Utilizing Airborne Laser Scanning Technology in Predicting Bearing Capacity of Peatland Forest

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Abstract – Nacrtak

Airborne laser scanning (ALS) technology is receiving increasing attention in forestry. So far, ALS is mainly utilized at a rather abstract level to derive better estimations on the composition of forest stands (e.g. volumes of wood assortments per hectare). Recent rather expensive ALS inventory projects have raised interest in whether other purposes can also benefit from ALS data. The paper demonstrates a case study where the ALS data was utilized in predicting the bearing capacity of peatland forest. The study stand was divided into 16 × 16 m^2 grids within which the volume of trees in each cell was estimated. In addition, the height of the terrain (elevation) at each point was estimated. The stand was harvested with a harvester and a forwarder during the summertime, after which the ruts of the trails were measured. The results indicate that ALS may be a promising technology in making predictions on the bearing capacity of peatland forests prior to harvest. More research in this subject is however needed to develop the most effective methods. Both the volume of trees and the relative elevation of the surface of the peatland may be regarded as beneficial information in the prediction of bearing capacity.

Keywords: tree harvesting, ALS, rut depths

1. Introduction – *Uvod*

Airborne laser scanning (ALS) data has been shown to provide reliable estimates on growing stock. Hence, ALS-based forest inventories are gradually replacing field inventories in many countries. The estimation methods can be divided into two approaches. The aim of the individual tree delineation (ITD) approach is to discern individual trees or groups of trees based on 3D ALS data. The aim of the area-based statistical approach (ABSA) is to estimate mean forest stand variables for a fixed area using statistical correlations between explanatory variables derived from the ALS data and forest stand variables.

So far, ALS has mainly been utilized in a rather abstract level to derive better estimations of the composition of forest stands. Research around ALS technology has been very active recently, but these projects have mainly concentrated on making better predictions as to the quality attributes of trees (Maltamo et al. 2009; Bollandsås et al. 2010; Holopainen et al. 2010), improved predictions of tree species (Korpela et al. 2010) or estimation of saw log recoveries (Peuhkurinen et al. 2008). Recent rather expensive ALS inventory projects have also attracted interest in the benefits that ALS data can bring to other purposes.

Peatlands are problematic from a logging operations point of view. The mean tree size and stand density are generally lower than on mineral soils leading to low harvesting removal. The ditch network weakens machine mobility and the average primary transportation distance is generally double that of mineral soils. The low bearing capacity (the strength of soil to prevent vehicles from sinking into it) is, however, the most severe factor affecting timber harvesting.

The mobility of forwarders on peatland has been studied extensively. Comprehensive in situ driving tests have been arranged to compare the mobility of vehicles (Sirén et. al. 1987; Ala-Ilomäki et al. 2011), to

predict the mobility of vehicles in various types of peatland (Nugent et al. 2003; Zeleke et al. 2007), to compare the effects of wheels and bogie tracks on rut formation (Bygden et al. 2004; Suvinen 2006; Ala-Ilomäki et al. 2011), or to utilize the data recorded by the harvester to assist in planning the routes of the forwarder (Suvinen and Saarilahti 2006). These studies have resulted in recommendations on suitable vehicle sizes and the equipment needed to carry out logging in unfrozen peatland forests.

Peatland usually consists of a top layer with living and slightly decomposed plants, followed by a layer of decomposed peat and, finally, mineral soil. From the bearing capacity point of view, the top layer with considerable tensile strength provided by roots of trees and shrubs is essential, whereas the supporting function of the decomposed peat is of secondary importance. The strength of the top layer is subject to the variation of density and species of the vegetation, resulting in extreme spatial variation in trafficability (Ala-Ilomäki 2006).

Due to the low bearing capacity in peatland forest, special attention should be given to planning logging operations. Main logging trails should be placed on spots with the highest volumes of trees. Logging trail network should be planned in a way that minimizes the number of passes along the main logging trails. Stands where a main logging trail cannot be located on terrain having sufficient bearing capacity should only be harvested during the coldest period of winter. ALS might offer useful information when carrying out analyses on the trafficability of peatland forests prior to harvest. The aim of this study was to test whether it is possible to utilize DEM and ALS-based estimates on volumes of trees calculated using the ABSA method in predicting the bearing capacity of peatland forest.

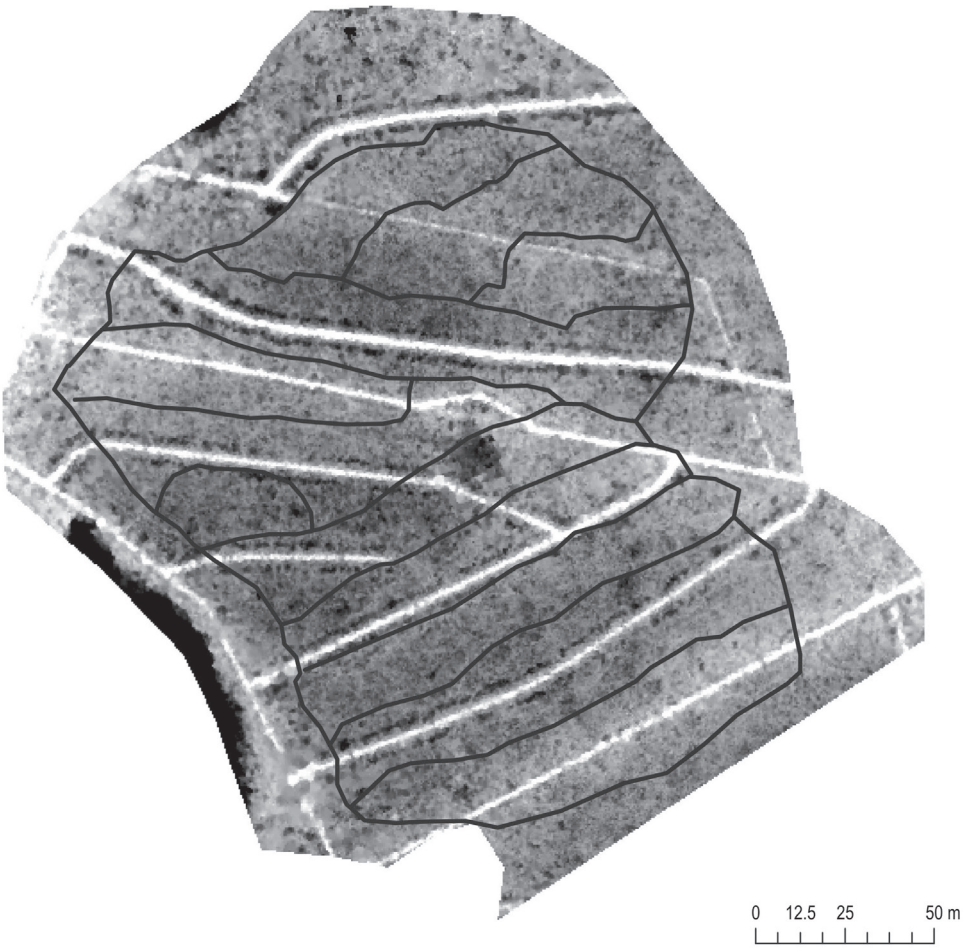

Fig. 1 Digital elevation model derived from the ALS data together with the logging trails. The darker the color of the point, the higher the elevation
Slika 1. *Digitalni model terena nastao iz podataka dobivenih laserskim snimanjem, zajedno s izvoznim putovima (područja obojena tamnije više su nadmorske visine)*

2. Material and methods – *Materijal i metode*

The study was conducted in a Pine mire in southern Finland, close to the Hyytiälä Forest Station, in Juupajoki. The area of the study site was 4.5 ha, the mean size of trees was 15 cm, basal area 24 m^2 and tree density 1500 trees/ha. The study site had been laser-scanned for study purposes several times, in 2004, 2006, 2008 and 2010. During those years the ground-truth, field inventory data on exact diameters and heights of trees, had been collected from more than 20 circular plots, each with a 9 meter radius.

The laser scanner surveys provided a point cloud, at which the points x, y and z were known. A digital elevation model (DEM) was produced from the last pulse data, whereas the first pulse data was used to produce the canopy height model (CHM). Since the last pulses include both ground and non-ground hits, the data was first classified with the Multiscale Curvature Classification (MCC) system proposed by Evans and Hudak (2007). Parameters –*s* 1.0 and –*t* 0.2 were used in the classification. The data was then interpolated using ArcGis software with the Inverse distance weighted (IDW) tool. The three closest observations were used in the interpolation (Fig. 1).

Canopy heights (z values) were calculated as the difference between the orthometric heights of laser hits and the estimated ground elevation values at the corresponding locations. The stand was covered by a 16 × 16 m grid. The volume of trees and the basal area were estimated for each grid cell with the aid of z values, field inventory data and regression models suggested by Holopainen et al. (2008).

The stand had been ditched a couple of times, the last ditching operation having been carried out roughly ten years prior to our tests. Hence, some ditches had

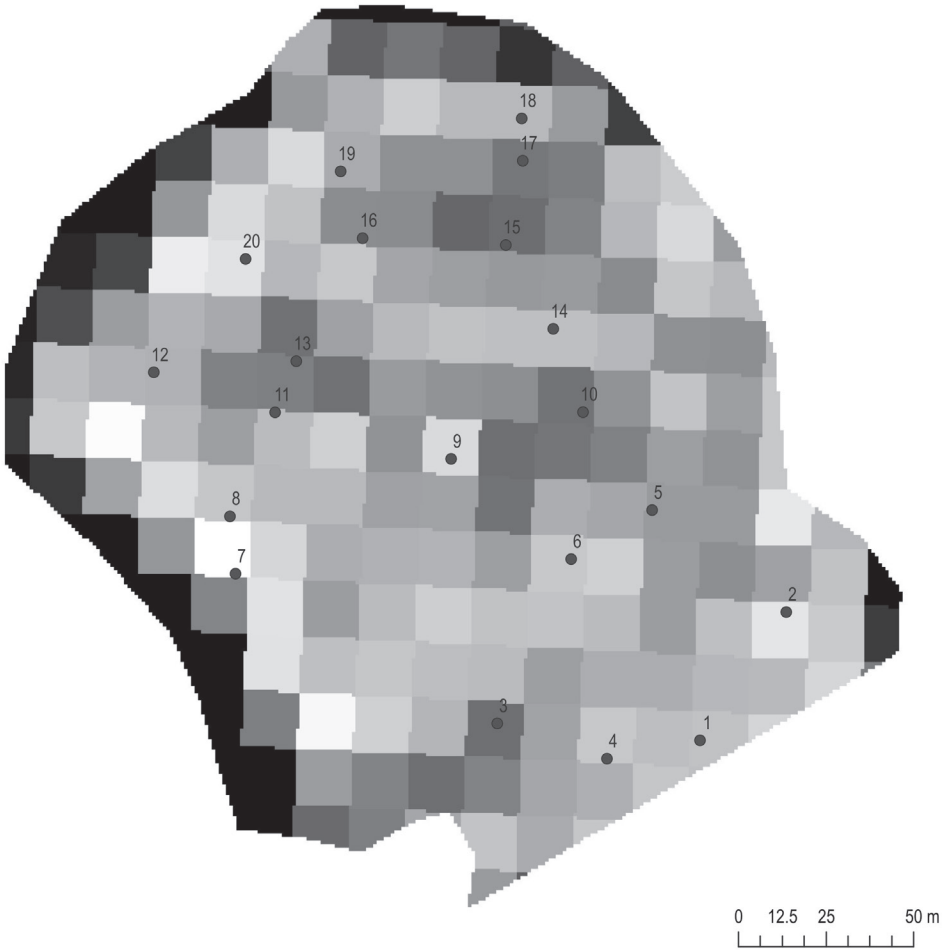

Fig. 2 Volume of trees for each grid cell and locations of the study plots. The darker the color of the cell, the higher the volume

Slika 2. *Obujam stabala u svakom kvadratu rasterske mreže i lokacije ploha na kojima je provedeno istraživanje (područja obojena tamnije imaju veći obujam stabala)*

dug soil at the edges of the ditch, giving higher elevation hits (altitude above sea level) than the surrounding area. In addition, the stand included two mineral soil spots being at a clearly higher level than surrounding peatland. The lowest points occurred at the bottoms of ditches. The maximum difference in altitude above sea level (ASL) within the stand was 1.5 m. Each 16 × 16 m grid was given an ASL value (the mean of ground elevation values within the grid).

The planning of the logging trail network for thinning operations was carried out prior to harvest. Following that, 20 study plots were systematically placed all over the stand along the logging trail network. The exact location of the logging trails and the study plots can be examined in Figs. 1 and 2.

The study stand was harvested using a John Deere 1070D harvester in early August 2010. The harvester driver was given a printed map of the pre-planned logging trail network, which he was asked to follow while executing the thinning operation. The logging trail network actually accomplished was tracked by the GPS recorder in the machine (Fig. 1). The final location of the central point of the study plot was recorded using the Trimble ProXH GPS recorder. A wooden pole was hammered into the ground beside the logging trail to ensure that the measurement, after cutting and forwarding operations, was carried out at the same points. A ten-meter-long vector was placed along the centerline of the logging trail, starting from the central point of the study plot. The depth of both ruts caused by the harvester was measured at one-meter intervals along the vector. The basic level of the ground was defined by pushing a 3.5 m long and 3 cm thick metal pole against the ground perpendicular to the centerline of the trail. The mean depth of rut caused by harvester (Rut_{harv}) for the sample plot is the mean of all twenty measurements taken within the plot. Subsequently, ten-meter-long sample plot vectors were drawn using ArcGIS software. The mean value for the ASL along the vector was calculated by weighting each ASL class value with the length of that class within the vector.

The forwarding operation was carried out the week after the cutting, using a John Deere 810E forwarder with band tracks in both the front and rear bogies. Each route from the storage point to the storage point of the forwarder was recorded using John Deere TimberNavi software. The bearing capacity of the soil was very low, so the operation was forced to stop before all the wood was forwarded to the roadside. Rut depths after forwarding (Rut_{forw}) were measured similarly to the measurements carried out after harvesting. Ruts after forwarding were measured from only 16 study plots. Based on the tracking reports of each route of the forwarder, the total over-driven mass for each sample plot was estimated. The total over-driven mass for the sample plot is calculated by summing up the mass of the harvester and the estimate of mass of the forwarder (mass of the machine + mass of load) for each time it passes the sample plot.

3. Results – Rezultati

3.1 Correlations between rut depth of harvester and the parameters estimating bearing capacity – *Povezanost dubine kolotraga harvestera i pokazatelja procjene nosivosti podloge*

The mean rut depth of the study plots varied between 2.0–17.1 cm. No clear spatial correlation was found. Small and high mean depths were found all over the stand. The correlations between rut depths and the most important parameters estimating bearing capacity are presented in Table 1.

The correlation between the rut depth of the harvester and volume is weak, and in this case it is also illogical, since the volume and the rut depth of the harvester should have negative correlation (i.e. the

Table 1 Correlation coefficients between volume, basal area, ASL and rut depth after harvesting (Rut_{harv})
Tablica 1. *Koeficijenti korelacije između obujma stabala, temeljnice, nadmorske visine i dubine kolotraga harvestera*

	Basal area *Temeljnica*	Volume *Obujam*	ASL *Nadmorska visina*	$Ruth_{arv}$ *Dubina kolotraga harvestera*
Basal area – *Temeljnica*	1	0.926(**)	–0.086	–0.059
Volume – *Obujam*	–	1	–0.199	0.125
ASL – *Nadmorska visina*	–	–	1	–0.378 (*)
$Ruth_{arv}$ – *Dubina kolotraga harvestera*	–	–	–	1

Significance levels – *Razine značajnosti:* (**) = 0.01; (*) = 0.1; $N = 20$

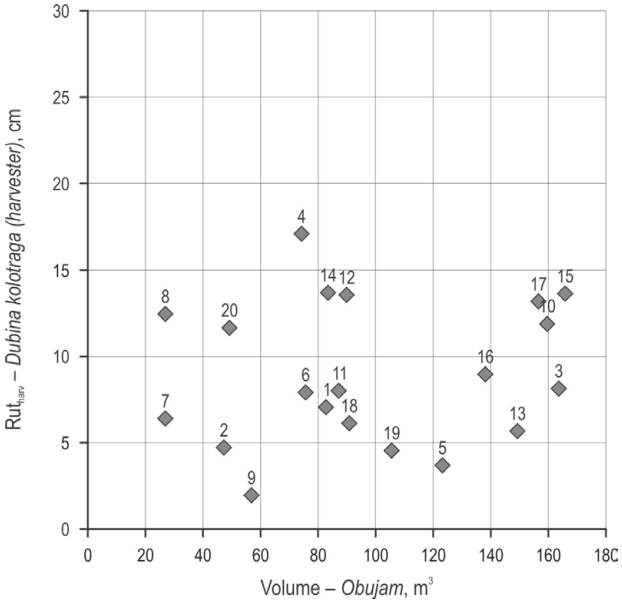

Fig. 3 Covariation between rut depth of harvester and volume
Slika 3. *Ovisnost dubine kolotraga harvestera i obujma stabala*

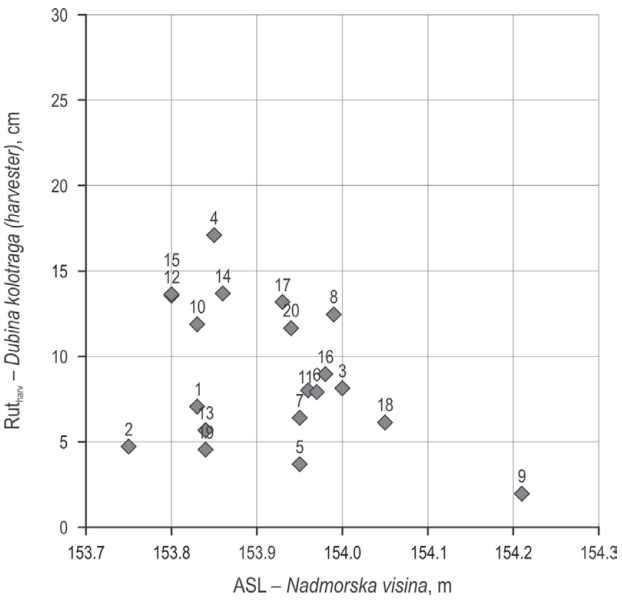

Fig. 5 Covariation between rut depth of harvester and ASL
Slika 5. *Ovisnost dubine kolotraga harvestera i nadmorske visine*

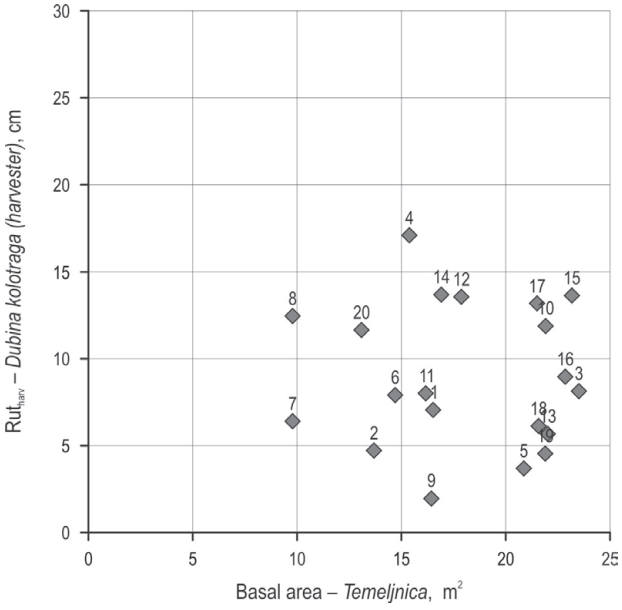

Fig. 4 Covariation between rut depth of harvester and basal area
Slika 4. *Ovisnost dubine kolotraga harvestera i temeljnice*

smaller volume, the deeper the ruts). Close examination of the results (Figs. 3 and 4) revealed that the most illogical observations, study plots 10, 15 and 17) are located in the north-east corner of the stand. In this area there are relatively high volumes and deep ruts. If these observations were removed from the data, the correlation between the volume and the rut depth of the harvester would be roughly –0.2. The correlation between the rut depth of harvester and the basal area is close to zero but it is neither negative nor illogical.

A moderate and statistically significant negative correlation was found between the rut depth of the harvester and ASL. The study plot located at the edge of the mineral soil spot clearly differs from the other data. The rut depth of the harvester of this plot is only 2 cm (Fig. 5).

3.2 Correlations between the rut depth of the forwarder and the parameters estimating bearing capacity – *Povezanost dubine kolotraga forvardera i pokazatelja procjene nosivosti podloge*

Forwarding caused very deep ruts for all trails and was highest for those main (arterial) trails that lead to the storages. Rut depths caused by the forwarder were measured in 16 plots. The forwarder passed through study plot 5 unloaded only once. Correspondingly, in study plot 6, forwarder passed through six times; three times unloaded, once half-loaded and twice fully loaded. The total over-driven mass for the sample plot varied between 17,200–123,100 kg.

The mean rut depth after forwarding varied 2.0–27.5 cm. The correlations between rut depths after forwarding and the most important parameters estimating bearing capacity are presented in Table 2. Vol-

Table 2 Correlation coefficients between volume, basal area, ASL, over-driven mass and rut depth after forwarding
Tablica 2. *Koeficijenti korelacije između obujma stabala, temeljnice, nadmorske visine, privučenoga drva i dubine kolotraga forvardera*

	Rutforw *Dubina kolotraga forvardera*
Basal area – *Temeljnica*	–0.681(**)
Volume – *Obujam*	–0.576(*)
ASL – *Nadmorska visina*	–0.205
Over-driven mass – *Privučeno drvo*	0.386

Significance levels – *Razine značajnosti:* (**) = 0.01; (*) = 0.1; $N = 16$

Table 3 Partial correlation coefficients between basal area, volume, ASL and rut depth of forwarder while controlling the over-driven mass
Tablica 3. *Parcijalni koeficijenti korelacije između obujma stabala, temeljnice, nadmorske visine i dubine kolotraga uz nadzor količine privučenoga drva*

	Rut_{forw} *Dubina kolotraga forvardera*
Basal area – *Temeljnica*	–0.622
Volume – *Obujam*	–0.470
ASL – *Nadmorska visina*	–0.234

$N = 16$

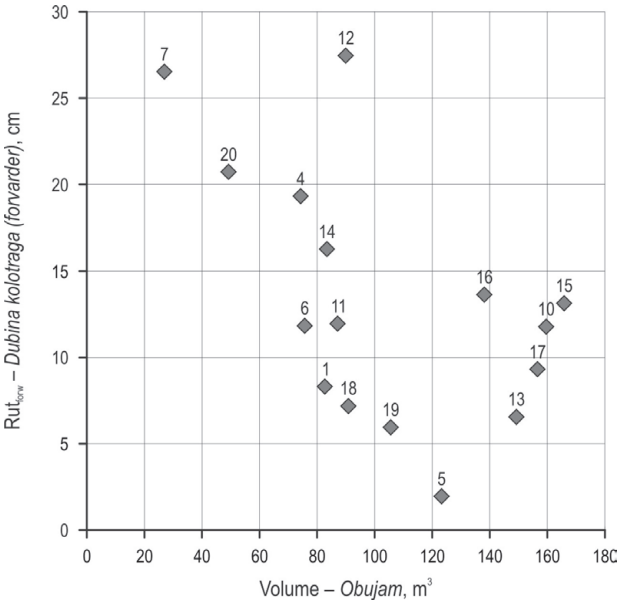

Fig. 6 Covariation between rut depth of forwarder and volume
Slika 6. *Ovisnost dubine kolotraga forvardera i obujma stabala*

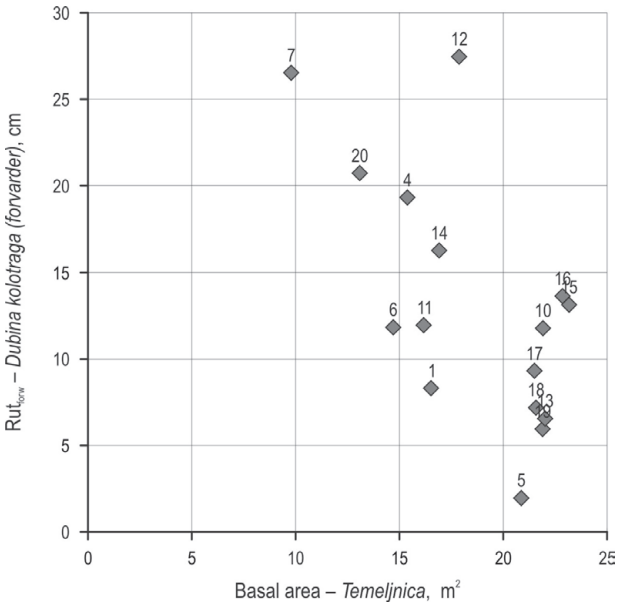

Fig. 7 Covariation between rut depth of forwarder and basal area
Slika 7. *Ovisnost dubine kolotraga forvardera i temeljnice*

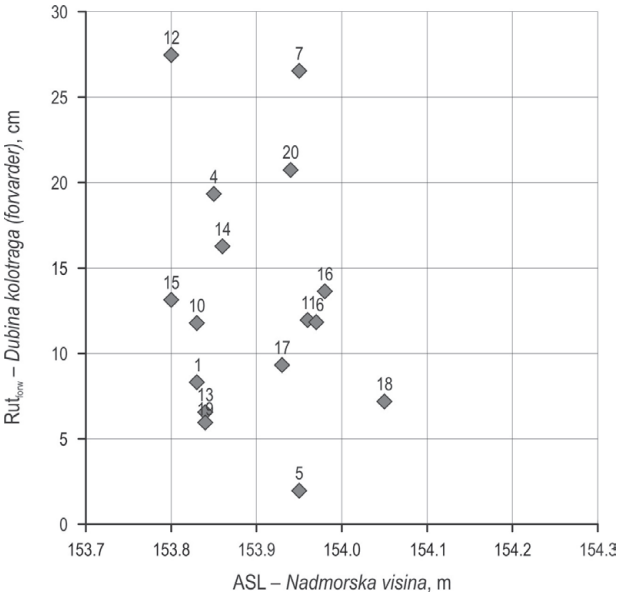

Fig. 8 Covariation between rut depth of forwarder and ASL
Slika 8. *Ovisnost dubine kolotraga forvardera i nadmorske visine*

ume, basal area and ASL have a distinct, negative correlation with the rut depth of the forwarder. This correlation is illustrated in Figs. 6, 7 and 8 to get a better insight into the covariation of these parameters. It is quite obvious that over-driven mass has a positive correlation with the rut depth of the forwarder and this factor has a distinct effect on the correlations giv-

en. Therefore, the relationship between the rut depth of the forwarder and other parameters should be examined by excluding the effect caused by the over-driven mass. The partial correlations between rut depth, basal area, volume and ASL while controlling the over-driven mass are given in Table 3.

4. Discussion – *Rasprava*

This field study was carried out in only one stand, so one cannot make strong judgement on the results of the study. No negative correlation was found between tree volume and rut depth caused by the harvester, which was rather surprising. One corner of the study stand gave the most illogical observations. The removal of these observations would have changed the correlation coefficient to negative (i.e. the less volume, the deeper the ruts). It might be that the structure of the peat layers within this area were different compared to the rest of the stand. There are also many other factors affecting the rut depth caused by the harvester that are irrelevant in terms of the relationships investigated here. These factors include the effect of the driver, the curve of the trail, individual tree stumps, logging residual, and so on.

A logical, negative correlation was found between tree volumes and rut depths measured after forwarding. Basal area gave a slightly higher correlation with rut depths after forwarding than volume. This is in accordance with earlier findings which state that in peatlands, a greater relative proportion of biomass is allocated into the root system compared to mineral soil (Laiho and Finer 1996; Finer and Laine 1998). This means that from a bearing capacity point of view, it is better to have two small trees than one big tree.

It is not clear why the correlation after tree volume and rut depths were illogical after harvesting but logical after forwarding. Other factors such as moisture content of peat, peat type, shear strength of the roots or the amount of cutting depris that were not measured in this study may have an effect on these results. It might also be so that the differences in bearing capacity appear distinctly only after forwarding because in many plots harvester alone do not break the root mat that have most important supportive function.

The relative elevation of the surface of the peatland seems to have an influence both on the rut depths measured after harvesting and forwarding. Peatland might include spots or areas where mineral soil is at a higher level than the surrounding area. There might even be areas where no peat layer exists. In areas where ditching operations have been carried out, the edges of the ditches where dug soil have been placed have higher elevation. These edges of the ditches have a higher bearing capacity than peatland far away from the ditch.

DEM and CHM are basic elements provided in typical ALS projects aimed at estimating tree volumes in forest stands. It seems to be very promising that the information produced can also be utilised in making predictions on bearing capacity within peatland stands. However, mean stand volume predicted for 16 x 16 m^2 grid cells may not be the most useful way of utilising information on trees detected by ALS. Future projects should concentrate on analysing the most cost-effective way to make predictions on the bearing capacity on peatlands. Information on the multitude of trees within the stand can be expressed in many alternative ways. Future projects should concentrate on identifying whether is worth calculating the volume of trees within a certain area or whether the CHM itself can provide sufficient information on the bearing capacity of peatland forests. It is also important that the most important factors affecting bearing capacity such as moisture content of peat, peat type, shear strength of the roots and the amount of cutting depris are measured in order to clarify the role of each factor.

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Sažetak

Primjena tehnologije laserskoga snimanja iz zraka za procjenu nosivosti tresetišta

Lasersko snimanje iz zraka (Airbourne laser scanning – ASL) postaje sve zanimljivije u šumarstvu. Do sada je ASL primjenjivan većinom za dobivanje procjene stanja sastojine (npr. procjena drvne zalihe po hektaru). No nedavni projekti ALS-a potaknuli su zanimanje za primjenu ALS-a i u drugim područjima šumarstva. S gledišta pridobivanja drva tresetišta su vrlo problematična staništa zbog svoje osjetljivosti. Na tresetnim staništima srednje kubno stablo i sječna gustoća većinom su manji nego na mineralnim tlima, što utječe na proizvodnost harvestera i forvardera. Mreža odvodnih kanala na tresetištima, koja je umjetno napravljena radi olakšanja odvodnje, smanjuje kretnost vozila te u prosjeku dva puta povećava srednju udaljenost privlačenja. Ograničena nosivost tla, karakteristična za tresetišta, značajan je čimbenik koji utječe na proizvodnost prilikom pridobivanja drva.

Zbog ograničene nosivosti tla na tresetnim staništima posebna se pozornost treba posvetiti planiranju pridobivanja drva. Tako bi se glavni izvozni putovi trebali postaviti da prolaze preko mjesta na kojima je najveći obujam stabala, a mrežu izvoznih putova treba planirati da se što više smanji broj prolazaka vozila po glavnim izvoznim putovima. Sve radove pridobivanja drva u sastojinama u kojima je nemoguće postaviti glavne izvozne putove na mjesta dobre nosivosti tla trebalo bi provoditi zimi dok je tlo smrznuto. Pomoću ALS-a možemo dobiti korisne informacije koje će pomoći pri analizi nosivosti tla i prohodnosti tresetnih staništa prije početka sječe. Cilj je ovoga rada testirati mogućnost primjene digitalnoga modela terena i ALS-a, temeljenoga na procjeni obujma stabala pomoću metode ABSA (metoda koja se koristi podacima izvedenima na osnovi laserskih snimaka i podacima prikupljenim na terenu) za procjenu nosivosti tla na tresetnim staništima.

Istraživanje je provedeno u poplavnoj borovoj šumi u južnoj Finskoj, blizu šumarije Hyytiälä, u Juupajoki. Područje obuhvaćeno istraživanjem protezalo se na 4,5 ha, srednji je prsni promjer iznosio 15 cm, temeljnica je bila 24 cm^2/ha, a gustoća stabala 1500 stabala/ha. Istraživano je područje laserski snimano za potrebe ove studije nekoliko puta 2004, 2006, 2008. i 2010. godine. Tijekom tih godina prikupljani su i terenski podaci, točni prsni promjeri stabala i visine su skupljene na više od 20 kružnih ploha, promjera 9 metara. Laserskim snimanjem dobiven je oblak podataka, gdje je svaka točka bila definirana koordinatom x, y i z. Iz dobivenih podataka zadnja je serija podataka

korištena za izradu digitalnoga modela terena, dok su podaci iz prve serije snimanja upotrijebljeni za izradu digitalnoga modela visine stabala. Visina stabala (koordinata z) izračunata je kao razlika između ortometrijske visine udara laserske zrake i procijenjene nadmorske visine za određenu lokaciju. Istraživano je područje pokriveno rasterskom mrežom 16 × 16 metara. Obujam stabala i temeljnica procjenjivani su za svaku rastersku plohu uz pomoć vrijednosti koordinate z, terenskih podataka i regresijskih modela. Sječa, izrada i izvoženje obavljeno je ljeti, nakon čega su mjerene dubine kolotraga.

Istraživanjem odnosa obujma stabala i dubine kolotraga harvestera nije ustanovljena negativna korelacija, što je bilo iznenađujuće, dok je kao rezultat istraživanja odnosa obujma stabala i dubine kolotraga forvardera dobivena očekivana negativna korelacija. Nije utvrđeno zašto odnos obujma stabala i dubine kolotraga poprima neočekivanu vrijednost nakon sječe i izrade harvesterom, dok nakon izvoženja forvarderom poprima očekivanu vrijednost. U ovom istraživanju nije utvrđeno imaju li ostali čimbenici, kao što su vlažnost treseta, vrsta treseta, posmična čvrstoća korijenskoga sustava i količina šumskoga ostatka, utjecaj na dobivene rezultate. Moguće je da se izrazita smanjena nosivost pojavljuje samo nakon prolaska forvardera jer na mnogim plohama, naknon prolaska harvestera, nije utvrđen slom korijenskoga sustava koja značajno pridonosi povećanju nosivosti tla.

Temeljnica, u odnosu na obujam stabala, u jačoj je ovisnosti o dubini kolotraga, nastalim nakon prolaska forvardera, što je u skladu s prijašnjim istraživanjima, koja kazuju da se na tresetištima relativno veća količina biomase nalazi u korijenskom sustavu nego kod mineralnih tala. Iz toga slijedi zaključak, s aspekta nosivosti tla, da je bolje imati dva mala stabla nego jedno veliko.

Na dubinu kolotragâ, nastalih nakon prolazka harvestera i nakon prolaska forvardera, relativna nadmorska visina ima značajan utjecaj, što dolazi do izražaja jer u samim tresetištima ponekad postoje dijelovi na kojima je mineralno tlo izdignuto od ostatka tresetišta, čak se znaju pojavljivati i dijelovi bez tresetnoga sloja. Nadalje, u tresetištima u kojima su prije kopani odvodni kanali iskopana je zemlja odlagana uz rubove odvodnih kanala te su zbog toga sad ti dijelovi nešto viši od okolnoga tresetišta i imaju bolju nosivost nego samo tresetište.

Rezultati ovoga istraživanja upućuju na ALS kao obećavajuću tehnologiju koja će pripomoći u donošenju procjena nosivosti tresetišta prije početka sječe. Doduše, potrebno je provesti još dodatnih istraživanja kako bi se razvile što učinkovitije metode procjene. Uz to je ovo istraživanje, što je jedan od važnijih rezultata, pokazalo da se obujam stabla i relativna visina površine tla u tresetištu mogu okarakterizirati kao vrlo dobri čimbenici za procjenu nosivosti tla.

Ključne riječi: pridobivanje drva, lasersko snimanje iz zraka, dubina kolotraga

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