A GIS Approach to Analyzing Off-Road Transportation: a Case Study in Sweden

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Abstract – *Nacrtak*

Off-road driving in logging operations began in Sweden in the 1960s. Those operations took place at final fellings during winter on prepared ice roads that protected the soil and mitigated possible soil damage. Today logging operations are fully mechanized and performed all year round. Thus forest strip roads may suffer severe impacts from off-road operations. Soil disturbances may have physical, chemical, biological, hydrological, and economic effects and affect the water quality. Similar problems are encountered in other regions, where driving occurs close to watercourses or vulnerable areas. The EU Water Directive has an impact on operations in forests, creating an incentive for improvements. Ongoing efforts in the design of vehicles and equipment are likely to improve operations. Soil damage can be avoided by applying GIS-based planning techniques, and by taking advantage of soil radar-scanned and ground laser-scanned data sets, which would facilitate safer off-road driving to a great extent. A case study in southern Sweden revealed that the use of digital planning for the improvement of strip roads in order to avoid vulnerable terrain made forwarding of timber more profitable. Using elevation, slope, aspect and soil type digital layers, a model has been created in 'model builder' environment of ArcGIS to build up a cost-index surface, which classifies the terrain suitability for driving into five different levels. Implementing distance analysis, the model designs the least costly roads connecting any desired destination to the landing point. The result of this study reveals that this kind of pre-planning tool can mitigate ecological damages to soil and water and at the same time it can also assist decision makers to evaluate different possible choices of road layouts regarding preserving sensitive regions in forest lands.

Keywords: GIS-based decision support system; Digital Terrain Model (DTM); ground damage; forest operations; forwarding; planning; rutting; soil

1. Introduction – *Uvod*

The mechanization of logging operations in Sweden and other countries began in the 1960s, and it led to off-road driving in order to bring timber to the landing. Those operations took place at final fellings during winter on prepared ice roads, thus protecting the soil and mitigating soil damage. Today, all logging operations are mechanized and performed throughout the year due to the all-year-round fresh timber demands of the pulp industry. Off-road driving is extensive on all forest lands during all seasons, even when the ground is vulnerable to soil disturbance. Any professional forester has to consider the great variety in the Swedish landscape in terms of topography, soil types and surface water.

In the 1970s, a terrain classification system was developed to aid the planning of off-road driving in conjunction with forest operations (Forskning stiftelsen Skogsarbeten 1969 and Skogforsk 1992). Recent guidelines (Ring et al. 2008) addressed the impacts of off-road driving from a water-quality perspective. Off-road driving close to surface water increases the surface water sediment load risk. Such sediments might be harmful to aquatic organisms (Skogforsk 2008). The guidelines allocate a 5–10 m zone bordering on lakes and streams in order to mitigate sediment release into water, avoiding driving on streams and wet areas, and utilizing technical devices in order to reduce physical soil disturbance at crossings. Planning is another important tool for reducing such negative impacts.

The aim of this paper is to;

⇒ elucidate the risky aspects of road driving in forest operations with respect to current forms of legislation.

⇒ investigate ways of mitigating soil damage by trying out a planning decision support system in a case study in South-Eastern Sweden. This decision support system facilitates routing in terrain considering soil, water and restricted areas. Proper route alignment for avoiding probable sliding of the loaded forwarders on steep slopes was considered as part of this method.

⇒ estimate possible financial gains by evaluating different route alternatives at a felling site.

1.1 Environmental and social significance *Okolišne i socijalne značajke*

Primary soil damage in conjunction with off-road driving may have secondary effects that cause physical, chemical, biological, hydrological, economic or aesthetic impacts. Although not specifically regulated in the environmental standards for forestry, the event of forest certification manifested in schemes like PEFC (2012) or FSC (2012) has stressed the importance of disturbance control in connection with off-road driving. One reason for this is the less permissive attitude to soil disturbance in Central Europe (Hauk 2001; Hildebrand and Schack Kirchner 2002). Off-road operations increase soil density down to 50 cm, and decrease soil aeration and thereby reduce root penetration (Eliasson and Wästerlund 2007). This impact varies with moisture content (Ziesak 2003; Yavuzcan et al. 2005). Rutting may result in compaction (Jamshidi et al. 2008) and adverse driving conditions, leading to costly interruptions and breakdowns, which eventually increase the energy use and related emissions. Reduction of soil disturbances at off-road operations can be beneficial both for the environment and for operational cost reduction. Physical soil disturbances may affect ecosystem pools of C and N in the soil (Finér et al. 2003). European environmental policies stipulate that processes in agriculture and forestry (e.g. draining, off-road driving and harvesting) which in general reduce C storage, should be avoided (Anon. 2004 and 2006). Increased nitrate leaching is commonly found after clear cutting and soil scarification (Ring et al. 2008). Logging tracks often induce similar disturbances to the soil and thus there is a risk of elevated N-mineralization and denitrification in these areas. Final fellings might result in the discharge of Hg and its consequent accumulation in fish (Bishop et al. 2009). This might be attributed to anoxic conditions in the soil caused by the raised water level in tracks.

Swedish environmental objectives (Swedish EPA 2011) regulate several impacts likely to be caused by soil damage in conjunction with forest operations and off-road driving. Under the EU Water Framework Directive (Anon. 2000), there is also a legal responsibility to maintain the water status. The generally anticipated process leading toward global warming (Peters 1990) is likely to affect the frequency of rainfall, droughts and what is nowadays called extreme weather, especially in Europe (Bolte et al. 2009). The authors believe that similar legal and consequent political pressure will affect forest planning and forest operations.

1.2 Technical means for mitigating ground damage – *Tehničke mjere za ublažavanje oštećivanja podloge*

Ground damage is caused when forces and pressures are exerted on the ground surface via the wheels or tracks of terrain vehicles. The resultant effect is compaction of the soil, skidding, and shearing of vegetation or soil layers. These effects can technically be avoided either by the design of the machine/vehicle or mitigated via operational skills, for example adjusting vehicle properties by reducing the impact of the load on the ground (Ziesak 2003; 2004) or the use of ancillary equipment (Staland & Larsson 2002) along planned routes to enable passages over brooks or other watercourses. Technical improvements in laser scanning have also provided quite precise data layers representing terrain surfaces in the form of Digital Terrain Models (DTM). These DTM layers, especially high resolution ones, have been quite attractive in supporting forestry operations in recent years since they provide thorough and detailed information about terrain topography (i.e. terrain elevation and steepness), which in turn are used to choose the best skidding system in complex forest fields (Lubello 2008; Vega et al. 2009). Krč and Košir (2008) have also used Digital Elevation Models (DEM) to develop a model for terrain classification based on the best predicted skidding direction on steep terrain. Benefiting from DEM along with other inventory information about the rockiness and stoniness of a terrain, Mihelič and Krč (2009) analyzed how to define new skidding systems or forwarding possibilities on different terrain classes in Slovenia.

High resolution DTMs are also used to define various soil wetness indexes like the Depth to Water Index, DTW (Murphy et al. 2008), and Compound Topographic Index (CTI) (Goetz 2010), to predict vegetation terrain types and ground bearing capacity in forest lands which are of great help for planning silvicultural activities.

1.3 Design of machines – *Konstrukcija strojeva*

Via machinery design, basic properties of a machine impact can be altered and adjusted to actual conditions. This can be done by adjusting the wheel pressure exerted on the soil through changing the tire pressure (wheel width) or using wider tires (Jonsson 2011). Tracks might be added in order to distribute forces more evenly over the ground surface, which itself will enhance the risk of shearing at turns. By adjusting the air pressure in the tires to the soil and the load or vice versa, the operator has the means of reducing ground damage (rut depths). Tests made with a CTI-system (Löfgren 1994) on a forwarder showed that the rut depth of 600 mm – wide tires with low pressure is the same as that of 800 mm – wide tires and high pressure. Basic machine properties have an impact on the ability to negotiate terrain. Positioning of the wheels before driving over obstacles using hydrostatic driving may be beneficial. The reduction and damping of vibrations has a similar effect (Baez 2008). Geometric design is the determining factor for a beneficial distribution of pressure on the wheels.

1.4 Supporting equipment – *Pomoćna oprema*

With the aid of different sorts of technical equipment, it is possible to reduce the damage to virtually nil; however, there is a cost and the issue is to have the required equipment on the right spot at the right occasion. The means for doing this are fixed or temporary bridges along the hauling route, or carrying prefabricated bridges for immediate use, for example when crossing a ditch. Other solutions are to work with ground cover rigs made of timber or tire mats. Moreover, the use of harvest residues and downgraded wood logs constitute other possible means. Residues or straw can be spread out along the hauling route in order to mitigate the ground damage when passing over sensitive spots (Eliasson 2007; Saunders and Ireland 2005). Consequently, it is important to plan the harvesting of residues, considering where the residues are needed to improve the bearing capacity of the ground, and where they could be harvested as forest fuel.

1.5 Planning – *Planiranje*

The issue of the right application of routes and ancillary equipment, as well as where the residues should be used on the forest road, is coordinated by planning. In order to plan the operations and utilize the ancillary equipment, updated maps are mandatory. Planning based on the Geographic Information System (GIS) is a great step forward compared to former methods as it is feasible to explore a variety of digital layers of information, extract the required relevant knowledge, evaluate possible alternatives and, finally, make appropriate decisions. A number of researchers have assessed the trafficability of terrain types for different goals with the aid of GIS. Initially, GIS was used for military off-road planning (Lubello 2008), and gradually it was introduced in the fields of agriculture and forestry. In most cases, GIS has been used for choosing the optimal routes out of a number of already-existing possible networks: Rongzu and Mikkonen (2004) used GIS to provide an optimized wood logistics GIS model based on a combined cost surface created from road transport costs and off-road transport cost surfaces. Pentek et al. (2005) used GIS to analyze the quality and quantity of an existing forest road network to determine potentials for planning future routes. Suvinen (2006) used a GIS-based simulation model to assess terrain tractability regarding two sets of constant and dynamic factors as well as machine characteristics to suggest a proper route layout for different load/terrain conditions. However, lateral inclination, which is an essential factor for properly guiding a machine on steep terrain, was neglected in that study.

2. Materials and methods – *Materijal i metode*

2.1 Study area and scenario definition – *Područje istraživanja i definiranje scenarija*

The study area under consideration was the property of Selesjö in Östergötland, located in South-Eastern Sweden, and it was mainly dominated by Norway spruce and Scots pine, Fig. 1. In the close vicinity of the harvesting site, with an area of 6.72 ha, a possible landing point was selected, where the harvested timbers were to be stored for further operations. This landing point was to be reached from 4 arbitrary destination points at the harvesting site. However, there was a wetland between the landing point and part of the stands, which needed to be protected against driving damage. This area as well as other existing sensitive parts, like ditches and streams, were called 'No Go' areas and were totally excluded for the purpose of locating the routes. Possible route alignment to reach the destination points with minimum disturbances to the surrounding environment was evaluated under two different scenarios: in Scenario 1, the routes were expected to go beyond the wetland and reach the landing point, while in Scenario 2 the possibility of building a corduroy road to pass the wetland was analyzed to see how the route layout would have to be adjusted to the new conditions and how much it could reduce the cost of transportation by providing shorter route stretches.

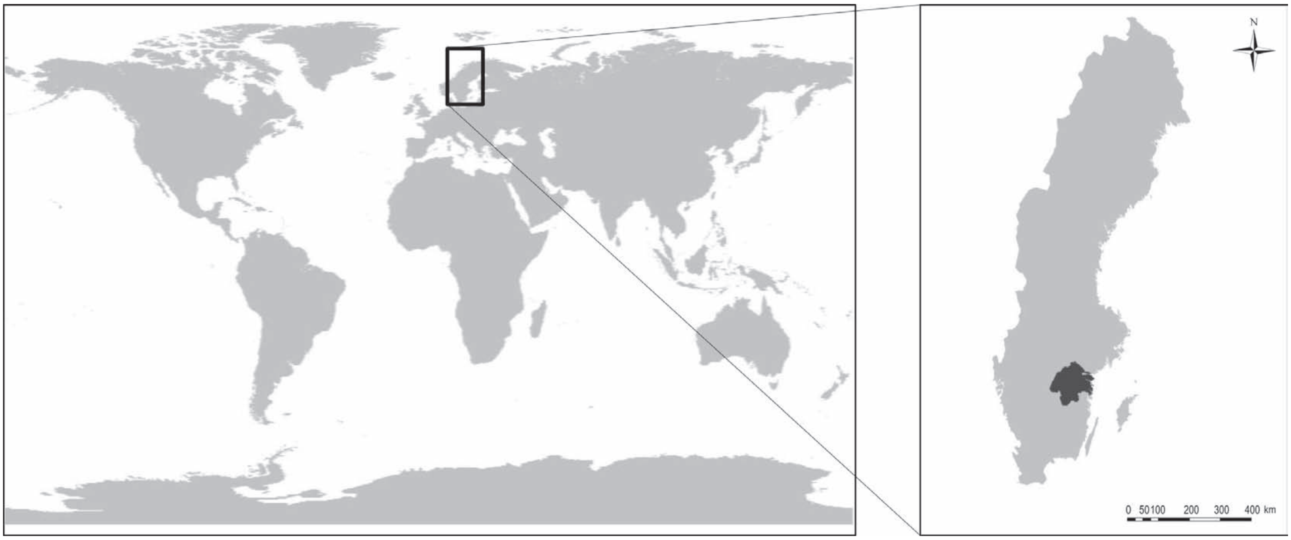

Fig. 1 Location of the study area on a map of the world (left) and in Sweden (right)
Slika 1. *Područje istraživanja na karti svijeta (lijevo) i u Švedskoj (desno)*

2.2 Input data and software – *Ulazni podaci i softver*

Data layers used in this model were as follows: a high resolution, 0.5 × 0.5 meter Digital Terrain Model (DTM), FORAN SingleTree® Laser Method, which are both the products of high density, 8–10 points/m^2, and laser scanning of the area using Foran Remote Sensing AB. The former layer was in raster format and the latter was in point format, containing information about tree species, crown diameter, stem diameter and the gross volume of stands. Slope and Aspect grid layers were extracted from the DTM and were used to evaluate the topography of the study area. All the grid materials were reclassified to a coarser resolution of 4 × 4 to be sure that each pixel can support the width of forwarders. Soil types, in polygon format, provided by the Swedish Geological Research Institute (SGU), represented different textures of the soil in the area. Environmentally-sensitive spots such as nature reserves, key biotopes and habitat-protected regions as well as historical values, were prepared by the Swedish Forest Agency, or Skogsstyrelsen (2011); these areas were to be set aside as protected. Separate shape layers localizing the landing point (source) and the destinations were other inputs in the model. In this study, the 10th version of the ArcGIS software packages provided by the Environmental Systems Research Institute, Inc. (ESRI 2012), including ArcMap, ArcCatalog were used for data preparation, data processing, information exploration, evaluation and, ultimately, for viewing the final results. The Slope, Aspect, Path Distance and Cost Path tools available from the Spatial Analysis and the 3D Analysis extensions were used to build up the desired model within the 'Model Builder' environment of ArcGIS.

2.3 Procedure of the analysis – *Postupak analize*

Planning sustainable forestry operations requires simultaneous consideration of the economic and ecological values in the forest. These two aspects do not always introduce similar approaches for forest managers in practice and consequently there is always an essential need to reach a consensus among all the stakeholders regarding evaluating and integrating various criteria and making the best decision. Eastman et al. (1998) defined it so simply: »decision is a choice between alternatives«, and Multi-Criteria Decision Analysis (MCDA) is a procedure that can unify several attributes and/or objectives as part of the decision-making process (Malczewski 2006). Therefore, this procedure formed the basis of the analysis for finding the optimal routes in this study. Weighted Linear Combination (WLC) was the rule applied in this process as it was compatible with the ArcGIS software.

Applying MCDA, elevation, slope and soil types were regarded as the most determining factors for estimating different levels of suitability of the area for driving. Since soil bearing capacity for supporting massive forest machinery has a direct relation with the degree of soil moisture, it has been assumed that the lower the elevation in an area, the higher the probability of having wetness in soil would be, and thus the worse the ground conditions for driving would be. Following this assumption, the elevation layer was used as

Table 1 Summary of data reclassification for cost-index surface preparation

Tablica 1. *Zbirni prikaz razredbe podataka za pripremu vrijednosnih indeksa površine*

Factors *Faktori*	Factor classification – *Razredba faktora*	
	Original values *Izvorne vrijednosti*	Cost-index values *Vrijednosti indeksa*
Elevation *Visina* (46–65 metres)	65–60	1
	60–55	2
	55–50	3
	50–46	5
Slope *Nagib* (0–90 degrees)	0–6	1
	6–11	2
	11–18	3
	18–27	4
	27–90	5
Soil classes *Tipovi tla*	Rocks-*outcrop*	1
	Till	3
	Silt	5

a simple model to identify the risky wet parts in the area. Slope layer was used to quantify the terrain steepness and to avoid driving on steep terrains (slope > 18 degrees). The soil type layer was used to find water courses, wetlands and similar sensitive parts in the area. These three layers were reclassified to a new scale of 1 to 5, called a cost index, in order to have a common scale for defining the suitability of the ground for terrain driving on all layers. The better the driving conditions, the lower the assigned cost index value to the corresponding class in each of the data layers was, Table 1.

For example the elevation values in this area ranged between 46 and 65, and therefore it was reclassified so that the values between 46 and 50 got the cost index (5), elevations between 50 and 55 got the cost index (3), elevations between 55 and 60 got the cost index (2), and the highest part with elevations between 60 and 65 got the minimum cost index (1). Finally, in order to integrate all these input layers into a single cost-index layer with 5 levels of suitability, different weights of importance were assigned to them based on ideas from a panel of 7 experts at the Forestry Research Institute of Sweden; Skogforsk. Elevation resulted in a weight gain of 50%, since in this case it had much better precision compared to the soil type layer for predicting where the moist soil texture could be located. Flat and low elevated areas are assumed to be wet and unsuitable for driving. The soil type layer gained 20% in terms of the weights and was used as a complementary layer to find the areas with the best bearing capacity, and finally Slope gained the remaining 30% in order to avoid technical problems under operational conditions. Later on, soil classes with unsuitable bearing conditions (such as wetlands, peat lands), as well as steep slopes (> 18 degrees) and ditches were regarded as constraints on the study area and were extracted from the cost-index surface by assigning »No Data« to their values and visualized with the darkest grey color in Fig. 2 and Figure 3. Afterwards, feeding the cost-index surface as a cost raster into the Path Distance tool together with the landing point layer, as the source, with DTM layer as the surface raster and Aspect as the horizontal factor into the Path Distance tool, the least accumulative cost of getting back to the landing point, raster distance, and also the proper direction of moving to the neighboring cell, backlink raster, was determined at this stage. A maximum inclination of 5 degrees with respect to the slope direction of the ground was meant to be achieved for the route layouts. This was implemented by applying the horizontal factor parameters in the Path Distance tool. The Aspect layer, defining the direction of the slope of the ground, was used as the input horizontal raster. The horizontal factor was set as a table type in ASCI format. This table consists of two columns; the first one is called the Horizontal Relative Moving Angle (HRMA) and defines the relationship of the moving direction with respect to the horizontal direction of the terrain, while the second column is called the Horizontal Factor (HF), and defines the difficulty of moving from one cell to another (ESRI 2011). In this case, all the HRMA between 5 and 175 degrees, which indicate uphill or downhill movement with too much tilting, were assigned very high HF (100), while for other HRMA ($0 \leq HRMA \leq 5$ degree or $175 \leq HRMA \leq 180$) that would not cause too much tilting on the terrain, the HF varied linearly between a value of 1 to 5; the smaller the tilting, the lower the assigned HF was.

The formula applied to calculate the values of the raster distance in Path Distance tool is (ESRI 2011):

⇒ For perpendicular movement:

Cost_distance = Cost_Surface * Surface_distance * {[Friction(a)* Horizontal_factor(a) + Friction(b) * Horizontal_factor(b)] / 2} * Vertical_factor

⇒ For diagonal movement:

Cost_distance = Cost_Surface * Surface_distance * 1.414214 * {[Friction(a) * Horizontal_factor(a) + Friction(b) * Horizontal_factor(b)] / 2} * Vertical_factor

The outcomes of this part aligned with the destination layer were inserted into the Cost Path tool to design the route layout in the harvesting site. As explained earlier, a wetland was located in the way of connecting the destinations within the site to the landing point, outside the harvesting border. In Scenario 1, the model was supposed to plan the routes by going beyond this restricted part, while in Scenario 2, a strip with the minimum cost-index (1) was added to the cost-index surface, over the wetland to a corduroy road that could be built on the wetland and contribute to a different route layout in the field.

3. Results – *Rezultati*

The model suggested the routes with the lowest cost index within the context of two different scenarios (Fig. 2 and Fig. 3). Both of these two route alignments are promising for reducing soil and water disturbances by suggesting the routes on the lowest cost-index values (i.e. the best driving conditions), while compensating for the surface distance and slope directions. Moreover, this model gives decision makers the opportunity of comparing the route alignments in two different scenarios, with or without a corduroy road, in order to find the most appropriate course of action. In this case, it was conceived that following the route design in Scenario 2 and building a corduroy road on the preserved wetland could contribute to a reduction of almost 700 m in the length of the routes to be passed from the destination points to the landing point. Using the FORAN SingleTree® Laser Method layer, the standing volume in the southern and central part of the area was measured as almost 2 526 m^3. This is actually the timber volume on the part that would be connected to the harvesting point through the corduroy road. The following table describes the equivalent volume in solid over bark and in tons, Table 2.

Thus, having almost 1 573 tons of timber at this site, and assuming the maximum possible load of large (PONSSE ElephantKing) forwarders to be 20 tons, the number of loaded forwarders required for collecting the timber is 79, which would result in 158 (79×2) passages of the mentioned forwarder over the terrain.

Fig. 2 Least costly routes suggested by the model for Scenario 1
Slika 2. *Izvozni pravci predloženi modelom za inačicu 1*

Fig. 3 Least costly routes suggested by the model for Scenario 2
Slika 3. *Izvozni pravci predloženi modelom za inačicu 2*

Table 2 Timber stands described as m^3 standing and volume solid over bark and mass as metric tons

Tablica 2. *Sastojinske značajke; drvo na panju u m^3, obujam s korom i masa u tonama*

m^3 standing *Drvo na panju* u m^3	m^3 solid over bark *Obujam s korom* u m^3	Tons *Masa u tonama*
2 526	2 097*	1 573**

* Conversion factor: m^3 solid over bark/m^3 standing = 0.83

** Conversion factor: tons/ m^3 solid over bark to = 0.75

Based on the experts' ideas at the Forestry Research Institute of Sweden, it has been assumed that the maximum velocity of a large forwarder is 0.8 m/s and its average operational cost is 85 Euro/hour. Thus, the second route layout over the corduroy road would result in a reduction of EUR 3,200 for the whole forwarding operation. The estimated cost of constructing the corduroy road was EUR 500, according to a panel of experts, which is less than the operational cost saving in Scenario 2 and therefore makes it more profitable.

4. Discussion and Conclusion – *Rasprava i zaključci*

Anticipated changes due to global warming and international agreements require well-considered planning of forest operations. The negative chemical, biological and physical consequence of soil damage is proven (e.g. Finér et al. 2003; Bishop et al. 2009). As a result of legislation and forest certification, it is important to show that operation managers have identified this aspect, and actions have been undertaken in order to remedy or improve deviations from the standards, which means that the operations must be close to best practices.

Means are available for mitigating damage, namely equipment for crossing water streams and wetlands, or tracks to mitigate rutting, but their successful use depends on access to relevant terrain information. Not just any equipment will be used when the right equipment is not available when needed. The advent of better pre-planning tools with the aid of GIS can facilitate that. High-resolution digital terrain models generated from laser scanning of the forest lands have improved the task of planning by providing comprehensive details about the terrain structure e.g. elevation, slope, etc. The digital maps in general use, with information about factors such as wetland areas or other objects of concern to be safeguarded, can ensure improved plans for achieving sustainable forestry in practice that are probably more economically rewarding and are likely to be asked for by planners, decision-makers or auditors from any certification agency. The case investigated in this study demonstrated that a practical application of available digital information and models for the planning and construction of alternative shorter and better routes in fact resulted in improved profitability of timber forwarding. Applied in a wider context, such improvements might result in substantial monetary savings and less disturbance to soil and water.

The impact any vehicle has on soils is influenced by its basic design, its wheels, and its load. The damage caused is a combination of the driving and planning applied. Improvements in machine properties will take a long time before they have an effect on the fleet of logging machines, and some will be more effective than others. Planning tools will have an immediate effect and will enable better allocation of logging machines to appropriate logging areas.

Acknowledgement – *Zahvala*

This research was performed at the Swedish Forestry Research Institute, Skogforsk, and the authors would like to thank the program managers Johan Sonesson and Magnus Thor for their valuable support. Dr. Wayne McCallum is also acknowledged for his help in checking the authors' English. The editor and reviewers are thanked for their comments and recommendations.

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Sažetak

Raščlamba terenskoga transporta uz pomoć GIS-a: primjer iz Švedske

Izvoženje drva pri njegovu pridobivanju započelo je u Švedskoj 1960-ih godina. Taj se oblik primarnoga transporta obavljao nakon dovršnih sječa tijekom zime na pripremljenim zaleđenim sekundarnim prometnicama, što je štitilo šumsko tlo i ublažavalo njegovo moguće oštećivanje. Današnji šumski radovi u potpunosti su mehanizirani i provode se cijele godine. Zbog toga su sekundarne šumske prometnice (vlake i putovi) pod značajnim utjecajem radova koji se provode u šumskom bespuću. Oštećivanje tla izaziva mehaničke, kemijske, biološke (smanjen prirast), hidrološke i ekonomske promjene i narušava kakvoću podzemnih i površinskh voda zbog prekomjernoga otpuštanja zagađivača, kao što je metil-živa koja nastaje od anorganske žive u anaerobnim uvjetima u jezerima ili rijekama (http://en.wikipedia.org/wiki/Anaerobic_organism). Slični problemi pojavljuju se i u drugim regijama, gdje se privlačenje drva izvodi u blizini vodotoka ili u područjima podložnim oštećenju tijekom toplijih godišnjih razdoblja. Direktiva Europske unije o vodama utječe na šumske radove tako što stvara poticajno okruženje za ublažavanje i otklanjanje tih problema. Trenutačni napori u konstrukciji vozila i pripadajuće opreme vjerojatno će poboljšati provedbu šumskih radova. Oštećivanje tla može se izbjeći primjenom privremenih prijelaza preko ugroženoga područja ili pomoćne opreme, ali i upotrebom nove generacije tehnika i tehnologija laserskoga skeniranja u šumama, s 8–10 lokacija po kvadratnom kilometru, koje pruža prilično precizne podatke o sastojinskim i terenskim značajkama.

Ta je vrsta sustava za pomoć pri donošenju odluka o određivanju izvoznih pravaca s manjim posljedicama za okoliš bila izrađena i testirana u pokusnom području smještenom u jugoistočnoj Švedskoj. Različiti digitalizirani slojevi, na primjer nadmorska visina i nagib, izlučeni su iz digitalnoga modela reljefa visoke razlučivosti (0,5 m × 0,5 m) radi pronalaženja najpovoljnijih područja za vožnju izbjegavajući pri tome tehničke probleme koji se javljaju na strmim terenima. Ti su slojevi bili združeni sa slojevima tipova tla i zaštićenih područja da bi se dobila osnovna karta vrijednosnoga indeksa područja. Ta karta dijeli područje u pet razina prikladnosti za vožnju primjenom razredbe koja se zove vrijednosni indeks. Niži indeks označuje pogodniji teren s obzirom na nosivost tla. U sljedećem koraku pomoću navedenoga indeksa vrijednosti površine model pronalazi najkraće putove najmanjega kumulativnoga vrijednosnoga indeksa spajajući bilo koje željeno odredište u sječini s odabranom lokacijom pomoćnoga stovarišta. Svakako, u tom *je studijskom području močvara, koja je trebala biti izuzeta od vožnje, bila locirana uz pomoćno stovarište, što je zahtijevalo da se pri planiranju procijene dva različita pristupa izradi izvoznih pravaca za prikupljanje drva, 1) vožnjom iza močvare i dosegom odredišta u sječini za utovar drva, ili 2) izgrađivanjem prijelaza preko močvare radi dolaska do pomoćnoga stovarišta. Rezultati su pokazali smanjenje udaljenosti vožnje dobivene prelaskom preko izgrađenoga mosta uz smanjenje operativnih troškova, ali i povećanje troškova zbog izgradnje mosta, do čega se došlo uz pomoć opisanoga modela za planiranje izvoznih putova.*

Ključne riječi: sustav GIS za pomoć pri odlučivanju, digitalni model reljefa, oštećivanje tla, šumski radovi, izvoženje drva, planiranje, gaženje, tlo

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Received (*Primljeno*): February 17, 2012
Accepted (*Prihvaćeno*): April 30, 2012