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Ecoefficient Timber Forwarding on Lowland Soft Soils

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1. Introduction

Environmental acceptability is one of the criteria for assessing work efficiency of sustainable forest management. Environmentally acceptable timber harvesting is determined by procedures involving different machines and tools and adequate ways of timber processing, after which the damage to habitat (soil, water) and stand (standing trees, seedlings) are as low as possible. Due to an increasing influence of the public opinion on the current forest environment, the aesthetic appearance of the ongoing forest work site should also be taken into account as well as its appearance after the works have been completed.

Timber harvesting in main felling of lowland even-aged forests of Croatia is based on felling and processing timber by chain saws and forwarding timber processed by cut-to-length method. For this purpose, medium-weight (12–16 t) and heavy (>16 t) forwarders are used, whose mass with the load ranges between 25 and 40 t, and it is distributed to three or four axles. A three-axle (six-wheel) forwarder is equipped with two larger wheels on the front axle and four smaller wheels on the rear axle, which is constructed as a tandem, bogie axle. Four-axle (eight-wheel) forwarder is equipped with wheels of the same dimensions on the front axle and on the rear bogie axle of the vehicle. Bogie axle, with wheels in the so-called tandem distribution, increases the mobility and stability of the forwarder in forest off-road operations.

The soils of lowland forests in Croatia are of heavy mechanical content, and under conditions of frequently excessive moisture (underground water, precipitation, flood or sink water) during the whole year their bearing capacity decreases and these sites are classified as sensitive forest habitats. According to Ward and Lyons (2000), forest habitats where it is necessary to modify the common procedures of wood harvesting so as to avoid damaging effects to ecological, economic and social functions of forests, are sensitive.

The decrease of the soil bearing capacity restricts the mobility and lowers the productivity of forwarders (Poršinsky & Stankić, 2006a), and also increases the level of soil disturbance (Poršinsky & Stankić, 2006b), which can be seen in the form of soil compaction and rutting (Fig. 1). It can be concluded from the above that vehicles with the least possible contact pressure will be the most suitable for off-road wood transport in the Croatian lowland forests. From the point of view of economic use, the Croatian forestry requires the forwarder with the load capacity of 14 t and lifting torque of the hydraulic crane of 100 kNm, which can provide loading and extracting of large logs from main felling sites (Horvat et al., 2004).

Fig. 1. Forwarder mobility and soil disturbance in main felling of lowland even-aged forests of Croatia

The paradox between the application of machine work and site disturbance as side effect of its usage determines an ecoefficient mechanized timber harvesting, involving: 1) efficiency (productivity and costs) of machine work and 2) decreased impact on habitat of machines used in the system of timber harvesting (Owende et al., 2002; Akay et al., 2007; Pentek et al, 2008).

The aim of this paper is to show based on the example of a medium-weight forwarder: 1) the impact of load decrease on productivity and unit costs of timber forwarding, 2) the impact of load mass on forwarder wheel pressure, 3) the impact of tire width and use of tracks depending on load mass on nominal ground pressure. The results can be used to guide decision making in purchasing forwarders, and such approach would provide an efficient and environmentally friendly timber forwarding under conditions of limited bearing capacity of gley soils in main felling sites of lowland forests.

2. Scope

In assessing the environmental soundness of forest vehicles, whose contact with the soil is likely to cause soil damage, the main criteria are trafficking and soil compaction (Poršinsky & Horvat, 2005). Trafficking causes compaction of the soil surface due to moving of forest machines (MacDonald et al., 2002), and it depends on secondary openness of the felling unit and the highest distance of timber reach (Pentek et al., 2010) of the catching device (hydraulic crane, pulling rope of winch) of a certain means of work (forwarder, skidder).

Soil compaction, or rutting, is the consequence of the vehicle off-road travel due to short effect of contact pressures and slippage of drive wheels as well as pulled load (Horn et al., 2004). Soil compaction causes breaking of structural aggregates which decreases inter-aggregate space as well as pore quantity and soil volume (Poršinsky, 2005). Consequently the soil thermal regime is disturbed, water-air relationship in the soil changes and conditions for feeding plants are lowered to a certain extent (Arnup, 1999), for instance microbiological activity is decreased as the soil is brought into anaerobic conditions (Frey et al., 2009). Compaction primarily results in the decrease of the quantity of non-capillary pores and soil permeability to water (Halvorson et al., 2003), which accelerates surface water drainage on slopes covered with a network of vehicle ruts and eventually causes erosion (Owende et al., 2002).

Sensitivity of forest soil to compaction is determined by the following factors: value of vehicle contact pressures, soil texture, soil moisture during timber forwarding, proportion of skeleton and sand particles in the soil, soil structure, bulk density and soil porosity as well as thickness of humus accumulation layer (Arnup, 1999).

Under conditions of restricted ground bearing capacity, the wheels of the forwarder tandem (bogie) axle are equipped with semi-tracks, by which multiple benefits are achieved: 1) soil protection from damage, primarily against compaction and movement of soil layers caused by the increase of the contact area, or decrease of the contact pressure (Bygdén et al., 2004; Gerasimov & Katarov, 2010), 2) vehicle mobility by decrease of wheel slippage, as well as rut depth and vehicle rolling resistance (Bygdén et al., 2004; Bygdén & Wästerlund, 2007; Suvinen, 2006), 3) efficient timber forwarding because of the possibility of use of the vehicle payload, and also increase of the vehicle speed (Poršinsky & Stankić, 2006a), 4) reduction of fuel consumption due to lower wheel slippage (Suvinen, 2006), 5) increase of the forwarder lateral stability during timer loading and unloading, and also during vehicle travel especially when working on slopes (Sutherland, 2003).

In order to reduce the damage of soils of restricted bearing capacity, apart from semi-tracks, additional measures are taken aimed at decreasing the forwarder contact pressures such as the use of multi-wheel vehicles (Nugent et al., 2003; Partington & Ryans, 2010), wheel doubling (Ireland, 2006; Owende et al., 2002), use of wide tires (Saarilahti, 2002b), and also the regulation of tire air pressure (Eliasson, 2005; Sakai et al., 2008), use of chains on the vehicle front wheels (Suvinen, 2006), reduction of the quantity of loaded timber (Poršinsky, 2005), planning the time of work operations (Saarilahti, 2002a).

Apart from the above measures, the researchers have also dealt with the idea of improving the conditions of the soil bearing capacity by covering skid trails by sawmill slabs or pallets (Owende et al., 2002), or by the ever more present cover made of forest residues (Poršinsky & Stankić, 2006b; Eliasson & Wästerlund, 2007; Ampoorter et al., 2007; Gerasimov & Katarov, 2010), which is still treated as waste in cutting and processing timber.

2.1 Ground bearing capacity

Soil bearing capacity (strength, trafficability) is the capability of the soil to resist to external forces (action of the vehicle wheels and tracks), and it is determined by soil settling (rut depth) under external load. In forestry, the soil bearing capacity is determined as the maximum allowed contact pressure of the vehicle wheel (Saarilahti, 2002b) not causing damage to soil, which depends on the type and texture content of the soil, proportion of humus and skeleton particles (constant soil parameters) and a variable parameter – current moisture (Poršinsky, 2005).

The last classification of terrains for harvesting operations was made within the EcoWood project, and as it paid special attention to the ecoefficient wood harvesting on sensitive sites, it categorized the soil strength into four classes and prescribed the maximum contact pressure for each class (Fig. 2). This descriptive classification of the bearing strength of forest soil also recommends the use of the equation nominal ground pressure of the vehicle

(Mellgren, 1980) for determining the suitability of individual types of vehicles for timber harvesting depending on the limit contact pressure on the soil of individual strength classes (Ward et al., 2003).

Soil Strength Classes	General Description of the Soil Types	Cone index *CI*, kPa	Young's modulus E, MPa	Shear Strength τ, kPa	Ground Bearing Capacity *GBC*, kPa
1 – Strong soil	Dry sands and gravels, Firm mineral soils	>500	>60	>60	>80
2 – Average soil	Soft mineral or iron-pan soils	300–500	20–60	20–60	60–80
3 – Soft soil	Wet gleys and peaty soils	<300	<20	<20	40–60
4 – Very soft soil	Wet peats	<<300	<<20	<<20	<40

Source: Owende et al. (2002)

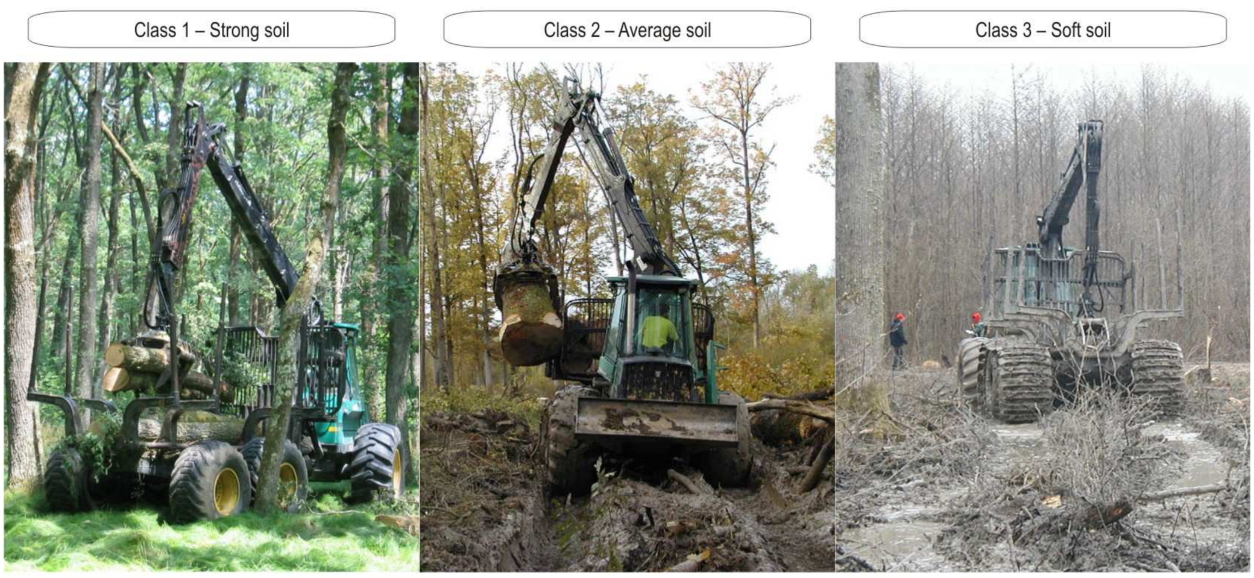

Photo: Poršinsky (2005)

Fig. 2. Soil strength classes

2.2 Nominal ground pressure

The vehicle contact pressure is the ratio between the weight and contact surface of the vehicle with the ground (soil), and it expresses the environmental suitability of a specific forest vehicle. The problem in calculating the vehicle contact pressures for forest off-road travel is the dependence of the tire and soil contact area on: 1) elastic deformations of the loaded wheel (tire characteristics, air pressure) and 2) plastic-elastic soil deformations (granulometric content, moisture).

Wishing to standardize the way of calculation of contact pressures of forest vehicles, primarily for providing comparison of vehicles (or different equipment levels of individual vehicles) used for forest off-road timber extraction, Mellgren (1980) introduced nominal ground pressure (Fig. 3). Nominal ground pressure is static pressure (vehicle at standstill), and theoretically it occurs in case of a rigid wheel on plastic-elastic ground where the wheel-soil contact area is calculated as the product of multiplication of the wheel semi-diameter and tire width. When identifying the contact length of the wheel and plastic ground with the wheel semi-diameter, it is important to assume that 15% of the wheel diameter sinks into the soil (wheel rut), by which full contact between the wheel tire and soil is provided

(Partington & Ryans, 2010). In case of lower wheel sinking into the soil (depending on soil bearing strength) the contact area decreases and the contact pressure of vehicles increases, and it is higher with respect to the nominal ground pressure. Actually, the nominal ground pressure is the lowest pressure realized by the vehicle under conditions of reduced soil bearing strength and hence it cannot be used for comparing the suitability of two different wheels under different soil conditions.

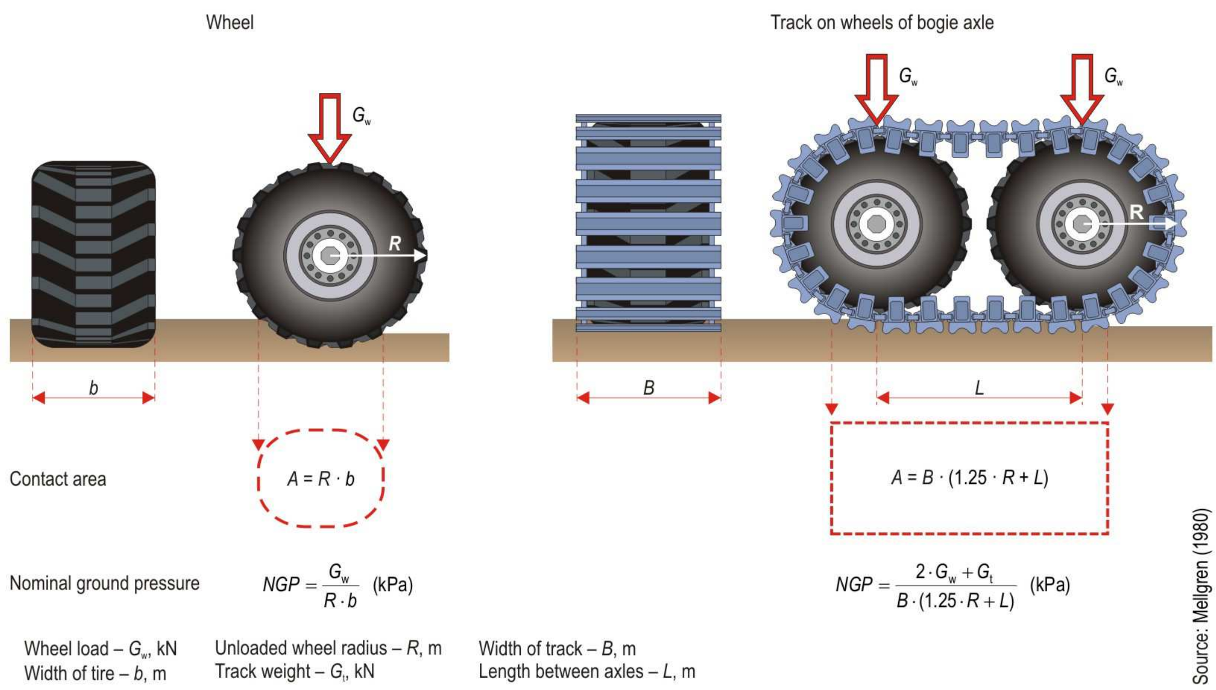

Fig. 3. Calculation of Nominal Ground Pressure

Simplification of the calculation of the contact area, i.e. approximation of the contact length of the loaded wheel with the rut depth of 15% of the wheel diameter, theoretically limits a wide use of this model. The basic objection to approximation of the wheel-soil contact length, with the wheel semi-diameter, is that it applies only in case when the angle between the beginning and end of the wheel/ground contact is 1 radian (≈57.3°), meaning that the model is geometrically sustainable only in certain cases (Poršinsky & Horvat, 2005).

The advantage of the nominal ground pressure is its simple calculation, and the deficiencies are neglecting the impact of tire deflection of the loaded wheel during movement, tire air pressure, independence on soil characteristics and overestimation of use of wide tires (Saarilahti, 2002b).

3. Materials and methods

The analysis of efficiency and environmental soundness of timber forwarding was carried out on the example of a medium-weight six-wheel forwarder Valmet 840.2 with nominal payload of 12 t, whose dimensions and load distribution of unloaded vehicle are shown in Fig. 4. The surface of the cross-cut of the bunk area is 4.1 m^2, and 4 m in length. The vehicle is driven by a six-cylinder diesel engine with pre-charging of the nominal power of 125 kW at 2200 min^{-1} and 670 Nm of the maximum torque at 1400 min^{-1}. The forwarder is equipped with hydraulic crane Cranab CFR7C, with the lifting force of 7.1 kN at the maximum range of 9.1 m.

The effect of load reduction (4 t, 8 t related to 12 t of the vehicle payload) on the forwarder efficiency with respect to the distance of timber forwarding is expressed in accordance with the multi-criteria planning model of productivity of these vehicles (Stankić, 2010). This model takes into account: 1) forwarder class, 2) soil bearing strength, 3) forwarder equipment with tracks, 4) felling density, 5) volume of the mean felling tree, and 6) distance of timber forwarding. Unit cost of timber forwarding is calculated according to machine rate made by the company »Hrvatske šume« Ltd Zagreb for the Valmet 840.2 forwarder amounting to 58.15 EUR/PMH.

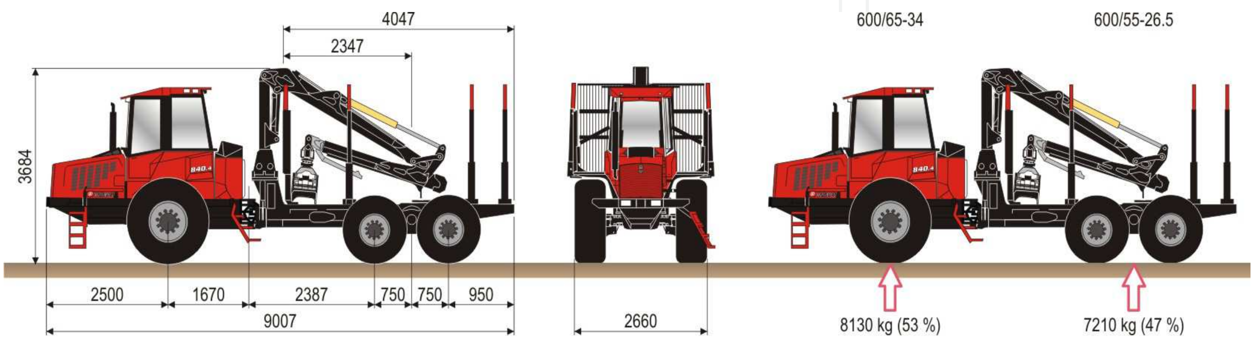

Fig. 4. Valmet 840.2 Forwarder

For calculating the nominal ground pressure, a theoretical model of axle load distribution was used, the case of vehicle at standstill on level ground, depending on mass and length of loaded logs in the forwarder load area (Poršinsky & Horvat, 2005). The analysis of axle load distribution was based on an average length of logs (4 m) made by cut-to-length method in the area of the Croatian lowland forests (Stankić, 2010), and the mass of 1800 kg of a pair of semi-tracks in case when the wheels of the rear (bogie) axle are equipped with them. The wheel load assumed even load distribution of axle load by pertaining wheels. The contact surface between wheels (semi-tracks) and soil was calculated according to Mellgren (1980), for narrow (front – 600/65-34, rear – 600/55-26.5) and wide (front – 710/55-34, rear – 710/45-26.5) tires recommended by the manufacturer of this forwarder.

The analysis of the forwarder environmental soundness was based on: 1) values of nominal ground pressure of front and rear wheels of the vehicle depending on the load mass, and equipment of the vehicle with narrow and wide tires, i.e. equipment of the wheels of the rear axle with tracks, and 2) the upper limit value of the allowed ground pressure (<60 kPa) of the limited bearing strength (Fig. 2 – class 3, soft soil), which prevails at the time of main felling in the Croatian lowland forests.

4. Results and discussion

In accordance with the objectives of the study, the results of soundness of timber forwarding, under conditions of limited soil bearing strength of the Croatian lowland forests carried out by medium-weight forwarders, are presented with respect to: 1) the impact of load decrease on forwarder efficiency, and 2) nominal ground pressure as the measure of environmental soundness considering the vehicle equipment and load mass.

4.1 Forwarder efficiency

In the Croatian forestry, six-wheel forwarders prevail, mostly equipped with tires characterized by deeper and sparser tread pattern (so-called aggressive tread). Such form of tread pattern reduces wheel slippage, but increases damage to soil and tree roots (Sutherland, 2003). The use of tires with shallower and denser tread pattern (so-called non-aggressive tread), which reduces soil damage but increases wheel slippage, and is more suitable for the use of tracks on the wheels of the rear (bogie) axle of forwarders, is more an exception than a rule (Poršinsky, 2005). The same is applicable for the improvement of conditions of soil bearing capacity on skid trails by forming a cover of branches or 3–4 m long fuelwood.

Source: Bosner et al. (2008)

		Full height of loading area	Up to 2/3 height of loading area	Up to 1/3 height of loading area
Load	Mass, kg	12160	8130	4130
	Volume, m^3	12.21	8.19	4.32
	Payload, %	101	68	34

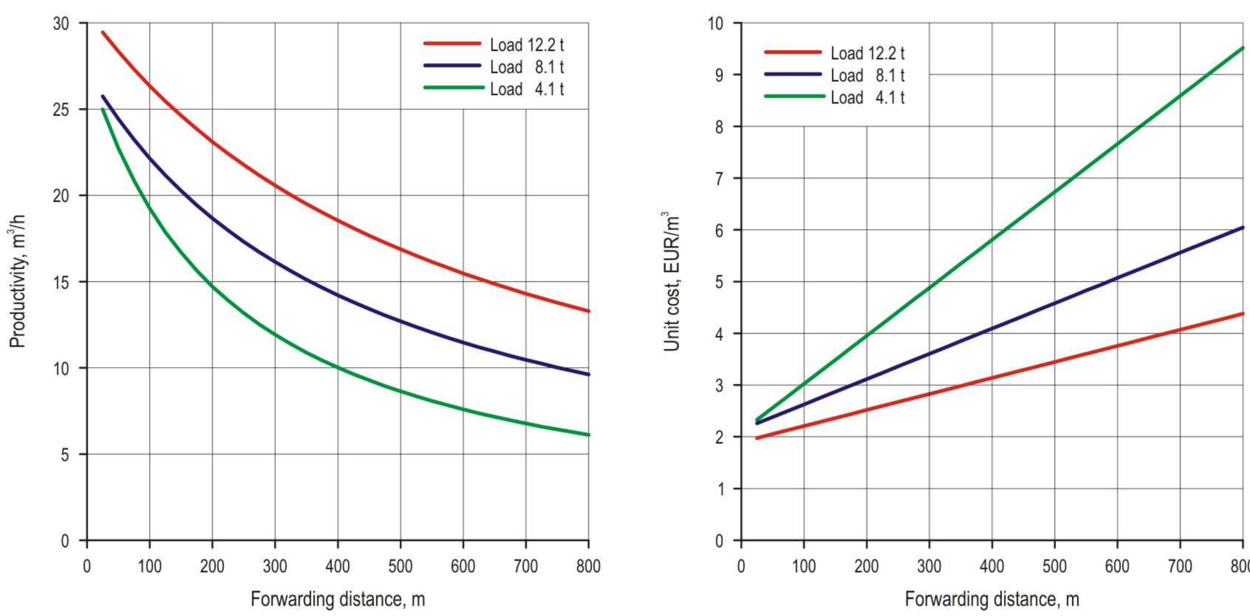

Fig. 5. Impact of load reduction on efficiency of Valmet 840.2 Forwarder

The most frequent form of providing forwarder mobility under conditions of limited soil bearing strength of the Croatian lowland forests is the reduction of the quantity of the loaded timber (load mass, volume), which has an adverse effect on the forwarder efficiency. The impact of the reduction of load volume on the efficiency of Valmet 840.2 forwarder is shown in Fig. 5 with respect to timber loading up to: 1) the full height of the load area (load – 12.2 t, 12.2 m^3), 2) 2/3 height of the load area (load – 8.1 t, 8.2 m^3), and 3) 1/3 height of the load area (load – 4.1 t, 4.3 m^3). It should be emphasized that the load volume is expressed based on the measurement of the length and diameter with bark on the thicker end, in the middle and on the thinner end of each log in the load of the forwarder, and the volume is estimated by Riecke-Newton equation (Köhl et al., 2006).

Load reduction, up to 2/3 height of the load area (68% of the vehicle payload), resulted in the decrease of productivity ranging from 16% (distance of 100 m) to 28% (distance of 800 m) and increase of unit costs from 19% (100 m) to 38% (800 m) with respect to the nominally loaded forwarder (12 t load).

Additional load reduction up to 1/3 height of the load area (34% of the vehicle payload) resulted in the decrease of productivity ranging from 27% (distance of 100 m) to 54% (distance of 800 m) and increase of unit costs from 37% (100 m) to 117% (800 m) with respect to the nominally loaded forwarder (12 t).

Such wide range of productivity decrease and increase of the forwarder unit costs due to higher distance of timber forwarding are the consequence of interaction between time consumption of vehicle travel and loading and unloading timber or load volume (Poršinsky & Stankić, 2006a; Stankić, 2010). Obviously the decrease of the loaded timber highly affects the forwarder efficiency (especially with the increase of the forwarding distance) and therefore, from the economic point of view the method for providing vehicle mobility as well as environmental soundness of timber forwarding under conditions of limited soil bearing strength of the Croatian lowland forests is absolutely not acceptable.

4.2 Environmental soundness

Nominal ground pressure of vehicles is based on interaction between the load of vehicle wheels and its contact area, by which the methodological applicability is only restricted to the case of equal wheel tire dimensions and equal load distribution by the vehicle wheels. In case of different dimensions of the front and rear wheels, i.e. unequal load distribution between front and rear axle of the vehicle, (transfer from wheel–soil system into vehicle–terrain system), Saarilahti (2002a) uses the so-called »reference wheel« (the wheel with the highest contact pressure) or the contact ground pressure is expressed separately depending on the wheels of the front and rear axle, respectively (Poršinsky & Horvat, 2005).

Depending on mass (0–12 t) of roundwood loaded in the forwarder load area (Fig. 6a), the total vehicle mass increases, and there is a considerable increase of the load on rear wheels (1.8–4.6 t) and a relatively insignificant increase of load on front wheel (4.1–4.5 t). With mass increase of the loaded timber <11.5 t, the wheels of the front axle are the reference wheels, after which (just before reaching the vehicle payload) the rear wheels take over this role. The Bavarian federal forests have developed a special approach to the assessment of the environmental soundness of vehicles used in timber harvesting aimed at protecting soil from compaction, which is based on 4 classes of wheel load (Fig. 6a), i.e. in using wide (≥700 mm) tires (Wolf, 2010). According to the Bavarian guidelines for the whole carrying capacity range (<12 t), the wheels of the front axle of the tested forwarder are in the area of »acceptable« wheel load, while the rear wheels are in the area of »optimal« load <9.5 t of the load mass.

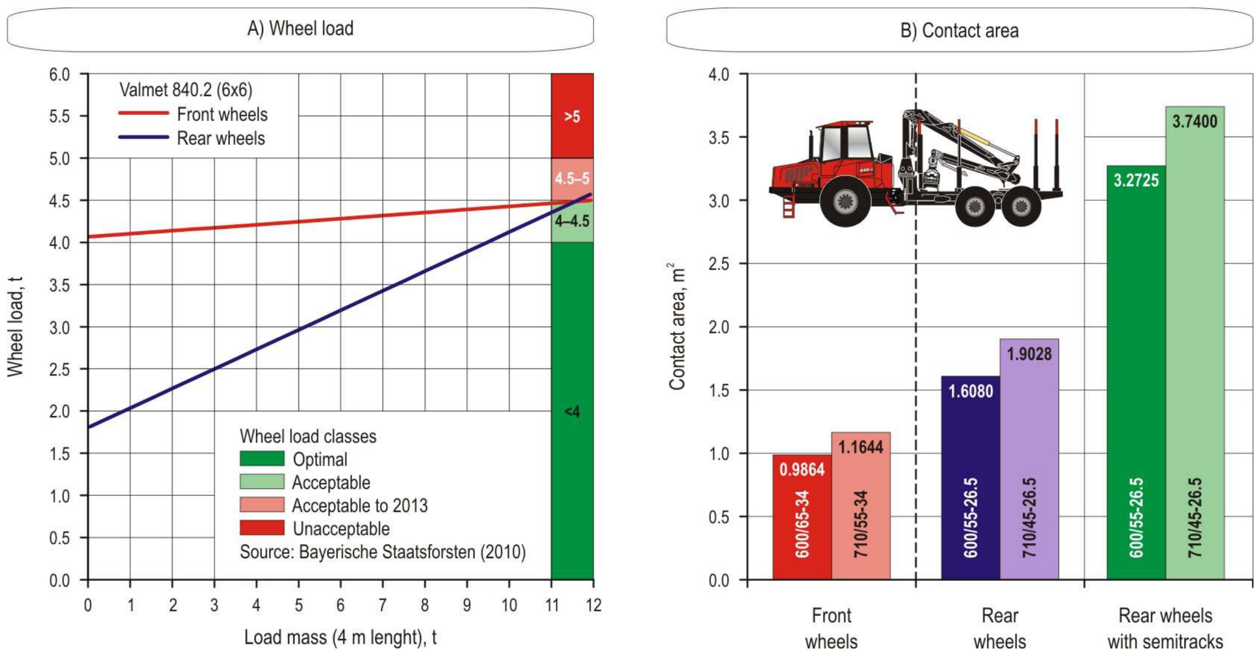

Fig. 6. Wheel load and contact area – Valmet 840.2 (6x6) Forwarder

The analysis of the vehicle-soil contact area (Fig. 6b) showed that the contact area increased by 18% (under the front wheels, but also under the rear wheels) when using wide tires (710 mm) compared to narrow tires (600 mm). The use of semi-tracks on rear wheels of the bogie axle resulted in an almost double increase of the contact area.

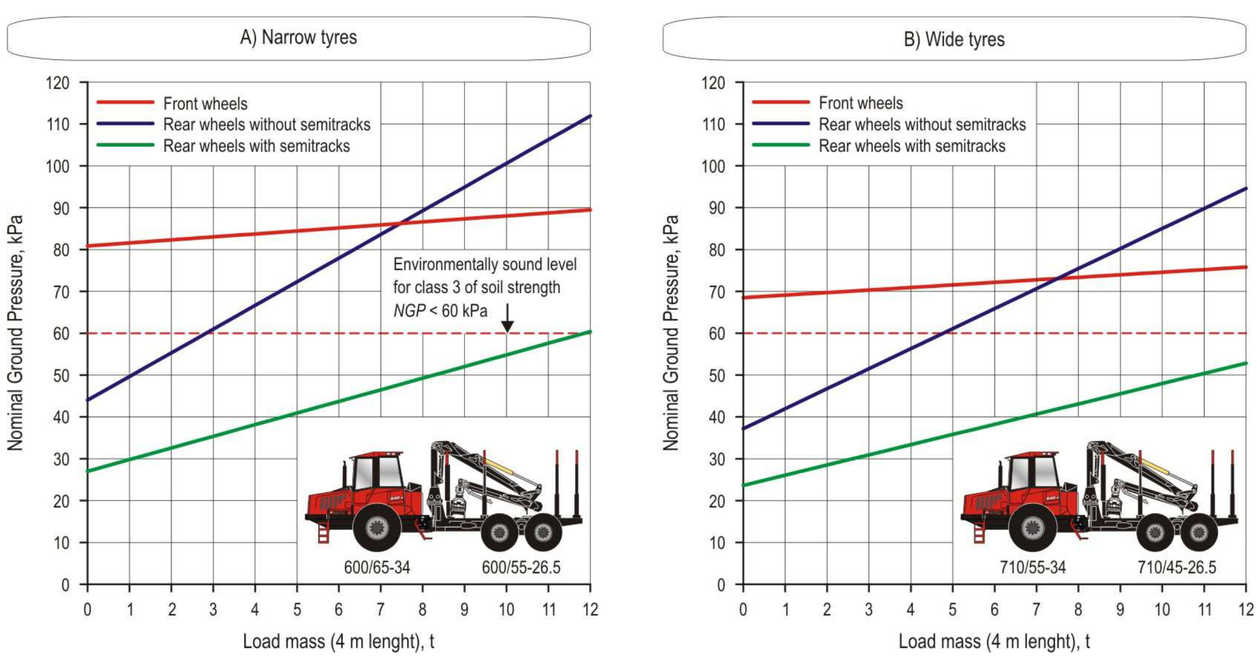

Fig. 7. Nominal Ground Pressure of front and rear wheels (track) vs. load mass

The analysis of the impact of the mass of roundwood loaded into the forwarder load area on the value of the nominal ground pressure under the front and rear wheels of the vehicle, or under the wheel semi-tracks of the rear tandem axle is shown in Fig. 7a for narrow tires (600 mm) and in Fig. 7b for wide tires (710 mm).

Regardless of the use of narrow or wide tires, and also of the load mass, the nominal ground pressure under the forwarder front wheels exceeds the allowed load of the soil of limited bearing strength (<60 kPa). With narrow tires (600/65-34), for the carrying capacity range of the vehicle (<12 t), the nominal pressure is 35–49% higher than allowed. The advantage of using wide tires (710/55-34) on the front wheels of the vehicle can be seen in the decrease of the exceeded nominal pressure, which ranges between 14 and 26% with respect to the allowed value. From the aspect of environmental soundness, the solution of the overloaded front axle of the six-wheel forwarder is an eight-wheel forwarder.

The nominal ground pressure under the forwarder rear wheels equipped with narrow tires (600/55-26.5) exceeds the allowed load of the soil of limited bearing strength in loading timber of the mass >3 t, and when using wide tires (710/45-26.5) in loading timber of the mass >5 t, which is extremely unfavorable from the aspect of timber forwarding (Fig. 5).

By using semi-tracks on rear wheels of the tandem swinging axle with narrow tires, the nominal ground pressure is lower by 55–2 % (depending on load mass) compared to the allowed value. Equipping the forwarder with semi-tracks on wide tires is additionally suitable for the environmental soundness of timber forwarding due to the additional decrease of the nominal ground pressure, which is lower ranging from 61% (unloaded vehicle) to 12% (loaded vehicle) compared to the allowed contact pressure of the soil of limited bearing capacity.

5. Conclusion

Under conditions of limited soil bearing capacity of gley soils due to increased moisture, the decrease of forwarder load, as a measure that provides vehicle mobility and also reduces the level of damage to forest soil, is highly unacceptable from the point of view of timber forwarding efficiency.

The analysis of the nominal ground pressure under the wheels (tracks) of the front and rear axle gave the following guidelines for efficient and environmentally acceptable timber forwarding, under conditions of limited soil bearing capacity:

- due to higher nominal pressure under the front wheels of the three-axle forwarder with respect to the allowed load on the soil of limited bearing capacity (<60 kPa), the use of four-axle (eight-wheel) forwarders is recommended,
- the use of wide tires (710 mm) still provides unsatisfactory increase of load mass with respect to the vehicle equipped with narrow tires (600 mm), provided that the allowed soil load is not exceeded,
- in order to provide adequate mobility, full use of the vehicle payload that assures forwarding efficiency, but also environmental soundness, the use of semi-tracks on wheels of tandem front and rear axle of an eight or ten wheeled forwarder is recommended (Fig.8).

These results should be used as guidelines for future purchasing of forwarders, by which efficient and environmentally sound timber forwarding would be provided under conditions of limited bearing capacity of gley soils in main felling sites of lowland forests in Croatia and elsewhere.

Source: www.ponsee.fi

Fig. 8. Eight and ten wheeled forwarder with semi-tracks

6. Acknowledgment

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