. 02.	1	2.37	2.37
		2	2.37	4.74
	4. 02.	3	3.61	8.35
		4	3.61	11.96
		5	1.51	13.47
		6	1.51	14.98
30 %	8. 02.	1	2.37	2.37
		2	3.61	5.98
		3	4.51	10.49
		4	1.51	12.00
	9. 02.	5	2.37	14.37
		6	2.78	17.15
		7	0.90	18.05
		8	2.16	20.21
		9	1.51	21.72
		10	1.51	23.23

5.1 Pedological characteristics of soil – *Pedološka svojstva tla*

A pedological profile was opened aimed at determining the basic pedological characteristics of the researched soil. The slope, on which the pedological profile was opened, has a north-east exposition and a 20 % inclination. Considering the terrain slope, the place for opening the profile was determined so that the terrain slope was between the measured longitudinal slopes of the chosen skid trail directions.

The soil horizons were determined on pedological profile with their sequence and range depth, and samples were taken of the soil by horizons with the aim of determining mechanical soil content, native bulk density, water capacity and total pore content.

Based on morphological soil characteristics and its physical analyses, the defined soil is distric cambisol. Table 2 presents the basic pedological characteristics for an open pedological profile.

5.2 Soil and air temperature – *Temperatura tla i zraka*

During the research, the changes of soil characteristics of skid trails, apart from dynamic load of skidders, were also affected by climate conditions. Winter research conditions were characterised by low air and soil temperatures and snow cover (Fig. 2 and 3). As far as the research of the effects of timber skidding on soil compaction in winter conditions is concerned, it is necessary to be well acquainted with the climate data during research, which affect the condition and characteristics of soil. Table 3 presents the data of air and soil temperatures during the days of research according to the climate month report of

Table 2 Pedological characteristics of soil on research site
Tablica 2. *Pedološka svojstva tla mjesta istraživanja*

Soil *Tlo*	Horizons *Horizonti*				Granulometric composition *Granulometrijski sastav*					Soil density *Gustoća tla*		Soil porosity *Porozitet tla*	
Type – *Tip*	Horizon mark *Oznaka horizonta*	Subhorizon mark *Oznaka pothorizonta*	Upper border *Gornja granica*	Lower border *Donja granica*	Coarse grained sand *Krupni pijesak* (2–0.2 mm)	Fine grained sand *Sitni pijesak* (0.2–0.02 mm)	Silt – *Prah* (0.02–0.002 mm)	Clay – *Glina* (< 0.002 mm)	Texture type *Teksturna oznaka*	Solid density *Gustoća čvrste faze*, ρ_p	Native bulk density *Prirodna gustoća*, ρ_b	Total porosity *Ukupni porozitet*, ϕ	Water capacity *Retencijski vodni kapacitet*, θ_{VS}
			cm		%					g/m^3		vol. %	
Distric cambisol *Distrični kambisol*	A	oh	0	3		-	-	-		2.54	1.03	59.62	48.10
	E/(B)		4	50–55	7.8	35.8	44.3	12.1	loam *ilovača*	2.64	1.27	51.89	35.80
	(B)	v	56	130–135	3.6	46.9	32.6	16.9	loam *ilovača*	it was impossible to take soil sample due to skeleton-like horizon *nije bilo moguće uzeti uzorak zbog skeleta*			
	C		136	165	4.1	74.3	10.9	10.7	sandy loam *pjeskovita ilovača*	2.59	1.72	33.75	25.30

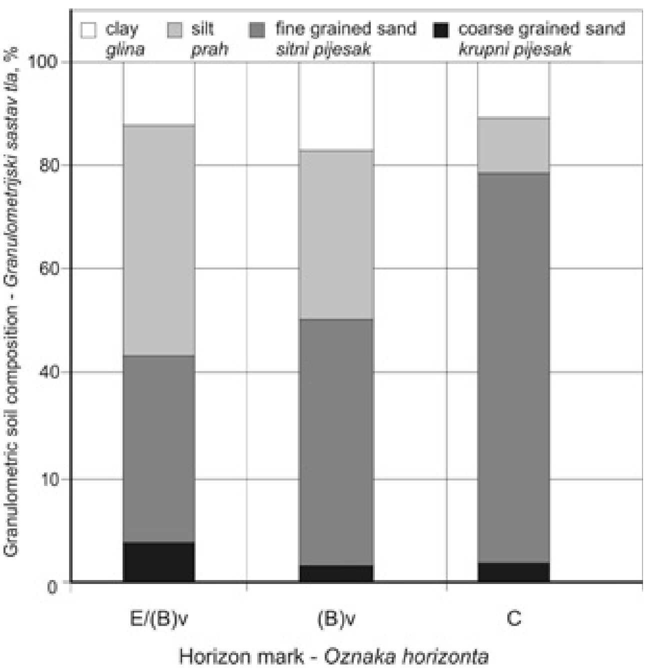

Figure 1 Granulometric composition of soil by horizons
Slika 1. *Granulometrijski sastav tla po horizontima*

Considering the granulometric content within a horizon of the researched soil, we can say that up to the depth of 135 cm the researched soil is loam, and deeper than 135 cm it is sandy loam. The fractions of fine sand and silt dominate in E/(B)v and (B)v horizons, while the fraction of fine sand dominates in horizon C (Fig. 1).

Based on physical parameters, it can be concluded that the soil is porous, with a medium water capacity to the depth of 50–55 cm in E/(B)v horizon. (B)v horizon is extremely skeleton-like and hence it was impossible to take soil samples in an undisturbed state.

the Meteorological and Hydrological Service of Croatia, Maksimir Station, which is situated near the research site. The values related to days when measurements were performed on untreaded soil and skid trail soil after timber skidding are more clearly expressed in the table.

All measurements on untreaded soil were carried out under the snow cover. In its first pass, the skidder travels on untreaded soil covered with snow. With each following pass, the snow thickness decreases as a result of wheel load, rut formation and skidding of one part of the load on the soil.

Table 3 Soil and air temperature and snow depth during research period

Tablica 3. *Temperatura zraka i tla te debljina snijega tijekom istraživanja*

Date *Datum*	Air temperature *Temperatura zraka*			Soil temperature – *Temperatura tla*									Snow depth *Debljina snijega*
February *veljača* 2005				Depth – *Dubina* – 5 cm			Depth – *Dubina* – 10 cm			Depth – *Dubina* – 20 cm			
	7 h	14 h	21 h	7 h	14 h	21 h	7 h	14 h	21 h	7 h	14 h	21 h	
	°C			°C									cm
2	**–6.2**	**3.1**	**1.6**	**–0.8**	**–0.4**	**–0.3**	**–0.4**	**–0.3**	**–0.3**	**0.4**	**0.4**	**0.4**	**6**
3	0.3	1.6	0.3	-0.3	0.1	-0.2	-0.3	-0.2	-0.2	0.4	0.3	0.3	11
4	**–0.8**	**2.5**	**–2.2**	**–0.2**	**0**	**–0.8**	**–0.2**	**–0.1**	**–0.4**	**0.4**	**0.6**	**0.2**	**10**
5	-5.9	-1.7	-7.2	-0.9	-0.2	-0.5	-0.4	-0.3	-0.2	0.1	0.3	0.4	9
6	-11.7	-2.5	-8.6	-1.2	-0.4	-0.7	-0.6	-0.4	-0.4	0.4	0.1	0.2	8
7	-13.4	-5.6	-10.8	-1.4	-1.0	-1.8	-0.7	-0.8	-0.9	0.1	0.3	0.2	8
8	**–14.7**	**–6.2**	**–11.8**	**–1.7**	**–1.4**	**–2.2**	**–1.0**	**–1.0**	**–1.6**	**–0.1**	**0.1**	**–0.6**	**8**
9	**–17.1**	**–5.4**	**–12.5**	**–3.2**	**–2.2**	**–2.7**	**–1.9**	**–1.5**	**–1.8**	**–0.5**	**0.1**	**–0.7**	**8**

Figure 2 Skid trail – slope 15 %

Slika 2. *Šumska vlaka nagiba 15 %*

Figure 3 Skid trail – slope 30 %

Slika 3. *Šumska vlaka nagiba 30 %*

The measurements were carried out on a skid trail with a slope of 15 % in the period February 2 to February 7. In this period, considerable changes were recorded of the climate data. On the first day the soil was frozen to the depth of 20 cm, and snow thickens was 6 cm. However, the air temperature above 0 °C caused thawing of the snow and the increase of soil moisture. On the second day, the measurements were postponed due to heavy snow. The wheel ruts, formed the first day after the skidder pass, were covered with new, fresh snow cover of 5 cm, while the snow cover on untreaded soil was 10 cm. After multiple passes of the skidder, the snow disappeared again from the skid trail surface.

Researches on skid trail with a steeper slope (30 %) were carried out on February 8 and 9, when the climate data remained unchanged. The air and soil temperatures were very low and stayed low (maximum air temperature was –5.4 °C and soil temperature –1.4 °C).

5.3 Momentary moisture content – *Trenutna vlažnost*

Momentary moisture content represents the share of water in the soil at the moment of sampling. The changes of momentary soil moisture content, depending on the number of a loaded skidder passes, are shown in Figure 4 and 5. The measure-

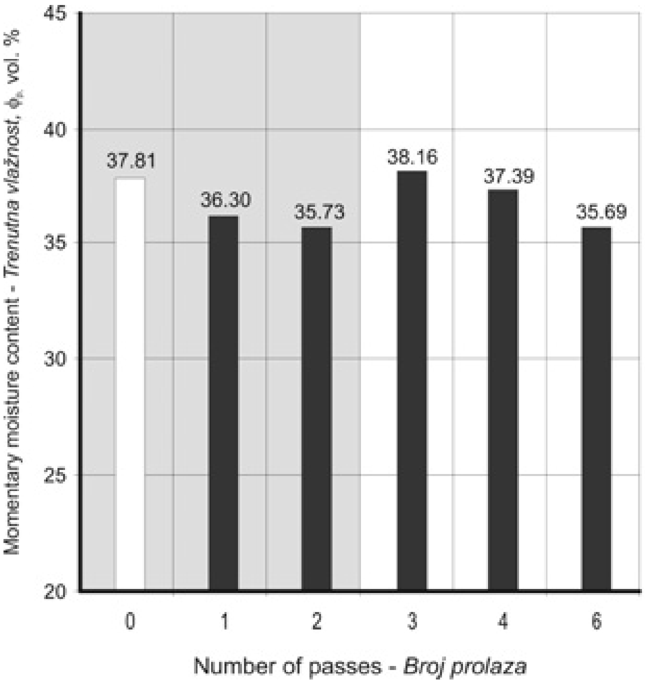

Figure 4 Changes of momentary soil moisture content according to number of skidder passes on skid trail with a slope of 15 %

Slika 4. *Promjena trenutne vlažnosti tla po broju prolaza opterećenoga skidera na vlaci nagiba 15 %*

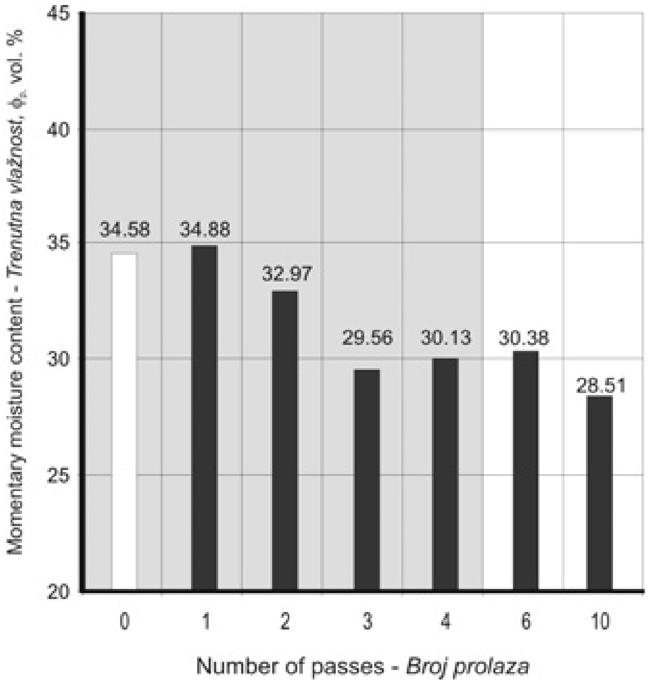

Figure 5 Changes of momentary soil moisture content according to number of skidder passes on skid trail with a slope of 30 %

Slika 5. *Promjena trenutne vlažnosti tla po broju prolaza opterećenoga skidera na vlaci nagiba 30 %*

ments on untreaded soil under the snow cover were carried out under the snow cover along the same skid trail with the same terrain slope.

The highest value of the momentary moisture content was recorded on untreaded soil with terrain slope of 15 %. A slightly lower value of the momentary moisture content with a slope of 30 % can be explained by higher soil drainability. On the first day during skidder passes on the skid trail with a slope of 15 % the momentary soil moisture content decreased. On the second day, higher momentary moisture content was recorded in wheel ruts, which can be explained by thawing of the new layer of snow on the surface of the skid trail due to air temperature higher than 0 °C. The passes that followed caused the decrease of the momentary moisture content.

The values of the momentary moisture content were not changed after the first skidder pass on a 30% slope skid trail compared to untreaded soil. By the second and third skidder pass, the soil was compacted and water was squeezed out from the soil macropores. The fourth pass of a less loaded skidder had no impact on further soil compaction.

5.4 Native soil bulk density – *Prirodna gustoća tla*

Native soil bulk density (ρ_b, g/cm^3) is a parameter that shows how »complex« the solid phase is, i.e. how many times a certain soil volume is heavier (or lighter) than the same volume of water. The values of the native soil bulk density depend on mineral content of the original substrate on which the soil was developed, quantity of humus, as well as on the quantity of pores, which is related with the soil structure. In superficial horizons, the native soil bulk density ranges between 1.0 to 1.6 g/cm^3, and as with the increase of depth the humus content is rapidly lowered, the soil becomes more compact and the values in the compact soil layer reach up to 2 g/cm^3 (Škorić 1991).

The research of the values of native bulk density performed on soil samples taken from the depth of 15 cm ranged between 1.3 and 1.6 g/cm^3. Approximately the same values of the native bulk density (1.34 and 1.38 g/cm^3) were recorded in testing the samples of untreaded soil taken along both skid trails. Also, after the first pass of the skidder on both skid trails, native bulk density increased to equal values (1.43 and 1.41 g/cm^3).

A considerably higher native soil bulk density was recorded in the wheel rut on a skid trail with a slope of 15%, which implies higher soil compaction (Figure 6). The reason of higher soil compaction lies in the increase of air and soil temperature, which caused thawing of the soil and collapse of macropores due to wheel load. The research on this skid

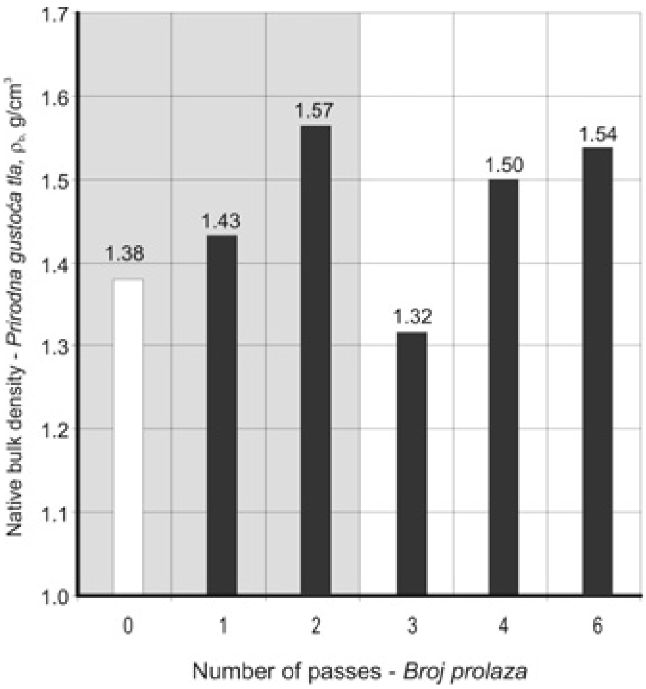

Figure 6 Changes of soil bulk density according to number of skidder passes on skid trail with a slope of 15 %

Slika 6. *Promjena prirodne gustoće tla po broju prolaza opterećenoga skidera na vlaci nagiba 15 %*

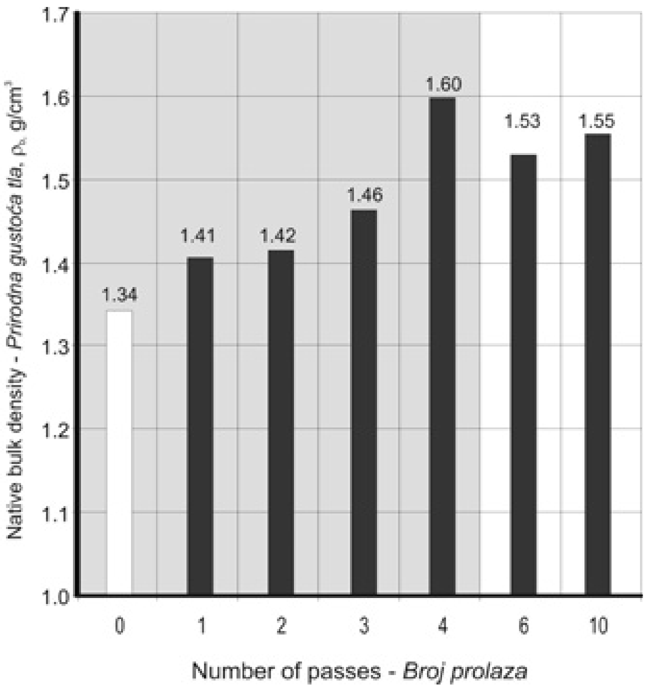

Figure 7 Changes of soil bulk density according to number of skidder passes on skid trail with a slope of 30 %

Slika 7. *Promjena prirodne gustoće tla po broju prolaza opterećenoga skidera na vlaci nagiba 30 %*

trail continued two days later. The decrease of the native soil bulk density was observed due to soil freezing and thawing. The following passes of the skidder caused increased native soil bulk density, i.e. increased soil compaction.

The first day of research on a forest skid trail with a slope of 30 %, the native soil bulk density increased slightly after the first three passes (from 1.41 to 1.46 g/cm^3), and higher soil compaction was recorded after the fourth pass of the skidder with the load volume of 4.50 m^3 travelling down the slope (Figure 7). Due to low air temperatures and disappearance of snow from wheel ruts, the soil of wheel ruts in timber skidding showed higher freezing than the untreaded soil. The soil bulk density after the sixth traction test was 1.53 g/cm^3 i.e. it had a lower value than the last measurement the day before.

Further to the above, it can be concluded that the passes of a loaded skidder during the day affected the degree of soil compaction. Soil compaction is higher if the soil is not frozen. The soil has a great regeneration power under the influence of the processes of freezing and thawing.

5.5 Soil porosity – *Poroznost tla*

Between the particles of the soil solid phase i.e. mechanical elements and structural aggregates, there are cavities called soil pores. The contact between individual particles and aggregates is not complete. Therefore, the characteristics of soil pores depend on mechanical soil content and the way of aggregation of individual particles in structural aggregates, as well as on the quantity of very porous organic matter. Porosity (ϕ, vol. %) is a very significant feature of the soil, as pores are partly filled with water and partly with air. Consequently, the soil porosity determines water-air relationship in the soil.

Skidder travel causes forest soil compaction and in doing so the structural aggregates are broken into small pieces, the inter-aggregate space decreases, as well as the volume of pores and soil volume. The sequence of pores decrease was observed during multiple passes of a skidder in one day (Fig. 8 and 9). Soil freezing during night causes the increase of soil porosity due to the transformation of the soil water into ice crystals.

5.6 Soil water capacity – *Retencijski kapacitet tla za vodu*

Maximum soil water capacity corresponds to the quantity of water which can be absorbed by the soil. In this case all soil pores (micro and macro) are filled with water, i.e. the soil water capacity is equal to porosity, and air soil capacity is zero. In the dynamics of soil water flows, this state is very short, because when the infiltration stops (except in cases when

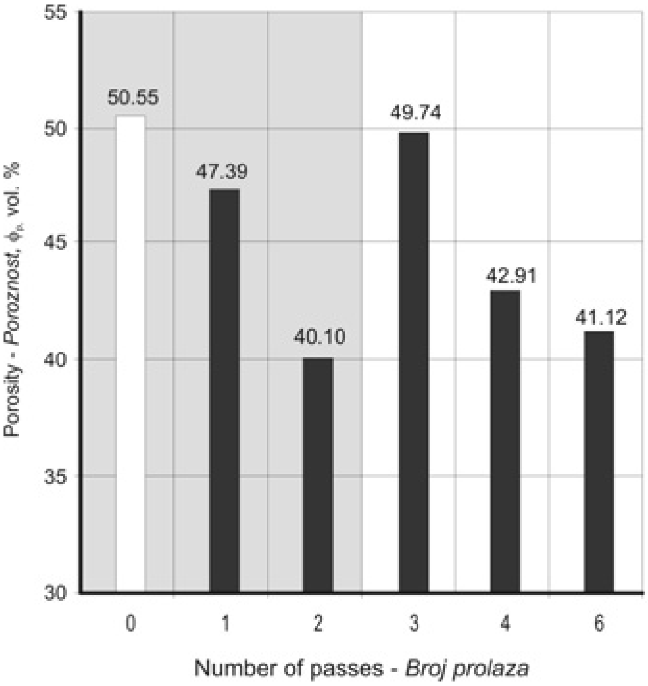

Figure 8 Changes of soil porosity according to number of skidder passes on skid trail with a slope of 15 %

Slika 8. *Promjena poroznosti tla po broju prolaza opterećenoga skidera na vlaci nagiba 15 %*

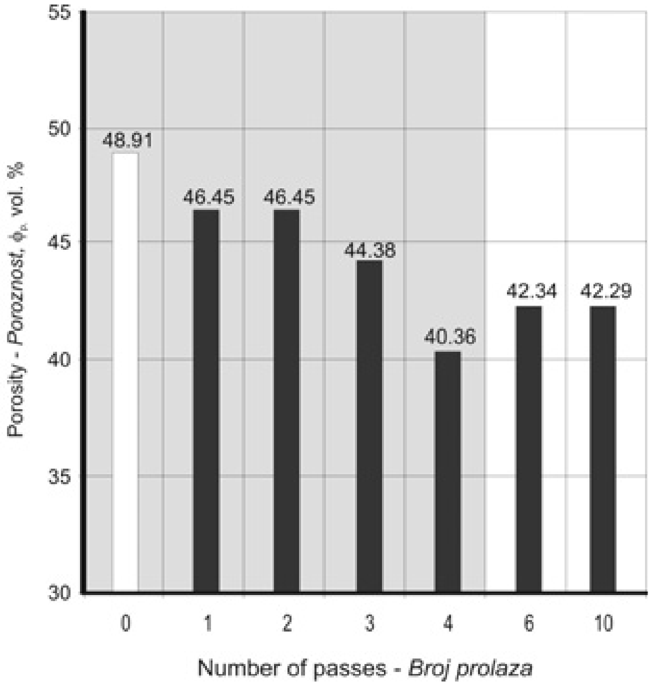

Figure 9 Changes of soil porosity according to number of skidder passes on skid trail with a slope of 30 %

Slika 9. *Promjena poroznosti tla po broju prolaza opterećenoga skidera na vlaci nagiba 30 %*

flood waters appear in the forest), water is redistributed into deeper soil layers.

Due to the above reason, soil water capacity (θ_{VS}, vol. %) is a better indicator, as it represents the quantity of water that can be absorbed by the soil in a part of its pores (water capillaries) and around its solid particles, i.e. water which is not drained. In this case all soil micropores are filled with water, and macropores with air.

The measurements performed during the same day showed a decrease of the soil water capacity due to multiple passes of a skidder (Figure 10 and 11). During the day, soil compaction did not cause squeezing out of water from the soil micropores, and hence its freezing resulted in the enlargement of micropores volume and increase of soil water capacity.

The research on the skid trail with a slope of 15 % was not carried out in two consequtive days as on the skid trail with a slope of 30 %. A day of break in the research affected the dual process of soil freezing and thawing and caused a higher change of the value of the soil water capacity on the skid trail with a slope of 15 %. The soil water capacity was 36.03 % after the second pass and 43.26 % after the third pass (or after the first pass on the second day of research).

6. Conclusions – *Zaključci*

The research of soil compaction in timber skidding was carried out on two skid trails with uniform slope of 15 % and 30 %. The selection of skid trails was based on the actual work conditions of skidders in the Croatian forestry. The directions of skidder's travel were determined before the research and skid trails were formed by multiple passes. The research was carried out in winter conditions at low air and soil temperatures and with the research site covered with snow.

The degree of soil compaction is shown by changes of water-air soil characteristics of the skid trail after a certain number of passes of a loaded skidder and comparison between these values and the same characteristics of untreaded soil during the research.

Based on the results of research the following conclusions can be drawn:

When the research of soil damage caused by timber skidding is performed in winter conditions, it is necessary to measure the air and soil temperatures due to their impact on the soil state and characteristics.

Multiple passes of a loaded skidder affect the degree of soil compaction. Soil compaction causes the decrease of momentary moisture, porosity and water capacity of the soil, and the increase of native

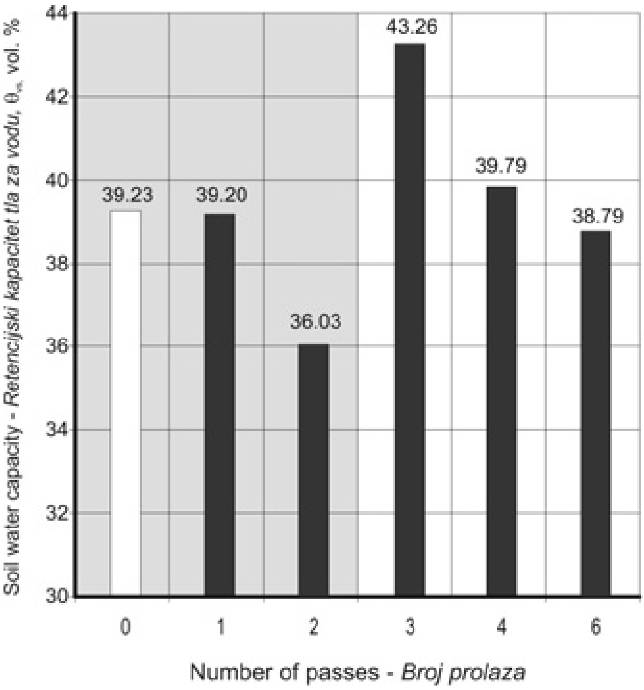

Figure 10 Changes of soil water capacity according to number of skidder passes on skid trail with a slope of 15 %

Slika 10. *Promjena retencijskoga kapaciteta tla po broju prolaza opterećenoga skidera na vlaci nagiba 15 %*

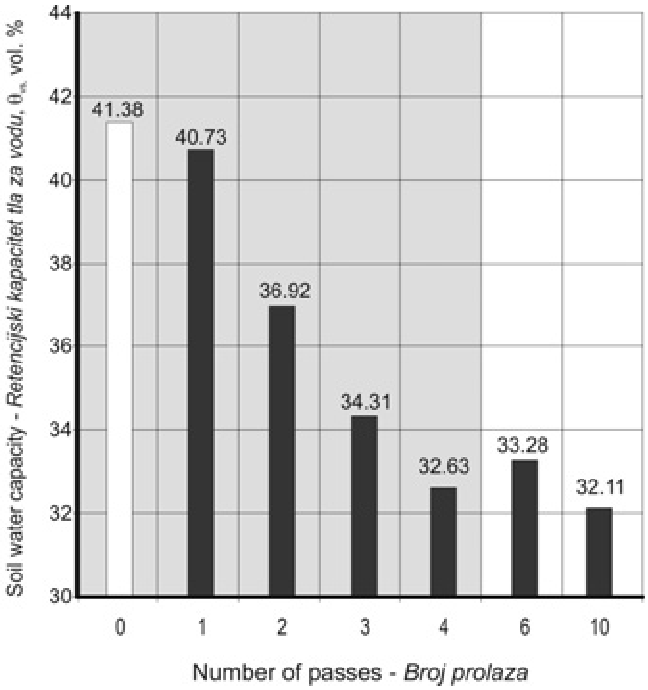

Figure 11 Changes of soil water capacity according to number of skidder passes on skid trail with a slope of 30 %

Slika 11. *Promjena retencijskoga kapaciteta tla po broju prolaza opterećenoga skidera na vlaci nagiba 30 %*

bulk density and shear strength of the soil. Soil compaction is greater if the soil is not frozen.

Due to low air temperatures and disappearance of snow from wheel ruts in timber skidding, the soil of wheel ruts is frozen more quickly during the night than the untreaded soil.

Water is not squeezed out from the soil micropores by soil compaction during the day, and its freezing enlarges the micropores volume, thus increasing soil porosity and water capacity, and decreasing the native bulk density.

Further researches of soil compaction in timber skidding under different conditions could show the most favourable time for performing some work operations in terms of limiting soil damage and achieving higher skidder efficiency.

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Sažetak

Zbijanje tla pri privlačenju drva u zimskim uvjetima

U prigorskim i brdskim predjelima Hrvatske za privlačenje se drva upotrebljavaju u prvom redu kotačni skideri opremljeni šumskim vitlom. Šumsko tlo, po kojem se drvo privlači, bitno utječe na mogućnost kretanja vozila. U pravilu se skideri kreću po izrađenim i obilježenim traktorskim vlakama, ne silazeći u sastojinu. Na taj se način smanjuje gaženje tla i oštećivanje stabala. Kretanjem skidera po traktorskim vlakama oštećuje se šumsko tlo. Oštećenja na šumskom tlu pri prolazu vozila mogu se podijeliti u tri sastavnice: zbijanje tla, nastanak kolotraga i premještanje tla. Zbijanje tla je obujamna deformacija tla (Gameda i dr. 1987) i povećanje gustoće tla kao rezultat približavanja čestica tla zbog djelovanja vanjske sile (Arnup 1998). Veličina nastalih oštećivanja ovisit će o masi vozila i tovara te o svojstvima šumskoga tla.

U odsjeku 11a gospodarske jedinice »Dotršćina« Nastavno-pokusnoga šumskoga objekta Šumarskoga fakulteta Sveučilišta u Zagrebu odabrani su pravci dviju traktorskih vlaka. Nagibi ispitivanih traktorskih vlaka određeni su metodom niveliranja. Uzdužni nagibi traktorskih vlaka imaju vrijednosti 15 % i 30 %.

Veličina je zbijanja tla prikazana promjenama vodno-zračnih svojstava tla šumske vlake nakon određenoga broja prolazaka skidera s tovarom te usporedbom vrijednosti s istim svojstvima neizgaženoga tla u vrijeme trajanja istraživanja. Radi utvrđivanja osnovnih pedoloških svojstava tla mjesta istraživanja otvoren je pedološki profil.

Zbijanje tla istraživano je pri privlačenju drva skiderom Ecotrac 120 V u zimskim uvjetima pri niskim temperaturama zraka i tla te snježnim pokrivačem na mjestu istraživanja. Pri prvom prolasku opterećeni se skider kretao neizgaženim tlom po označenom smjeru traktorskih vlaka.

Uzimanjem uzoraka tla (valjci Kopeckoga) na neizgaženom tlu i tlu na vlakama, ovisno o broju prolazaka skidera, utvrdila se razina zbijenosti šumskoga tla zbog privlačenja drva. Nakon prolaska skidera vađeno je nekoliko valjaka iz lijevoga i desnoga kolotraga skidera na dubini tla od 15 cm. Analize uzoraka tla provedene su u Pedološkom laboratoriju Zavoda za uzgajanje šuma Šumarskoga fakulteta Sveučilišta u Zagrebu. Iz uzoraka tla u nenarušenom stanju laboratorijskim su analizama utvrđena ova vodno-fizička svojstava: trenutna vlaga tla, prirodna gustoća tla, poroznost tla, retencijski kapacitet tla za vodu. Vrijednosti su vodno-zračnih svojstava tla prikazane kao srednje vrijednosti rezultata dobivenih laboratorijskim analizama uzoraka tla po pojedinom prolasku skidera.

Višekratnim prolascima skidera s tovarom utječe se na veličinu zbijanja tla. Zbijanjem tla smanjuje se trenutna vlaga, poroznost i retencijski kapacitet tla, a povećava prirodna gustoća tla. Zbijanje je tla veće ako tlo nije smrznuto.

U zimskim uvjetima ispitivanja posljedičnosti privlačenja drva na oštećenja tla potrebno je mjeriti temperature zraka i tla zbog njihova utjecaja na stanje i svojstva tla. Zbog niskih temperatura zraka i nestanka snijega iz kolotraga pri privlačenju tlo se kolotraga više smrzava tijekom noći u odnosu na neizgaženo tlo.

Zbijanjem tla tijekom dana nije istisnuta voda iz mikropora tla te se njezinim smrzavanjem širi obujam mikropora i povećava poroznost i retencijski kapacitet tla za vodu, a smanjuje prirodna gustoća.

Daljnjim istraživanjima zbijanja tla pri privlačenju drva skiderima pri različitim uvjetima moguće je odrediti najpovoljnije vrijeme izvođenja radova u smislu ograničavanja oštećenja tla i ostvarivanja veće učinkovitosti skidera.

Ključne riječi: *zbijanje tla, višekratni prolasci, šumska vlaka, privlačenje drva, vodno-zračna svojstva tla*

Authors address – Adresa autora:

Assoc. Prof. Dubravko Horvat, Ph.D.
Marijan Šušnjar, Ph.D.
Forestry faculty of University of Zagreb
Svetošimunska 25
HR-10 000 Zagreb
CROATIA
E-mail: horvat@sumfak.hr
E-mail: susnjar@sumfak.hr

Josip Šešelj, BSc.
Jadranska 3
HR-20 355 Opuzen
CROATIA
E-mail: seselj@sumfak.hr

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