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Soil Compaction – Impact of Harvesters' and Forwarders' Passages on Plant Growth

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1. Introduction

The goal of forestry management is to sustain continual development of forest ecosystems that optimally fulfil their productive and non-productive functions. In order to achieve this goal, the full productive capacity of forest stands needs to be maintained while respecting all the natural processes in the soil, including microbiological organisms, physical properties, nutrient reserves and regeneration processes of the ecosystem.

We need to approach herbs as well as woods holistically, including the root system architecture and functions. Growth of the above-ground system depends on the state of the root system functions, and vice versa. If the conditions for an activity of the root system are limited, the functioning of the above-ground system will be limited too.

During thinning activities in all age groups of forest stands and during the subsequent recovery, progressive harvesting technologies that use mobile means of mechanisation (predominantly harvesters and forwarders) are applied more and more commonly. In contrast to the motomanual technologies that were used in the past, harvesters and forwarders are considerably safer and more productive. However, the passage of heavy machinery on the soil surface causes disruption of the soil environment and mechanical damage to roots. In 1947, it was found that harvesting disrupted soil by modifying its structure and moisture characteristics (Munns, 1947). Despite more than sixty years of research, we still do not fully understand the impact of soil compaction on forest productivity. Due to the global interest in maintaining forest resources and the sustainable development of forest production, a number of conferences have been organised, including the Earth Summit in 1992, which gave rise to the Montreal Process (Burger & Kelting, 1998). At this summit, soil compaction was defined as one of the soil indicators of the forest health state.

Soil compaction is affected by both endogenous and exogenous soil factors. Horn (1988) defined the following endogenous factors as responsible for soil compaction: distribution and size of soil elements, type of clay mineral, type and amount of absorbed cations, content of organic matter, soil structure, soil stabilisation, topsoil material, bulk density of soil, pore continuity and water content. Exogenous factors include the duration, intensity and means of wood harvesting and wood loading. For instance, different machines, or even the same machines with different tyres, differ in their loading and pressure on the soil. Work by Greacen & Sands (1980) and Ole-Meiludie & Njau (1989) support the finding that the compaction rate depends on the concrete soil characteristics, pressure and vibrations of the machines. The rate of soil erosion varies depending on the loading technology and intensity of harvesting. Generally, soil is disrupted by harvest cutting more than it is by selective logging or thinning (Reisinger et al., 1988). The high number of variables leading to soil compaction makes it difficult to find a single parameter that best defines the impact of the passage of a harvester or a forwarder.

2. Harvester and forwarder machinery

Most of the machines currently in use today are heavy and wheeled. The interaction of the wheels with the soil surface in a stand during harvesting and forwarding activities puts pressure on the soil, the intensity of which depends on tyre inflation, toughness and adhesive loading of the traction mechanism. Brais (2001) identified soil compaction by the passage of forestry machines as one of the main factors in soil degradation. Soil compaction during harvesting usually changes the soil structure and moisture conditions by disruption of soil aggregates, decreased porosity, aeration and infiltration capacity, and increased soil bulk density, soil resistance, water interflow, erosion and paludification (Kozlowski, 1999; Grigal, 2000; Holshouser, 2001). Soil compaction may become even more problematic as the weight of harvesters and forwarders increases (Langmaack et al., 2002).

A harvester is a mobile, multi-operational machine that can fell timber, cut branches and chop trunks into assorted lengths in a single cycle (Fig. 1). Individual cut-outs remain in the stand in piles and heaps. The entire process is fully mechanised and automated. Harvesters are classified into four groups based on the kind of undercarriage (wheeled, tracked, walking and combined harvesters). The undercarriage of multi-operational machines has two sections linked by an articulated joint. A forwarder collects the logs made by a harvester and loads them onto a load section of a tractor and forwards them to a storage area (Fig. 2). The main loading function is carried out by a hydraulic crane that reaches 6-10 m with a rotator and a grab.

Fig. 1. Harvester John Deere 1270E with a rotating cab

Fig. 2. Forwarder John Deere 810 D at the platform balance

Forest managers have to concern the total weight of forwarders for particular applications and also the maximal load of tyres has to be observed. Prescribed values for allowable load of tyres according the German Forestry Council (KWF) are given in Table 1. The maximum allowable load of tyres should be up to 4.9 tunes with optimal load up to 4.0 tunes.

Max. weight of forwarder in tunes	Total weight of forwarder (with load) in tunes	Ratio of load on loading part	load of tyre in tunes
8	20	65%	3.2
12	26	65%	4.2
14	30	65%	4.9
16	38	65%	6.2

Table 1. Values for allowable load of forwarder tyres according the German Forestry Council (KWF).

3. Impact of the passage of harvesters and forwarders on soil

The soil compaction that occurs as a consequence of the passage of harvesters and forwarders is connected with significant changes to the soil structure and moisture conditions (Standish et al., 1988; Neruda et al., 2008). Increased bulk density of soil, decreased porosity, decreased water infiltration, increased erosion and changes in plant physiology can all arise from soil compaction. Other changes include the disruption of soil aggregates and loss of pore continuity (Kozlowski, 1999).

3.1 Soil bulk density

Higher soil bulk density is caused by lower porosity and lower water capacity, and it can inhibit root growth (Gebauer & Martinková, 2005). Soil compaction usually occurs in the 30 cm surface layer of soil, which contains the majority of the root biomass (Sands & Bowen, 1978; Kozlowski, 1999) (Fig. 3). The bulk density of soil in the upper layers (0-8 cm) increases by 41-52% after the passage of tractors (Kozlowski, 1999). In the case of a forwarding line, the bulk density of soil in the surface layers (0-10 cm) rose by 15-60% and, in the case of a crossing line, it increased by 25-88% (Lousier, 1990). The compaction decreased in deeper layers; nonetheless, it was recorded even at depths of 30 cm and more. The highest rate of compaction occurred during the first several passages of tractors (Lousier, 1990). The following passages had less effect, but could still lead to rates of compaction that might significantly affect root growth. The critical value of soil bulk density ranges from 1200 to 1400 kg m^{-3}. When this value is exceeded, root growth is reduced in most soil types (Lousier, 1990).

Fig. 3. Superficial root system of a Norway spruce tree showing the majority of the roots growing in the upper soil layer

3.2 Soil porosity

Soil compaction changes the porosity by reducing macroscopic spaces and raising the number of microscopic spaces. The change in porosity affects the balance of soil air and water in pores, which is critical for plant growth. Soil air is a gaseous compound that exists in pores that are not filled with water. Compared with atmospheric air, it includes less oxygen and more CO_2 (ranging from 0.5 – 5% or even higher) (Hillel, 1998). The higher CO_2 content in the soil arises from root respiration and the aerobic decomposition of organic matter. Grable & Siemer (1968) defined the critical value of aeration for plant growth as 10% porosity. Soils with a high content of CO_2 and a low content of oxygen are poorly aerated, and there may even be anaerobic conditions within such soil (Hillel, 1998). A concentration of CO_2 in the soil higher than 0.6 % indicates significant changes to the soil structure that can impact root growth (Güldner, 2002). Our measurements show that this critical value was significantly exceeded in almost all cases after the passage of harvesters and forwarders, and in some cases, the value was exceeded by severalfold (e.g., 1.2% and 3.4% CO_2 in a harvester track as opposed to 0.4 % and 0.5% CO_2 on the surface unaffected by harvesters) (Fig. 4).

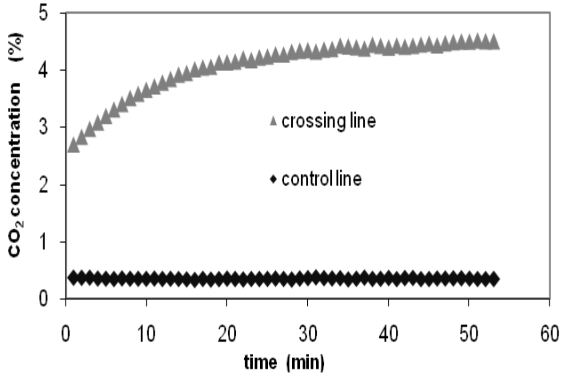

Fig. 4. Upper panel - Concentration of CO_2 in soil air in a crossing line after several harvester passages (soil moisture: 35%). Lower panel – CO_2 measurement in control line with GMP 221 Carbon dioxide probe (Vaisala, Finland)

3.3 Water infiltration and erosion

Soil compaction is often related to the creation of crust, causing decreased water infiltration and ultimately increasing water runoff (Malmer & Grip, 1990). In the places where water runoff is not possible (e.g., holes after passage, terrain depressions), there is weak drainage, which causes local inundation (Jim, 1993) (Fig. 5). Experiments have shown that harvesters and forwarders can accelerate the rate of surface erosion from 2 to 15 times, compared with unpassaged soil and 85% of the total surface erosion appears in the first year after disruption (Lousier, 1990).

We should consider the soil capability i.e. the ability of soil to cope with external forces, which can cause permanent or temporal deformation, when heavy machines are moving in the forest. The rut depth from 15 - 50 cm (according the soil humidity) brings high ecological risk (Fig. 6). The soil capability of different soil types is given in Table 2.

Fig. 5. A case of unsuitable preparation of a site with disruption of soil aggregates. If an Eco-Baltic wheeled track had been used, the lines would not have been cut to a depth of 50 cm and deeper along the way.

Fig. 6. A case of rut depth up to 25 cm, which is a point when an ecological risk may appear.

3.4 Plant physiology

3.4.1 Disorders in photosynthesis and water regime

Heavy compaction leads to a variety of physiological disorders in plants. Roots react to soil compaction by increasing demand for photosynthates (Zaerr & Lavender, 1974), which are needed to support the metabolism required to overcome the increased soil resistance to elongation growth. The physiological cost of recovering the functions of fine roots may be as high as 70% of the accessible carbon flow (Ågren et al., 1980; Vogt et al., 1996). Kozlowski (1999) found that the increased carbon flow due to soil compaction leads to an overall decrease in photosynthesis. This is a result of reduced foliage surface, which is an outcome of reduced water intake caused by changes in the soil structure and moisture conditions (Arvidsson & Jokela, 1995). Therefore, a plant might not have enough energy to reconstruct its root system, and the growth of roots as well as the above-ground parts stagnate or even die. Reduced foliage surface is a reaction to a water deficit in the leaves, which is brought about by soil compaction and may lead to the closing of pores and further loss of photosynthesis (Masle & Passioura, 1987).

degree of resistance	soil capability	rut depth, soil consistence	soil taxonomy
1	extremely low dry: 30 -50 kPa wet: 5-12 kPa	≥ 35 cm, incohesive, strongly crumble, slush	Histosols, Gleysols
2	very low dry: 50-140 kPa wet: 12-22 kPa	25-35 cm crumbly, clay, loam, very soft	Stagnosols, gleyic Stagnosols
3	reduce dry: 140 - 300 kPa wet: 18-50 kPa	15-25 cm hardly dig, loam, sandy clay, soft	Cambisols, Luvisols, Fluvisols - subtype - gleyic
4	slightly reduce dry: 300-600 kPa wet: 50-80 kPa	7-15 cm hardly dig, solid, sandy loam	dry and slightly wet Cambisols, Luvisols, Regosols, Chernozems
5	bearable dry: > 600 kPa wet: 80-120 kPa	< 7 cm solid, hard, stony	Podzols, Leptosols

Table 2. Soil capability measured as a rut depth after one passage of the special forest tractor (LKT 80) with inflation of tyres 200 kPa. Dry and wet means humidity of sandy and loam-sandy soil 4-8 % and 18-30%; sandy-loam and loam soil 8-15% and 35-45%; clay-loam and clay soil 15-25% and 45-55%, respectively.

3.4.2 Disorders in nutrient uptake

Often, extreme soil compaction leads to reduced absorption of mineral nutrients by the roots, especially nitrogen, phosphorus and potassium. Nutrient uptake is reduced as a result of the loss of minerals from soil, reduction of root access to nutrients and decreased root capacity for nutrient intake (Kang & Lal, 1981; Kozlowski & Pallardy, 1997). A reduction of nutrient uptake caused by soil compaction in the upper as well as deeper soil layers (Kozlowski, 1999) might be the reason for different reactions to the compaction among species, as some have higher nutrient demands than others.

3.4.3 Effects on mycorrhizas and plant hormones

Soil compaction also affects the structure, development and function of mycorrhizas (Entry et al., 2002) and causes changes in the levels of stress hormones in plants, mainly abscisic acid and ethylene (Kozlowski, 1999).

3.4.4 Respiration disorders

Soil compaction induces hypoxia, which is related to the reduction of aerobic micro-organism activity and an increase of denitrification. As compaction increases, reduction of macro-pores enhances the development of anaerobic spaces (Torbert & Wood, 1992). Insufficient aeration of compacted soils leads to anaerobic respiration in roots and insufficient energy for maintaining the basic root functions, namely nutrient uptake (Kozlowski & Pallardy, 1997).

4. Impact of compaction on plant growth

Several studies have shown that tree growth and wood production decrease with increasing compaction (Froehlich, 1976; Cochran & Brock, 1985). Growth inhibition as well as the death of woody plants caused by soil compaction has been documented in zones of recreation, harvesting areas (Sand & Bowen, 1978; Cochran & Brock, 1985), agro forestry (Wairiu et al., 1993) and tree nurseries (Boyer & South, 1988).

Soil compaction strongly reduces plant growth as it limits root growth (Rosolem et al., 2002; Gebauer & Martinková, 2005). There is a non-linear relationship between root elongation and soil resistance in the majority of plants (Misra & Gibbons, 1996). Because compaction usually occurs in the upper soil levels, species with a surface root system are disadvantaged (Godefroid & Koedam, 2003). Generally in the case of large trees, root growth is limited by increasing soil bulk density and excessive soil resistance (typical in dry and skeletal soils) or insufficient aeration if the soil is heavily saturated by water (Greacen & Sands, 1980). The greater the root growth reduction and the smaller the soil space occupied by roots, the slower the growth of a tree in its above-ground parts (Halverson & Zisa, 1982; Tuttle et al., 1988).

The exposure of roots to mechanical pressure induces a number of physiological changes that have been well described on the macroscopic level. For example, the elongation growth decreases, and the response period varies from several minutes (Sarquis et al., 1991; Bengough & MacKenzie, 1994) to many hours (Eavis, 1967; Croser et al., 1999). The root tip generally rounds, becoming concave, the root width behind the meristem increases and the root meristem and the elongation zone shorten (Eavis, 1967; Croser et al., 2000). The data on root thickening behind the root tip demonstrate the effects of long-term mechanical pressure on the root tips (Abdalla et al., 1969; Martinková & Gebauer, 2005). The growth of roots is reported to be a more sensitive indicator of soil disruption than the growth of the above-ground parts (Singer, 1981; Heilman, 1981) because the reduction of root growth precedes the phase when the extreme soil resistance is achieved (Eavis, 1967; Russell, 1977; Simons & Pope, 1987).

The critical value of soil resistance that can lead to significant physiological changes is measured by penetrometers (Atwell, 1993; Greacen & Sands, 1980) (Fig. 7), which better express conditions of root growth as penetrometers also measure the influence of bulk density and soil moisture (Siegel-Issem, 2002). Heavy, humid soils are more easily penetrated by roots due to lower soil resistance, while in arid soils of the same density, the growing resistance limits root growth. Critical values of compaction, expressed by penetrometric soil resistance, for different kinds of soil are listed in Table 3. It has been determined that a soil resistance of 2.0 MPa or more causes root shortening in most plant species (Atwell, 1993). The critical soil resistance on compacted sands limiting root growth measured for *Pinus radiata* was 3.0 MPa (Sands et al., 1979). However, roots usually have a lower resistance to soil penetration than the resistance measured by penetrometers, due to the radial expansion and smaller diameter of roots and the ability to curl and minimise friction by means of polysaccharide slime.

Only a few studies, mainly using herbs, have measured the soil resistance against roots directly in soil (Eavis, 1967; Misra et al., 1986; Bengough & Mullins, 1991; Clark & Barraclough, 1999). Roots were found to be capable of exert the outer pressure from 0.9 to 1.3 MPa (Gill & Miller, 1956; Barley, 1962; Taylor & Ratliff, 1969). Eavis (1967) demonstrated that elongation of roots in peas was reduced by 50% at a pressure of 0.3 MPa. Our measurements show that soil compaction causes reduced root elongation growth in Norway spruce by 50% compared with control seedlings (Gebauer & Martinková, 2005) (Fig. 8). In the case of one-year-old buds of Scotch Pine (*Pinus sylvestris*), the soil compaction did not have a significant impact, but for Macedonian Pine (*Pinus peuce*) of the same age, the root growth was negatively affected by soil compaction (Mickovski & Ennos, 2002; 2003). The authors of this study reasoned that the weak impact on *Pinus sylvestris* was due to the fact that its roots have thinner diameters than those of *Pinus peuce*.

Fig. 7. Measurement of soil resistance by penetrometer

Soil type	**penetrometric soil resistance (MPa)**
Sandy loam and sand	more than 4
Sandy clay	4 – 3.7
Silt	3.7 – 3.5
Silty clay	3.5 – 3.2
Clay	less than 3.2

Table 3. Critical values of penetrometric resistance of soil types

The above study shows that compaction significantly reduces plant growth; yet, other studies show that the compaction of soils with a coarse structure (sandy soils) might have a positive impact on the growth of conifers. This contradiction may be because the compaction of sandy soils creates microscopic spaces and enhances water retention in the soil (Troncoso, 1997; Gomez et al., 2002; Siegel-Issem, 2002). Mild soil compaction in sand supports the contact between roots and soil, resulting in higher absorption of water and nutrients (Gomez et al., 2002; Alameda & Villar, 2009). Alameda & Villar (2009) found that a mild compaction positively affected the growth of 53% of seedlings from 17 species (including both foliage and coniferous seedlings) growing in controlled conditions. Miller et al. (1996) found that in forwarding lines with an increased soil bulk density of 40% or more, growth was not affected at all, and 8-year-old seedlings of *Pseudotsuga menziessi* and *Picea sitchensis* survived.

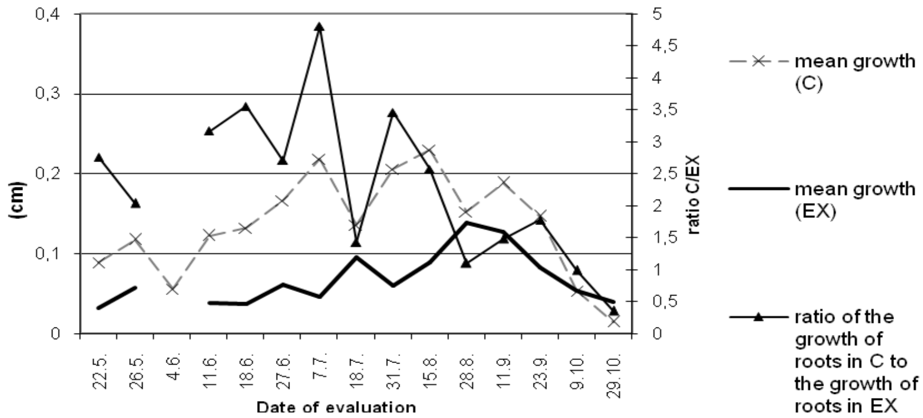

Fig. 8. Root growth and dynamics of Norway spruce seedlings grown in control non-compacted root boxes (C) and in root boxes exposed to a long-term pressure of 5.1 kPa (EX). A C/EX ratio above one indicates higher root growth in the non-compacted soil (Gebauer & Martinková, 2005).

In general, soil compaction is a stress factor that negatively affects the growth of plants, but the rates of compaction and differences among soil types need to be taken into account in these analyses (Kozlowski, 1999; Alameda & Villar, 2009). For instance, Alameda & Villar (2009) showed that growth increases in most seedlings grown in a sandy substrate with rising compaction of 0.2-0.6 MPa, but exceeding this value generally led to a reduction in growth.

5. Recording of harvesters' and forwarders' pressures on soil

During the passage of heavy vehicles on unsurfaced soil, the soil environment gets disrupted and roots are mechanically injured. A method for measuring and recording the immediate pressure on soil was developed and tested by the institute of Forest and Forest Products Technology of MENDELU in Brno (Czech Republic). This method is applicable in forest stands that grow on mild soil surfaces where large and extremely heavy machines (forwarders) pass. Pressure sensors were placed in the soil near the surface, and a unique measuring chain was used to measure the immediate pressure on the soil.

The pressure on a concrete point (e.g., a root or stress sensor) exerted by a wheel is short-lived (approx. 0.04 s) and has a stress impulse character (Fig. 9). The impulse does not have a permanent value, so its rise, apex and fall can be clearly observed. The apex values of stress impulses were used in measuring the stress on the soil. This method is helpful for determining suitable precautions in forestry management, e.g., the effect of different covers on soil protection and the optimal height of the layer. Moreover, this method establishes the optimal inflation of tyres because over-inflated tyres, even the low-pressure type, lead to higher stress on the soil.

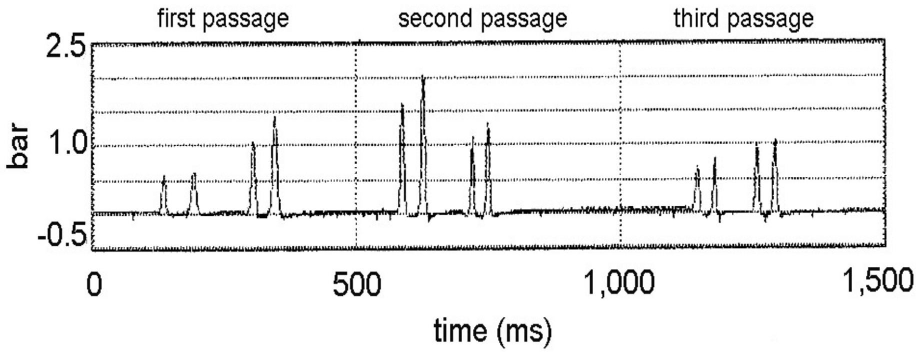

Fig. 9. Recording of the measurement of soil pressures during a forwarder's passage

6. Recovery of compacted soil

Revitalisation and amelioration of compacted soil is a long-term process and it is not known if it is fully achievable (Heninger et al., 2002). The regeneration period after the compaction may be less than 10 years near the soil surface (Thorud & Frissel, 1976; Lowery & Schuler, 1994), but others claim it could last several decades (Wert & Thomas, 1981; Jakobsen, 1983; Froehlich et al., 1985). It is necessary to fully understand the process of compaction, its impact on soil and plant growth and to find means and technologies that minimise the influence of compaction (if at all possible).

The recovery of compacted soil is a result of the combination of root activity, freeze-melt cycles and humid-dry cycles (Reisinger et al., 1988). After a period of 5 years, the bulk density of the surface, which consists of fine sandy-silt soil, was higher by 12% in former lines compared with places unaffected by the compaction (Lockaby & Vidrine, 1984).

The revitalisation of compacted soil also depends on the content of the organic matter in the soil, as it has a significant impact on the soil structure, aeration, water retention and chemical properties. Soil bulk density and porosity increase or decrease with the growing content of organic matter (Childs et al., 1989). Differences of 2-5% may significantly affect soil properties such as bulk density and porosity in sandy soils (Rawls, 1983).

We do not know of any ways to revitalise compacted forest soil on a large scale by technical means or technologies. Thus, it is necessary to prevent soil compaction by forestry management.

7. Prevention of soil compaction

The rate of soil compaction varies considerably depending on the method of felling, the type of soil preparation, the terrain conditions, the timing of the activity and the preparation and personal responsibility of the workers. Soil disruption by harvesting is also affected by soil conditions during the activity (e.g., soil resistance, humidity, frost, snow cover), concrete features of the activity (e.g., frequency of passages) and the impact (stress and vibration) on the soil by harvesters and forwarders.

During the movement of heavy tractors through areas with little bearing capacity of the subsoil, permanent deformations of terrain (lines 20 – 50 cm deep) arise. Even though these lines might be relatively short (5 – 15 m), they make the given section permanently impassable and inaccessible to wheeled or tracked tractors. Such sections include friable sand, drift sand, wet sand, permanently flooded places, passages to bridge inundated areas of watercourses, ford beds, passages in marshy or peaty terrain and dumps. Subsoils at extreme risk include clay soils, because they absorb high amounts of water and their bearing capacity is problematic in the spring and autumn. This highlights the necessity of clearing such a stand prior to activities on weakly bearing terrain.

Preparation of weakly bearing surfaces for harvesting is carried out in two ways:

1. The forwarding route is reinforced with additional material.
2. The road structure is temporarily reinforced (gabions, plastic mobile grids, plastic mobile boards, low-pressure tyres, route reinforcing –old used forest fences, harvesting waste). The extent of the reinforcement needed mainly depends on the axle pressure of the vehicle, construction and strength of the road, mechanical and physical properties of the terrain and the required number of passages of the vehicle.

The advantage of grids and screens is that they are quick and easy to use (Fig. 10). Local reinforcement of a road by means of screens can be achieved along the whole route for minimal costs. After pressing through the bottom layers of the soil, the skid of the wheels on the screen falls rapidly too. The producer recommends 8 tons as the maximal bearing capacity of screens; however, they have been successfully tested with forwarders loaded with 10 – 15 tons (Schlaghamersky, 1991; Ulrich & Schlaghamersky, 1997). Placement of a screen can open the way to a very wet biotope without soil damage by deep lines. One disadvantage of screens is that they cannot be placed directly on unprepared terrain; the lines resulting from the wheels need to be filled with brushwood or harvesting waste, for example. After a long period, soil gets through the screen and needs to be removed by a blade.

Fig. 10. Plastic mobile grids are quick and easy to use.

Besides the proper preparation of the terrain for the passage, there are other ways of minimising soil compaction by the modification of harvesting technologies. For example, the application of lighter technology (Jansson & Wästerlund, 1999), lower inflation of tyres (Canillas & Salokhe, 2001), placement of harvesting waste in locations where harvesting and forwarding is planned (Hutchings et al., 2002) (Fig. 11), harvesting in winter on frozen soil (Alban et al., 1994), planting species tolerant to compaction (Bowen, 1981; Ruark et al. 1982) and limitation of drawing logs using a winch can all help reduce soil compaction. Limitation of the number of passages would not help because 80% of soil compaction occurs during the first passage (Holshouser, 2001). The most efficient precaution is prevention against soil compaction, as the other methods might be ineffective and, furthermore, could do harm to the roots (Howard et al., 1981).

Fig. 11. Placement of harvesting waste in places of forwarders' and harvesters' passages is one way to minimise soil compaction.

8. Conclusion

The passage of forestry machines causes soil compaction, leading to significant changes in the soil structure and moisture conditions. When soil is compacted, soil bulk density increases, porosity and water infiltration decrease, erosion speeds up, and all of these processes lead to changes in plant physiology. Photosynthesis, transpiration, nutrient uptake, mycorrhizas and plant hormones are all possible avenues for these changes.

Soil compaction is influenced by endogenous soil factors (distribution and size of soil elements, soil bulk density, pore continuity, water content, etc.) as well as exogenous factors (choice of equipment, loading of wood, length of loading, intensity and means of harvesting, site preparation, etc.). When soil is compacted, the soil resistance grows; resistance over 2.0 MPa, as measured by penetrometer, limits elongation root growth in most plant species. Our measurements have shown that this critical value is often exceeded when forestry machines pass through an area without any preparation of the site.

Poor aeration of soil caused by soil compaction also prevents the development of root systems and limits the water penetrability of roots. Our measurements show that the critical value of CO_2 in the soil air (defining the rate of aeration) was exceeded as a result of the passage of forestry machines in almost all cases. To establish the optimal inflation of tyres the pressure sensor (a sensor developed and tested by us) was found to be very useful tool.

This sensors are also applicable in forestry management because it aids in the determination of suitable precautions, e.g., whether the soil surface is covered with a sufficient layer of brushwood.
Although compaction is usually considered to be a factor of growth deceleration, some studies of conifers show that compaction of certain soils with a coarse structure (sandy soils) may, on the contrary, enhance growth due to the multiplication of microscopic pores, thus increasing the soil's capability to retain a higher amount of water.
Since the revitalisation and amelioration of compacted soil is a long-term process, and it is not unknown if it is fully achievable, compaction should be minimised as much as possible. Its minimisation could be achieved by the modification of technologies in forestry activities; for instance, by using lighter machines, reducing tyre pressure, placing harvesting waste in places where forestry machines are expected to pass, harvesting in the winter on frozen soil and controlling tractor movement. We should also mention that human factors play often a critical role in the soil compaction.

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10. References

Abdalla, A.M.; Hettiaratchi, D.R. & Reece, A.R. (1969). The mechanics of root growth in granular media. *Agric Eng Res* 14:236-248.
Alameda, D. & Villar, R. (2009). Moderate soil compaction: implications on growth and architecture of 17 woody plant seedlings. *Soil Till Res* 103:325–331.
Alban, D.H.; Host, G.E.; Elioff, J.D. & Shadis D. (1994). Soil and vegetation response to soil compaction and forest floor removal after aspen harvesting. *US Department of Agriculture, Forest Service, Res. Pap. NC-315*. North Central Forest Experiment Station, St. Paul, MN. 8 pp.
Arvidsson, J. & Jokela, W.E. (1995). A lysimeter study of soil compaction on wheat during early tillering. II. Concentration of cell constituents. *New Phytol* 115:37-41.
Atwell, B.J. (1993). Response of roots to mechanical impedance. *Environ Exp Bot* 33:27-40.
Ågren, G.; Axelsson, B.; Flower-Ellis, J.G.K.; Linder, S.; Persson, H.; Staaf, H. & Troeng, E. (1980). Annual carbon budget for young Scots pine. – In: *Structure and Function of Northern Coniferous Forest,* T. Persson, (Ed.), An Ecosystem Study -Ecol Bull (Stockholm) 32:307-313.
Barley, K.P. (1962). The effects of mechanical stress on the growth of roots. *J Exp Bot* 13: 95-110.
Bengough, A.G. & Mullins, C.E. (1991). Penetrometer resistence, root penetration resistence and root elongation rate in two sandy loam soils. *Plant Soil* 132:59-66.

Bengough, A.G. & MacKenzii, C.J. (1994). Simultaneous measurement of root force and elongation rate for seedling pea roots. *J Exp Bot* 45:95-102.

Bowen, H.D. (1981). Alleviating mechanical impedance. In: *Modifying the Root Environment to Reduce Crop Stress*, G.F. Arkin & H.M. Taylor (Eds.). St. Joseph, MI: ASAE. 21-57 pp.

Boyer, J.N. & South D.B. (1988). Date of sowing and emergence timing affect growth and development of loblolly pine seedlings. *New For* 2:231-246.

Brais, S. (2001). Persistence of soil compaction and effects on seedlings growth in northwestern Quebec. *Soil Science Society of America Journal* 65:1263-1271.

Burger, J. A. & Kelting, D. L. (1998). Soil quality monitoring for assessing sustainable forest management. In: *The contribution of soil science to the development of and implementation of criteria and indicators of sustainable forest management*. E. A, Davidson; M. B. Adams & K. Ramakrishna (Eds). SSSA Special Publication Number 53. Madison, WI: Soil Science Society of America. 17-52 pp.

Canillas, E.C. & Salokhe W.M. (2001). Regression analysis of some factors influencing soil compaction. *Soil and Tillage Research* 61: 167-178.

Childs, S.W.; Shade, S.P; Miles, D.W.; Shepard, E. & Froehlich, H.A. (1989). Management of soil physical properties limiting forest productivity. In: *Maintaining the long-term productivity of Pacific Northwest forest ecosystem*, D.A. Perry et al. (Eds.). Timber Press, Portland, OR, USA.

Clark, L.J. & Barraclough, P.B. (1999). Do dicotyledons generate greater maximum axial root growth pressures than monocotyledons? *J Exp Bot* 50:1263-1226.

Cochrad, P.H. & Brock, T. (1985). Soil compaction and initial height growth of planted ponderosa pine. *USDA For Serv Res Note PNW-434*.

Croser, C.; Bengough, A.G. & Pritchard, J. (1999). The effect of mechanical impedance on root growth in pea (*Pisum sativum*). I. Rates of cell flux, mitosis, and strain during recovery. *Physiol Plant* 107:277-286.

Croser, C.; Bengough, A.G. & Pritchard, J. (2000). The effect of mechanical impedance on root growth in pea (*Pisum sativum*). II. Cell expansion and wall rheology during recovery. *Physiol Plant* 109:150-159.

Eavis, B.W. (1967). Mechanical impedance to root growth. *Agricultural Engineering Symposium*. Silsoe. Paper 4/F/39:1-11.

Entry, J.A.; Rygiewicz, P.T.; Watrud, L.S. & Donnelly, P.K. (2002). Influence of adverse soil conditions on the formation and function of arbuscular mycorrhizas. *Advences in Environmental Research* 7:123-138.

Froehlich, H.A. (1976). The effect of soil compaction by logging on forest productivity, part 1. *USDI Bureau of Land Management*. Final Report, Contract No. 53500-CT4-5(N).

Froehlich, H.A.; Miles, D.W.R. & Robbins, R.W. (1985). Soil bulk density, recovery on compacted skid trails in central idaho. *Soil Sci Soc Am J* 4:1015–1017.

Gebauer, R. & Martinková, M. (2005): Effects of pressure on the root systems of Norway spruce plants (*Picea abies* [L.] Karst.). *Journal of Forest Science* 51:268-275.

Gill, W.R. & Miller, R.D. (1956). A method for study of the influence of mechanical impedance and aeration on seedling roots. *Soil Science of America Proceedings* 20:154-157.

Godefroid, S. & Koedam N. (2003). How important are large vs. Small forest remnants for the conservation of the woodland flora in an urban kontext? *Global Ecology and Biogeography* 12:287-298.

Gomez, G.A.; Powers, R.F.; Singer, M.J. & Horwath, W.R. (2002). Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. *Soil Sci Soc Am J* 66:1334-1343.

Grable, A.R. & Siemer, E.G. (1968). Effects of bulk density, aggregate size, and soil water suction on oxygen diffusion, redox potentials, and elogation of corn roots. *Soil Sci Soc Am Proc* 32:180-186.

Greacen, E.L. & Sands, R. (1980). Compaction of Forest Soils: A Review. *Aust J Soil Res* 18:163-189.

Grigal, D.F. (2000). Effects of extensit forest management on soil produktivity. *Forest Ecology and Management* 138:167-185.

Güldner, O. (2002). Untersuchungen zu Bodenveränderungen durch die Holzernte in Sachsen und Entwicklung eines Konzepts zur ökologisch verträglichen Feinerschliessung von Waldbeständen. *Tagungsbericht der Sektion Forsttechnik des Verbandes Deutscher Forstlicher Versuchsanstalten*, Sopron, Ungarn, 10 p.

Halverson, H.G. & Zisa, R.P. (1982). Measuring the response of conifer seedlings to soil compaction stress. *USDA For Serv Res Pap NE-509*.

Heilman, P. (1981). Root penetration of Douglas fir seedlings into compacted soil. *For Sci* 27:660-666.

Heninger, R.; Scott, W.; Dobkowski, A.; Miller, R.; Anderson, H. & Duke, S. (2002). Soil disturbance and 10-year growth response of coast Douglas-fir on nontilled and tilled skid trails in the Oregon Cascades. *Can J For Res* 32:233–246.

Hillel, D. (1998). *Environmental Soil Physics*. Academia Press. USA.

Holshouser, D.L. (Ed.). (2001). *Soybean Production Guide*. Tidewater Agricultural Research and Extension Center, Information Series No. 408.

Horn, R. (1988). Compressibility of arable land. In: *Impact of water and external forces on soil structure*, J. Drescher et al. (Eds.) Catena suppl. 11, Catena Verlag, Germany. p.53-71.

Howard, R.F.; Singer, M.J. & Frantz G.A. (1981). Effects of soil properties, water content, and compactive effort on the compaction of selected California forest and range soils. *Soil Sci Soc AmJ* 45:231-236.

Hutchings, T.R.; Moffat, A.J. & French, C.J. (2002). Soil compaction under timber harvesting machinery: A preliminary report on the role of brash mats in its prevention. *Soil Use and Management* 18:34–38.

Jakobsen, B.F. (1983). Persistence of compaction effects in a forest Kraznozen. *Aust J For Res* 13: 305-308.

Jansson, K.J. &Wästerlund, I. (1999). Effect of tradic by lightwright forest machinery on the growth of young Picea abies trees. *Scandinavian Journal of Forest Research* 14: 581-588.

Jim, C.Y. (1993). Soil compaction as a constraint to tree growth in tropical and subtropical urban habitats. *Environ Conserv* 20:35–49.

Kang, B.T. & Lal R. (1981) Nutrient losses in water runoff from a tropical watershed, In: Tropical agricultural hydrology, R.Lal & E. W.Russell (Eds.). Wiley, Chichester. *pp.* 119–130.

Kozlowski, T.T. (1999). Soil compaction and growth of woody plants. *Scandinavian Journal of Forest Research* 14:596-619.

Kozlowski, T.T. & Pallardy, S.G. (1997). Physiology of Woody Plants, 2nd edition. Academic Press, San Diego.

Langmaack, M.; Schrader S.; Rapp-Bernhardt, U. & Kotzke K. (2002). Soil structure rehabilitation of arable soil degraded by compaction. *Geoderma* 105:141-152.

Lockaby, B.G. & Vidrine, C.G. (1984). Effect of logging equipment traffic on soil density and growth and survival of young loblolly pine. *South J App. For* 8:109-112.

Lousier, J.D. (1990). Impacts of Forest Harvesting and Regeneration on Forest Sites. *Land Management*. Report Number 67.

Lowery, B. & Schuler, R.T. (1994). Duration and effects of compaction on soil and plant growth in Wisconsin. *Soil Till Res* 29:205-210.

Malmer, A. & Grip, H. (1990). Soil disturbance and loss of infiltrability caused by mechanized and manual extraction of tropical rainforest in Sabah, Malaysia. *Forest Ecology and Management* 38:1–12.

Martinková, M. & Gebauer, R. (2005). Problematika mechanického poškození kořenů rostlin. In: *Metody pro zlepšení determinace poškození kořenů stromů ve smrkových porostech vyvážecími traktory. I. Výběr a ověření metod (In Czech).* J. Neruda (Ed.): Monograph. Brno. p. 7-10.

Masle, J. & Passioura, J.B. (1987). The effect of soil strength on the growth of young wheat plants. *Australian Journal of Plant Physiology* 14:643–656.

Mickovski, S.B. & Ennos, A.R. (2002). A morphological and mechanical study of the root systems of suppressed crown Scots pine *Pinus silvestris*. *Trees Struct Funct* 16:274-280.

Mickovski, S.B. & Ennos A.R. (2003). Anchorage and asymmetry in the root system of *Pinus peuce*. *Silva Fenn* 37:161-173.

Miller, R.E.; Scott W. & Hazard, J.W. (1996). Soil compaction and conifer growth after tractor yarding at three coastal Washington locations. *Can J For Res* 26:225–236.

Misra, R.K.; Dexter, A.R & Alston, A.M. (1986). Maximum axial and radial growth pressures of plant roots. *Plant Soil* 95:315-326.

Misra, R.K. & Gibbons, A.K. (1996). Growth and morphology of eucalypt seedling-roots, in relation to soil strength arising from compaction. *Plant Soil* 182:1–11.

Munns, E.N. (1947). Logging can damage soil. *J For* 45:513.

Neruda, J.; Čermák, J.; Naděždina, N.; Ulrich, R.; Gebauer, R.; Vavříček, D.; Martinková, M.; Knott, R.; Prax, A.; Pokorný, E.; Aubrecht, L.; Staněk, Z.; Koller, J. & Hruška J. (2008). *Determination of damage to soil and root systems of forest trees by the operation of logging machines.* Mendel University in Brno, Brně. 138 p.

Ole-Meiludiem R.E.L. & Njau, W.L.M. (1989). Impact of logging equipment on water infiltration capacity at Olmotonyi, Tanzania. *For Ecol Manage* 26:207–213.

Rawls, W.J. (1983). Estimating soil bulk density from particle size analysis and organic matter content. *Soil Sci* 135:123-125.

Reisinger, T.W.; Simmons, G.L. & Pope P.E. (1988). The impact of timber harvesting on soil properties and seedling growth in the south. *S J App For* 12:58–67.

Rosolem, C.A.; Foloni, J.S.S. & Tiritan, C.S. (2002). Root growth and nutrient accumulation in cover crops as affected by soil compaction. *Soil and Tillage Research* 65:109-115.

Ruark, G.A.; Mader, D.L. & Tatter, T.A. (1982). A composite sampling technique to assess urban soils under roadside trees. *J Arboric* 8:96-99.

Russell, R.S. (1977). Mechanical impedance of root growth. In: Plant Root Systems: Their function and interaction with soil. R.S. Russell (Ed.). McGraw-Hill Book Company, UK. 98-111 pp.

Sands, R. & Bowen, G.D. (1978). Compaction of sandy soils in Radiata pine forests. II. Effects of compaction on root configuration and growth of radiata pine seedlings. *Aust J For Res* 8:163-170.

Sands, R.; Greacen, E.L. & Gerard, C.J. (1979). Compaction of sandy soils in Radiata pine forests. I. A penetrometer study. *Aust J Soil Res* 17:101-113.

Sarquis, J.I.; Jordan, W.R. & Morgan, P.W. (1991). Ethylene evolution from maize (*Zea mays* L.) seedling roots sholte in response to mechanical impedance. *Plant Physiol* 96:1171-1177.

Schlaghamersky,A. (1991). Entwicklung von Methoden und einfachen Geraeten zur Bestimmung der Oberflaechentragfaehigkeit von Waldboeden. *Bericht Fachhochschule Hildesheim-Holzminden*. pp.74

Siegel-Issem, C.M. (2002). Forest productivity as a function of root growth opportunity. Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University. Blacksburg, Virginia. 86 p.

Simmons, G.L. & Pope, P.E. (1987). Influence of soil compaction and vesicular-arbuscular mycorrhizae on root growth of yellow poplar and sweetgum seedlings. *Can J For Res* 17:970-975.

Singer, M.J. (1981). Soil compaction – seedling growth study. *Final report to USDA Forest Service, Pacific Southwest Region*. Coop. Agree. USDA-7USC-2202. Suppl. 43.

Standish, J.T.; Commandeur, P.R. & Smith, R.B. (1988). Impacts of forest harvesting on physical properties of soils with reference to increased biomass recovery—a review. *Inf Rep BC-X-301, B.C.* Canadian Forest Service Pacific Forestry Research Centre.

Taylor, H.M. & Ratliff, L.F. (1969). Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. *Soil Sci* 108:113-119.

Thorud, D.B. & Frissel, S.S Jr. (1976). Time changes in soil density following compaction under an oak forest. *Minnesota Forestry Notes No. 257*. Univ. of Minnesota, St. Paul, MN.

Torbert, H.A. & Wood, C.W. (1992). Effects of soil compaction and water-filled pore space on soil microbial activity and N losses. Commun. *Soil Sci Plant Anal* 23:1321–1331.

Troncoso, G. (1997). Effect of soil compaction and organic residues on spring-summer soil moisture and temperature regimes in the Sierra National Forest. *M.S. thesis*. Oregon State Univ., Corvallis, OR.

Tuttle, C.L.; Golden, M.S. & Meldahl, R.S. (1988). Soil compaction effects on *Pinus taeda* establishment from seed and early growth. *Can J For Res* 18:628-632.

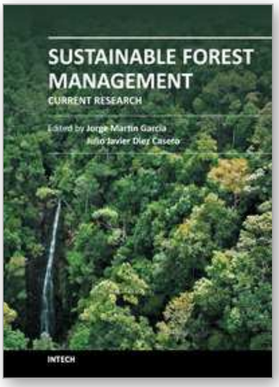
Ulrich,R., Schlaghamersky,A.(1997): Tool for bearability increase of the forest tracks (In Czech). Usable model. *Úřad průmyslového vlastnictví ČR.* Číslo zápisu:5479, MPT: E01 C9/02

Vogt, K.A.; Vogt, D.J.; Palmiotto, P.A.; Boon, P.; O´hara, J. & Asbjotnsen, H. (1996). Review of root dynamics in forest ecosystems grouped by climate, climatic forest type and species. *Plant Soil* 187:159-219.

Wairiu, M.; Mullins, C.E. & Campbell, D. (1993). Soil physical factors affecting the growth of sycamore (*Acer pseudoplatanus* L.) in a silvopastoral system on a stony upland soil in North-East Scotland. *Agrofor System* 24:295–306

Wert, S. & Thomas, B.R. (1981). Effects of skid roads on diameter, height, and volume growth in Douglas-fir. *Soil Sci Soc Am J* 45:629-632.

Zaerr, J.B. & Lavender, D.P. (1974). The effects of certain cultural and environmental treatments upon growth of roots of Douglas fir (*Pseudotsuga menziessii* /Mirb. / Franco) seedlings. *Proceedings of International Symposium on Ecology and Root Growth*. Biol. Gessellschaft. Postdam, Germany, pp. 27 – 32.



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Sustainable forest management (SFM) is not a new concept. However, its popularity has increased in the last few decades because of public concern about the dramatic decrease in forest resources. The implementation of SFM is generally achieved using criteria and indicators (C&I) and several countries have established their own sets of C&I. This book summarises some of the recent research carried out to test the current indicators, to search for new indicators and to develop new decision-making tools. The book collects original research studies on carbon and forest resources, forest health, biodiversity and productive, protective and socioeconomic functions. These studies should shed light on the current research carried out to provide forest managers with useful tools for choosing between different management strategies or improving indicators of SFM.