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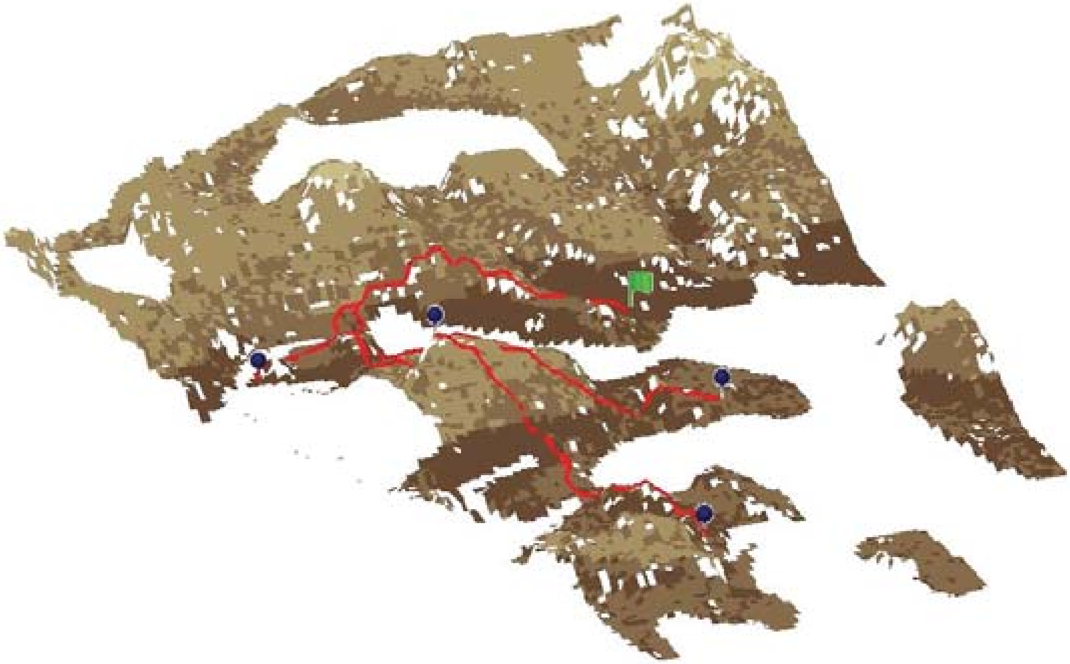

Planning forest routes for silvicultural activities using GIS based techniques

A case study of Selesjö in Östergötland, Sweden

Planering av terrängtransport vid avverkning med hjälp av GIS

En fallstudie av Selesjö i Östergötland, Sverige

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Keywords: Forests, GIS, Planning harvesting routes, Lateral inclination.

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Content

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Sima Mohtashami

Abstract

Forests are natural resources that provide essential services for different groups of users from human beings to native habitats. They are actually home of diverse range of biological groups; contribute to alleviate climate change through sinking carbon-dioxide from the atmosphere and supplying oxygen back to it and finally they are regarded as wood resources by human beings.

In recent decades, exploitation of forest woods, specifically by application of operational machineries, has exerted severe pressure on basic elements of forests, such as soil and water. Massive weights of harvesters and forwarders could cause soil compaction, rutting and runoff formation which threatens regrowth and biodiversity in soil and water systems. All these environmentally negative impacts could be avoided or at least minimized if forest operational activities are accompanied by proper and intelligent pre-planning. Geographic Information System (GIS) is one of the technological achievements with great potentials that can assist decision makers in exploring scientific questions, analyzing various alternatives and evaluating possible choices of actions through computer systems.

This study developed a GIS-based technique for planning main access routes for logging operations in harvesting sites in a manner to minimize environmental damages to soil and water. A model was created within the model builder environment of the ArcMap, version 10, using the existing tools in Spatial Analyst and 3D Analyst extensions of the ArcMap. A cost-index surface consisting of major effective factors i.e. elevation, slope and soil type was created to be fed into the Path Distance tool in order to perform distance analysis. The model was run over two separate study areas to evaluate possible route designs within the harvesting sites. Two distinct route layouts, corresponding to predefined scenarios, were suggested by the model for each of the study areas to connect the landing point(s) to some arbitrary destinations inside the harvesting border. The novel achievement of this study could be regarded as the proper route alignment with respect to the slope direction of the ground in the ArcMap environment, to avoid lateral inclination of loaded forwarders on the steep slopes.

Sammanfattning

Under de senaste decennierna har skogsmaskinernas utveckling lett till att maskinerna blir större och tyngre. Skogsmaskiner kan orsaka betydande skador på grundläggande element i skogarna, som till exempel mark och vatten. Tunga skördare och skotare orsakar komprimering och spårbildning, vilket kan leda till bl.a. till ökad erosion och avrinning, som hotar återväxten och den biologiska mångfalden i mark- och vattensystem. Alla dessa miljömässigt negativa effekter kan undvikas eller åtminstone minimeras om avverkningstrakten planeras noggrant.

I detta examensarbete utvecklades en modell baserad på Geografiska Information System (GIS), som är en teknisk landvinning med stor potential för att hjälpa beslutsfattare att utforska vetenskapliga frågor, analysera olika alternativ och utvärdera möjliga val av åtgärder via datorsystem. Modellen skapar möjligheten att planera avverkningsvägar på ett bättre sätt, så att skador på mark och vatten minimeras.

Modellen skapades inom 'Model Builder' som är ett gränssnitt i ArcMap, version 10, med hjälp av befintliga verktyg i Spatial Analyst och 3D Analyst. En digital terrängmodell över två studieområden i sydöstra Sverige tillhandahölls av Foran Remote Sensing AB. En upplösning på 0,5 meter användes för att extrahera höjddata, lutnings- och lutnings riktningsdata, vilka tillsammans med jordartsdata från Sverige Geologiska Undersökning (SGU) användes för att skapa en kostnadsindexyta med värden mellan 1 och 5. Det lägsta värdet för detta kostnadsindex visade de bästa körförhållandena inom ytan och det högsta värdet för kostnadsindexet motsvarade det sämsta läget i områdena. Den här ytan användes därefter i verktygen 'Path Distance' och 'Cost Distance' för att hitta miljövänliga vägar från avlägget till några slutpunkter i studieområdena. Modellen kördes över två olika studieområden för att utvärdera möjliga vägsmönster inom avverkningsområdet.

För att undvika för stora sidolutningar, speciellt då skotaren är fullastad, har det i detta examensarbete tagits hänsyn till lutningsriktningen på marken. Denna metod, där hänsyn till sidolutning betraktas, är helt ny mot tidigare studier där begränsningarna bara nämnts.

Slutsatsen är att mer hållbar skogsskötsel och bättre skydd av mark och vatten skulle kunna uppnås med tillämpning av denna typ av GIS-baserade beslutsstöd. Modellen har hög potential att hjälpa tjänstemän och förare till rätt beslut inför avverkning. Om det finns mer än ett möjligt avlägg, så kan modellen föreslå de som lämpar sig bäst med hänsyn både till skonsamhet och terrängtransportavstånd. Därför kan det hjälpa skogsföretag i både ekonomisk och ekologisk utvärdering av möjliga körvägsmönster som skulle vara till stor hjälp för att göra mer realistiska och samtidigt miljövänliga beslut inför avverkningsplanering.

Introduction

In Sweden forest clear cutting is usually performed using harvesters and forwarders. Due to their massive weights, these machines cause severe damages to soil and water in forest sites, specifically when forest operations lack proper preplanning. A large harvester may exceed 20 Mg and a fully loaded forwarder can approach 40 Mg, and thus increase the risk of soil compaction and rutting under undesirable soil conditions (Eliasson, 2005). Studies by Wu et al. (2007) showed that off-road vehicle movements affect negatively oxygen, nutrient and water content of the soil, disturbs natural infiltration rate and pH condition of the soil which eventually leads to reduction in growth, reproduction and diversity of biological systems in the forest lands. Soil compaction contributes to higher run-off formation which not only degrades the soil but also threatens aquatic ecosystems by mobilizing soil nutrients and probable existing contaminants, like mercury, and accumulating them in the recipients' water bodies. Scientific studies has shown that silvicultural practices are responsible for 10–25% of the mercury accumulation in fish, in high latitude managed landscapes in Sweden (Bishop et al., 2009). The adverse environmental impacts are more severe where the off-road tracks are highly trafficked and concentrated compared to disperse, low trafficked conditions (Wu et al., 2007). Figure 1 illustrates some of the environmental disturbances that occur at harvesting sites.

Figure 1A.
Negative environmental impacts: Disturbing natural infiltration of the water.

Figure 1B.
Negative environmental impacts: Soil disturbance during driving.

LEGISLATIVE CONCERNS

According to the Swedish forestry act, harvesting and transportation in forest must be planned so that damage to land and water is reduced or avoided. The natural and cultural environment must be protected during road planning. Leaving riparian buffer zones, reducing stream disturbance with bridges and avoiding operation in moist areas are other recommendations to mitigate the forest operation impacts.

Swedish environmental quality objectives, adopted by Swedish parliament in April 1999, are aiming for Sweden's major environmental problems to be solved by 2020. These objectives describe the quality of the environment desired to be achieved and hence provide guidelines for decision makers to define the required measures to be taken by all sectors of society. Sustainable forests, thriving wetlands, flourishing lakes and streams, and good quality ground water are some of the targets which need sufficient consideration during forest operational activities.

By definition, in sustainable forest, the value of forest and forest lands for biological production must be protected and at the same time biological diversity, cultural heritage and recreational assets must be safeguarded. According to Sweden's environmental objectives council's evaluation report (2008), it is very hard to achieve 'Sustainable Forests' by 2020 since forest resources are intensively exploited and in some respects, biodiversity is declining. Therefore, there is an essential need for further supervised measures in order to modify the opposing trends and pave the way to meet this target in longer term. The forest companies and other organizations involved in practical forestry give the issue a high priority.

CURRENT EXTRACTION ROAD PLANNING SITUATION IN SWEDISH FORESTS

Currently in Swedish forest companies, off-road networks are mainly designed by forest operators at logging sites using thematic maps. This procedure is rather complex, tedious, time and labor consuming. It requires simultaneous consideration of several significant factors, and hence the outcome results depend on the operators' individual skills and organizational prerequisites. Consequently minor disregards, even unintentionally, might result in disturbing the surrounding ecosystem.

Thus, there is an essential need to manipulate the already existing methods such as Multi- Criteria Decision Analysis (MCDA) and Spatial Multi-Criteria Decision Analysis (SMCDA), applicable through the ever developing computerized environment such as a Geographic Information System (GIS), to facilitate and ease the path of moving towards a more sustainable forest management in Sweden and worldwide.

OBJECTIVES AND TARGETS OF THE STUDY

The overall objective of the project was to develop a GIS-based method for utilizing existing spatial data for improved decision support for off-road routing planning in forest harvesting sites in order to minimize environmental impacts on soil and water, caused by forest operations. Proper route alignment with respect to lateral inclination of the ground, to support loaded forwarders on slopes, was also considered in this method.

The study specifically targeted two separate harvesting sites to design main routes for off-road machinery movements. Each of the study areas was evaluated under two possible scenarios. Suggested rout layouts were analyzed to provide a base for choosing a suitable scenario and its corresponding rout design in each site.

DECISION SUPPORT METHODS

Multi criteria decision analysis

Simply defined by Eastman et al. (1998) decision is "a choice between alternatives". Generally speaking, MCDA evaluates a set of diverse criteria to examine the suitability of possible alternatives. In most cases, these criteria are conflicting since they are introduced by different groups of planners, decision makers and stake holders who usually possess different ranges of interests and preferences. The aim of the MCDA procedure is to bring all groups of interest to a consensus for evaluating relevant criteria and making the best decision.

According to Malczewski (2006) the term 'criterion' could refer to both 'Attribute' and 'Objective' in a decision making procedure. Accordingly, MCDA is categorized as either Multi Attribute Decision Analysis (MADA) or Multi Objective Decision Analysis (MODA). MADA is regarded as a 'selection' procedure in a sense that it leads to a decision, based on a set of limited, predefined number of alternatives. On the other hand, in MODA, the best alternative would be chosen based on a surface of feasible possibilities. In order to evaluate the criteria, a measurement scale is needed for considered attributes. The degree to which each attribute could meet the objective would be the basis for comparing the alternatives (Malczewski, 1999).

There are a variety of rules and procedures which can assist decision makers to choose and prioritize alternatives according to their different perspectives, among which Weighted Linear Combination (WLC) has attracted the planners' attention significantly because it is easily comprehendible and also compatible with computerized tools (Malczewski, 2006).

Traditionally MCDA procedures assumed spatial homogeneity within the area under consideration, which is not an accurate assumption since many of the criteria encounters also spatial variation in reality. This reveals the need of a geographical dimension for criteria representation in MCDA, which could be achieved by application of a Geographic Information System, GIS (Malczewski, 1999).

Decision support systems, and spatial decision support systems

Decision Support System (DSS) has roots back in the 1960's when researchers started to employ computerized models to tackle their scientific problems (Lubello, 2008). Gory and Scott Morton (1971) defined DSS as an "interactive computer based system within which decision makers utilize data and models to solve unstructured problems." Malckzewski (1999) defined Spatial Decision Support system (SDSS), as any kind of computer interactive model that assists decision makers in solving semistructured spatially related problems to enhance human awareness and effectiveness during the process of decion making.

According to Lubello (2008), the main characteristics of DSS could be summarized as:

- Provision of a user-friendly interface.
- Ability of integrating data sets with the analytical models.
- Capability of supporting different decision-making procedures.
- The distinctive capabilities of SDSS are described as they:
- Have the potential to capture spatial data as inputs.
- Provide techniques for analysing spatial data sets.
- Are capable of representing spatially related features and objects.
- Provide the results of the analysis in a variety of spatial forms, such as 2D or 3D maps, etc.

Geographic Information Systems

There are two aspects in defining Geographic Information Systems (GIS); one focuses on technology values and the other on the problem solving potential (Malczewski,1999). Technologically GIS was defined by the Environmental Systems Research Institute (ESRI) as "A geographic information system integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information". Approaching from a problem solving perspective, Cowen (1988) defined GIS 'as a decision support system involving the integration of spatially referenced data in a problem solving environment'.

Both these functionalities have contributed to the capability of GIS as a technological tool which assists planners in exploring several datasets, extracting new information depending on the problem under assessment and contributing to making intelligent decisions.

Relevant studies on off-road routing

Terrain trafficability is a measure for evaluating the terrain's ability to support a vehicle's movement in the terrain. A high number of researchers with various goals and approches have studied different factors that determine this significant characteristic of the terrain. GIS for assessing soil trafficability was initially deployed for military off-road planning and later on these application were introduced to forest and agricultural land (Lubello, 2008). In some cases, terrain evaluation have been carried out based on economic considerations in order to optimize the road models regarding financial values. Rongzu and Mikkonen (2004) used GIS as an aiding tool in their suggested decision support for optimization of wood logistics based on a combined cost surface created from road transport costs and off-road transport cost surfaces. The off-road cost surfaces was constructed from indirect costs of a forwarder and the machine costs in the terrain. Streams were considered as barriers in the cost surface to avoid disturbance. They used GIS to create an optimum cost surface based on the amount of machinery (truck and forwarder) costs for driving on different road/terrain classes for road and off-road transportation of the wood. These costs were based on monetary values.

Dahlin and Fredricsson (1995) described how to compare different road alternatives from a set of already available possibilities,by evaluating the monetary costs of terrain transportation and road building and comparing it with the financial benefits gained from a road. Their model did not cover decision making concerning where to put the roads in a new area which lacks available optional road locations.In a more environmental approach, Abdi et al. (2009) used an ArcView GIS extension, called PEGGER, to design six alternative forest road networks in the Northern Province of Iran, Mazandaran. PEGGER was developed by Rogers (2005) and uses contour maps to automate road projection for forest planners in an ArcGIS environment. Abdi et al. (2009) evaluated some projected road alternatives using a suitability map which had integrated factors such as slope, soil, geology, aspect, altitude and volume of trees.

Lubello (2009) suggested a rule-based spatial decision support system for planning of forest operations using GIS techniques. His model actually consists of two parts: one for 'defining the skidding system' and one for 'systems optimization and cost'. The first part creates a feasibility map for different skidding systems based on the soil type, the amount of rain in different parts of the terrain per month and per year, a digital terrain model (DTM) of the area, and the existing road network. The author integrated soil type and amount of rain precipitation to define distinct classes of gradeability on the terrain. Upward and downward slope classes were defined based on subtracting DTM values of the area from that of the roads, as a base for comparison, and thus positive values would be indicating upward direction and negative values would be indicating downward slopes. These two outputs were integrated to determine maximum slope to which off-road systems could move inside the forest. Finally in the second part, the model evaluated technical and economical preferences for different skidding systems. This evaluation was also partly based on the already existed road network and thus could not be applied in the off-road planning phase.

Suvinen (2006) used a GIS-based simulation model to evaluate the interaction of terrain trafficabilty, vehicle mobility and terrain tractability that takes place through the machine wheel's surface. In this study, machine characteristics such as mass and dimension, load condition, wheel specification and engine power of the machines are the properties which were evaluated from the vehicle side, and on the other side, terrain condition and weather condition were considered to interact with the machine. Factors affecting terrain trafficabilty were divided into two types: 1) constant factors which are seasonally independent, like slope of the ground surface, and 2) dynamic factors which depend on the season, like moisture, snow, ice and frost. The model was capable of designing different road layouts depending on the load condition of the forwarder and the season of the year. However, lateral inclination, which has an essential role in guiding the vehicles properly in uneven terrain condition, was ignored in the model.

All these studies reveal the existence of a great potential of GIS to assist planners in assessing or designing off-road routing for forestry operations. What criteria to consider and what procedure to follow depend on the objectives of the operational designers.

Study area

The study area under consideration was the property *Selesjö* in *Östergötland*. It is located in south-east Sweden and is mainly dominated by Norway spruce and Scots pine. Figure 2 illustrates the location of *Östergötland* in Sweden and in the world map context.

Research materials

Research materials utilized in this study included datasets and map layers containing the required information. The GIS software (ArcGIS 10) was used for off-road route planning in the areas under assessment, and for evaluation of the results. Relevant research articles were investigated in order to review previous attempts, to avoid redundancy and to add some newer steps to these kinds of planning procedures.

INPUT DATA

A specification of the data used in this study is summarized in Table 1. A DTM layer, originating from a high resolution laser scanned layer (c. 10 pulses per m2) provided by Foran Remote Sensing AB, was resampled to a coarser resolution of 4 × 4 m, to ensure an aggregated condition within an area of such dimension, since the required width of the road to support the forwarders' dimension is 4 meter. Consequently soil type, environmentally sensitive areas, study areas and ditches with a buffer distance of 5m around them, were converted into raster layers with the same resolution of 4 × 4 m.

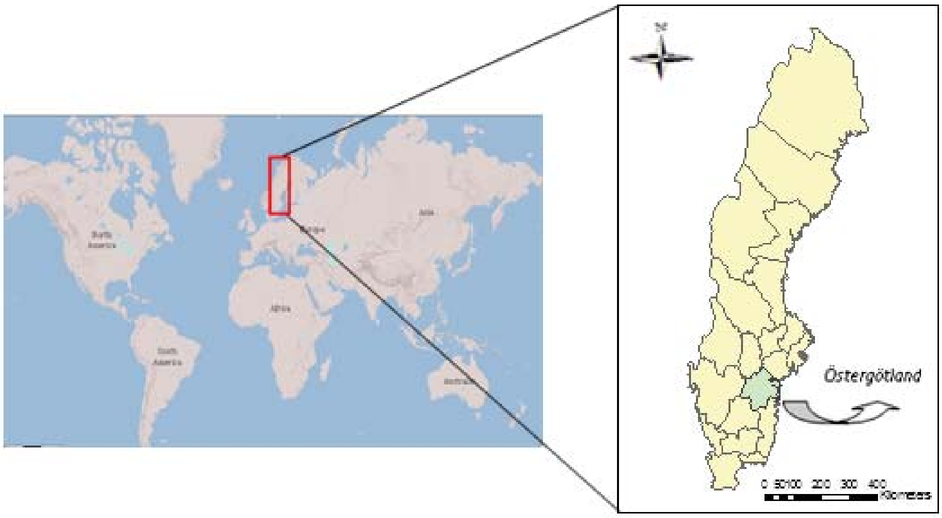


Figure 2.
Location of the study area in map of the world (left) and in Sweden (right).

The geographic reference system used for the data set was GCS_SWEREF99 and the projected coordinate system was SWEREF99_TM.

UTILIZED SOFTWARE

Environmental Systems Research Institute, Inc (ESRI) was founded by Jack Dangermond in Redlands, California, in the 1960's. ESRI's primary mission was to analyze geographic information to support land planners and resource managers in making informed decisions. Gradually, ESRI extended its scope of activity from the project managing level to the product development stage. ARC/INFO was one of the primary software products released by ESRI in the 1980's. It combines graphic display of geographic features with a database management system for assigning attributes to them. Later on, after proving its validation through implementation of several successful projects, ESRI developed ARC/INFO to the ArcGIS system, which is a modular and rescaleable GIS platform capable of working both on desktop PC's and across the enterprises (ESRI, undated page).

In this study, ArcGIS version 10, including ArcMap, ArcCatalog and ArcScene, were used for data preparation, data processing, information exploration, evaluation and at the end, 3D visualization of the final results. The Slope, Aspect, Path distance and Cost Path tools available from the Spatial Analysis and the 3D Analysis extensions where used to build up the desired model within the 'Model Builder' environment of ArcGIS.

Methodology

The model was supposed to plan the least costly routes through the best directions from destination points to the available landing point(s). Meanwhile it would help plan the routes with a proper orientation with respect to direction of the slope of the ground.

Table 1.
Description of the utilized data in the model.

Data Layer Name	Type	Content
Digital Terrain Model (DTM)	Raster Resolution of 0,5 × 0,5 m	Represents topography of the area
Soil Type	Shape file (Polygon)	Contains different classes of soil such as till, sand, peat land, water, etc.
Single Tree Stands	Shape file (Point)	represents every single tree, its type, height, volume and diameter
Roads	Shape file (Line)	Contains existing main roads surrounding the study areas.
Environmental Sensitive areas	Shape files (polygon)	Separate shape files containing various information on natural assets, habitat protection, key biotopes, historical values, etc.
Ditches	Shape file (Line)	Represents available ditches in the area.
Study Area	Shape File (Polygon)	Represents different harvesting compartments in Selesjö, contains information about the size of the area, in hectare, and their owner
No go Areas	Shape file (Polygon)	Contains Sensitive areas which delineated after directed observation of the site by Skogforsk experts.
Over passes	Shape file (Line)	Contains locality of two natural overpasses and one man-made bridge over the restricted region.
Ortophoto of the region	JPEG	Illustrates an aerial view of the region, tree stands and main roads.

In order to certify minimized environmental impacts and also secured condition for operational machineries on varying slope levels, there is an essential need for simultaneous consideration of several significant factors during the process of route planning for harvesting sites. This need contributed to the choice to follow the MCDA methodology for integrating all the evaluated criteria into a single map surface showing different levels of suitability. The weighted linear combination tool, applicable through the Weighted Overlay toolset in ArcMap, was applied for creating the cost-index surface. Afterwards, the cost-index surface together with the source layer were fed into the Path Distance tool, where for each single cell the least accumulative cost for getting to the cheapest source and also the proper direction to take for moving to the neighbor cell was determined. These two outputs aligned with the destination layer were inserted into the Cost Path tool to create the route layout in the harvesting site.

SCENARIO DESCRIPTION

Two different study areas were assessed in the context of this project. Each of them was evaluated under two different scenarios in order to examine possibilities in the harvesting sites and to evaluate the route layouts under different assumptions.

Study area 1

At study area 1, with an area of 6.72 hectares, there was just one possible landing point for the wood harvested within the borders of the study area. This landing point was selected on the last part of the existing main forestry road outside the study area and it was supposed to be reached from 4 destination points distributed on harvesting site (Figure 3). There was a wetland between the landing point and part of the stand which needed to be protected against probable damage by machinery; it was called the 'No Go' area and its border was defined by direct observation of the site. In Scenario 1, the routes were expected to go beyond this sensitive part and reach the end points, while in scenario 2 the possibility of building a bridge to pass the wetland was analyzed to see how the route layout would have to be adjusted to the new condition (Appendix 1, Figure 1).

Study area 2

At Study area 2, with an area of 15.12 hectares, the existence of main forestry roads both north and south of the borders of the harvesting section had created the opportunity of three different landing points around the study area. Two of the landing points were located in the northern part, and the third one was located in the southern part (Figure 3). In the first scenario, the routes were designed and distributed between all three possible landing points while in the second scenario, the southern landing point was removed from the analysis, and thus all the destination points needed to reach one of the landing points in north.

DATA PROCESSING

The scope of evaluated factors in this study was narrowed down to **elevation, slope, aspect and soil type**. Slope and aspect are two datasets which were extracted from the DTM layer. The DTM layer was fed in to the Slope tool to create slope variation of the terrain area. The slope tool is used to calculate the maximum rate of change of elevation over the distance between a cell and its eight neighbors and it is calculated either in percentages or degrees. Lower slope values represent flatter regions and higher slope values represent steeper conditions of the terrain. The aspect could be defined as the slope direction. The Aspect tool was used to create its corresponding raster output from the DTM layer. The values of this raster are compass direction of aspect, measured clockwise in respect to north and varied between 0 and 359.9. Flat areas were assigned the value of -1 (ESRI, 2011). An overview of the main input parameters is illustrated in Appendix 1, Figure 2, 3.

MODEL DESCRIPTION

Cost-index surface preparation

Since the utilized datasets had different scales of measurement, it was necessary to bring them all to a common relative scale of cost-index values, varying from 1 to 5. For each layer, the most desirable condition regarding our objective was assigned the minimum cost-index value (1), and the least desirable condition was assigned the maximum cost-index value (5). The Reclassify tool was run over all the considered criteria. How to assign the cost-indexes to values of each layer was decided through several meetings and discussions with the forestry experts at Skogforsk during January-April 2010.

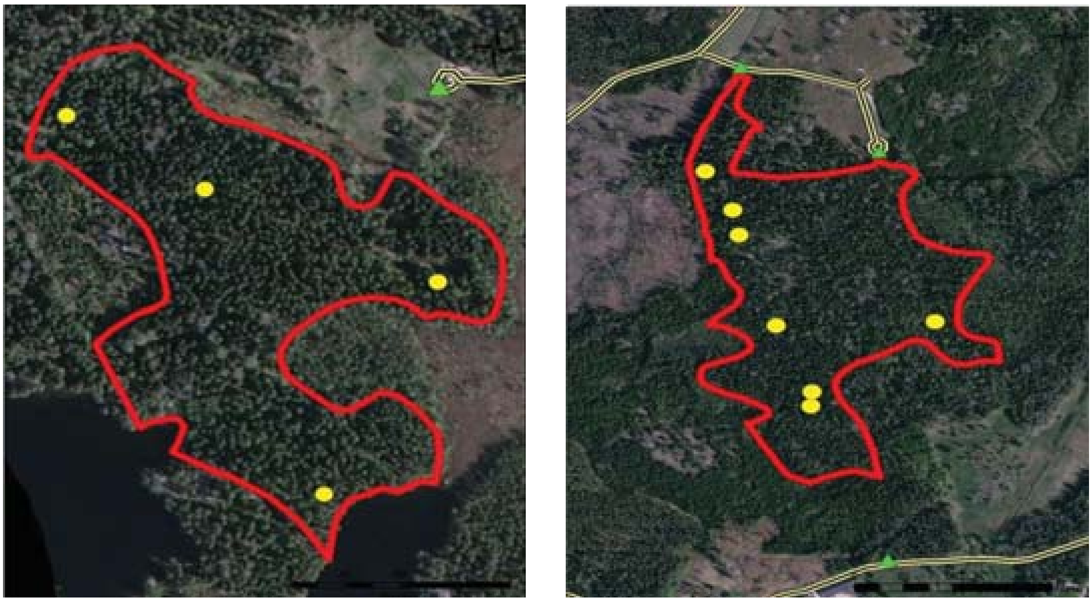


Figure 3.
Landing points and destinations in Study area 1. (left) and Study area 2 (right).

Elevation, slope and soil type reclassification

The routes were supposed to be laid out on high elevated surfaces in order to avoid damage to sensitive soil types, such as clay, and to protect bogs and other wetlands, which are mostly located on flat areas. The classification was relative since our different study areas had different variations in elevation. Study area 1, had elevation values between 46 and 65 meters while the second area had a variation of 52 to73 meters. Table 2 summarizes the old values and the new value classes for all evaluated criteria. The steeper the slope of the ground the more difficult it would be for the forwarders to move on it, especially when they are fully loaded. Based on the 'Terrain Classification for Canadian Forestry' Report (Mellgren, 1980) slope values were also reclassified into 5 levels of suitability (Table 2). The two study areas were covered with different soil types. Mountains and rocks were assigned minimum cost-index of 1, since they would have minimum disturbance under the pressure of heavy vehicle passage. Fine sands and sediments were assigned value 2, till as 3 and silt as 5 (Table 2). Water, clay and peat lands were regarded as constraints and removed from the final cost surface (Table 3).

Aspect classification

Since the values of the aspect layer could not be regarded as *suitable* or *unsuitable* inherently, they could not be evaluated by the above mentioned reclassifying procedure. Aspect values suitability was conceived when they were compared to the forwarder's direction of movement. According to experts' knowledge and experience at the Skogforsk, the aspect direction is regarded as *suitable* when it is parallel with the forwarder direction of movement and it would be extremely *unsuitable* when the angles are greater than 5 degrees compared to the forwarder direction of movement. The aspect layer was regarded as a horizontal factor within the Path Distance tool. An ASCII table was prepared and inserted into this tool to define variation of suitability with respect to possible angles between the aspect direction and the forwarder direction of movement (Table 4). More detailed information is provided in the Path Distance description part.

Weighted overlay

All the above mentioned reclassified factors, except aspect, was integrated into a single cost-index surface using the spatial analytical tool Weighted Overlay. This tool has the potential to merge these factors while applying different weights/level of importance to them. The applied weights are relative percentages and the sum of them must equal 100%. According to the expert judgments, elevation was regarded as the most important factor and hence it gained 50% of influence. Slope with 30% of the applied weights was the next, and finally the soil type achieved the remaining 20% of the importance (Table 2). We could not apply more weights to soil type due to data inaccuracy, for example comparing this data layer with the laser scanned layers of the same area it was seen that the ditches locations in the soil type are within a distance from their actual position in the laser scanned layer.

Constraint consideration

As mentioned earlier, constraints are the parts of the surface which would be excluded from the cost-index surface for specific reasons. The common constraints for both study areas were: very steep slopes i.e. slope greater than 18 degrees, and sensitive soil types like peat lands.

Table 2.
Summary of data reclassification.

Factors	Percentage of influence	Factors classification			
		Study area 1		Study area 2	
		Old values	New values	Old values	New values
Elevation	50%	65–60	1	73–68	1
		60–55	2	68–64	2
		55–50	3	64–60	3
		50–46	5	60–56	4
				56–52	5
Slope	30%	0–6	1	0–6	1
		6–11	2	6–11	2
		11–18	3	11–18	3
		18–27	4	18–27	4
		27–90	5	27–90	5
Soil type	20%	Rocks-Outcrops	1	Rocks-Outcrops	1
		Till	3	Fine sand, Glaciofluvial sediment	2
		silt	5	Till	3
Sum	100%				

At Study area 1, ditches with a buffer distance of 5 meters around them and the 'No Go' area, were other additional constraints. At Study area 2, an area of 'nature conservation' was identified within the harvesting site and thus it was removed from the cost-index surface. Ditches were located out of the harvesting border here.

All these constraint layers were reclassified to have 'No Data' values for those restricting conditions and the value of 1 for all other non-restricted areas. They were then combined together and finally were multiplied by the cost-index surface, which resulted in the final cost-index surface which would be fed in to the next part of the model.

Path Distance tool

The Path Distance tool is one of the available tools in ArcMap, within Spatial Analyst, to perform cost distance analysis. According to the ESRI definition, the Path Distance tool, calculates for each cell, the least accumulative cost distance to the nearest source, and has the potential to add more complexity to the analysis while accounting for surface distance, and for horizontal and vertical cost factors as additional factors.

Table 3.
Constraints Specifikation and reclassification for each study area.

	Study area 1		Study area 2	
Constrains	**Old values**	**New values**	**Old values**	**New values**
Slope > 18	18 – 27	No Data	18 – 27	No Data
	27 – 90	No Data	27 – 90	No Data
	0thers	1	0thers	1
Soil type	Peat land	No Data	Peat land	No Data
	Water	No Data	Water	No Data
	Clay	No Data	Clay	No Data
	others	1	others	1
Ditches	Ditches	No Data	Ditches	No Data
	others	1	others	1
'No go' areas	No go areas	No Data	——	
	others	1		
Nature reserves	——		Nature reserves	No Data
			Others	1

The No Data values would be regarded as barriers in the Path Distance tool. The parameters used as inputs to the Path Distance tool could be described as:

Source; a raster or feature data set, identifying the cells or locations to which the least accumulated cost of getting back from every single cell position, would be calculated. The possible landing points in each study area were regarded as source. It can include one or more feature locations. In the first study area, the source contained one location, while in the second study area, the source contained three different feature locations for distance analysis.

Cost raster; a raster representing the cost per unit distance of moving plain metrically through each cell. Thus, each cell location value needs to be multiplied by the cell resolution and also compensated for diagonal movement.

From a cell perspective, the formula used for calculating the cost of travel from cell a to cell b in 'Path Distance' tool is defined by ESRI (2011) as:

- **For perpendicular movement:**
  Cost_distance = Cost_Surface × Surface_distance ×[Friction(a) × Horizontal_factor(a) + Friction(b) × Horizontal_factor(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 cost-index surface, prepared by the Weighted Overlay function, was the input cost raster.

Surface Raster; a raster layer containing elevation information at each cell location. It was used to calculate the actual surface distance between the cell locations. The DTM layer was used as surface raster in this tool.

Horizontal raster; a raster specifying the horizontal direction at each cell location in integers, varying between 0 and 360 degrees with 0 as north and increasing clockwise. Flat areas were assigned the value of -1. The aspect layer containing exactly this required information was used as horizontal raster. The values of the horizontal raster together with the horizontal factor were used to evaluate the cost of moving horizontally from a cell to its neighbors.

Horizontal Factor (HF) object; defines the relationship between the horizontal cost factor and the Horizontal Relative Moving Angle (HRMA). The HF object can be in form of HF Binary, HF Forward, HF Linear, HF Inverse Linear and HF Table. In our model, HF Table was used to define the relation between HRMA and HF. It is an ASCII file with two columns. The first column represents the HRMA (varies between 0 to 180 degrees) and the second columns represents the assigned horizontal factor to each HRMA. Since we wanted the roads to have a maximum side inclination of 5 degrees, the assigned HF increased linearly from 1 to 5 when HRMA changed between 1 to 5. For all the other possible HRMA greater than 5 degrees up to 176 degrees, the HF was assigned a very large value (100) to create extremely undesirable conditions for the model and to avoid laying the routes with those angles with respect to the slope direction (aspect). For HRMA between 175 and 180, HF again decreased linearly from 5 to 1. For HRMA values of 0 and 180, the HF was defined as 1, since moving parallel with the slope direction, either upwards or downwards, is also a secure condition for loaded forwarders (Table 4).

Table.4
ASCII code used for defining variation of 'Horizontal Factor' respect to 'Horizontal Relative Moving Angel (HRMA).

Horizontal Relative Moving Angle (HRMA)	Horizontal Factor
0	1
1	1
2	2
3	3
4	4
5	5
10	100
20	100
30	100
40	100
50	100
60	100
70	100
80	100
90	100
10	100
110	100
120	100
130	100
140	100
150	100
160	100
170	100
175	5
176	4
177	3
178	2
179	1
180	1

The output parameters of the Path Distance tool are a *Distance Raster* and a *Backlink Raster*. The Distance Raster stores for each cell the least accumulated cost of getting back to the source while compensating for horizontal surface factors and surface distance. The Backlink Raster stores for each cell, values between 0 and 8, which are the code values for the direction to take from each cell along the least accumulative cost path to the least costly source available for it. Figure 4 illustrates an overview of the entire model. Later on, the tree stand layer was used to evaluate the number and volume of trees to be harvested within the interested sections of both study areas (Appendix Figure 4 and 5).

Cost Path tool

The output of the Cost Path tool is a raster file, determining the least cost path from a destination point to a source, using the Raster Distance and the Backlink Raster that were calculated in the previous stage. The destinations are shape files, selected within the borders of the study areas in a way to provide access to all parts of the harvesting sites (Figure 3).

The length of suggested roads for each scenario was measured in ArcMap, to provide some basis of economical comparison of the suggested route layouts in both study areas. The designed routes, together with the source and the destination locations where imposed on the cost surface layer in ArcScene. All the layers achieved their base heights from the DTM layer, and an exaggeration of 5 was applied to provide a better 3D visualization of the routes in the terrain.

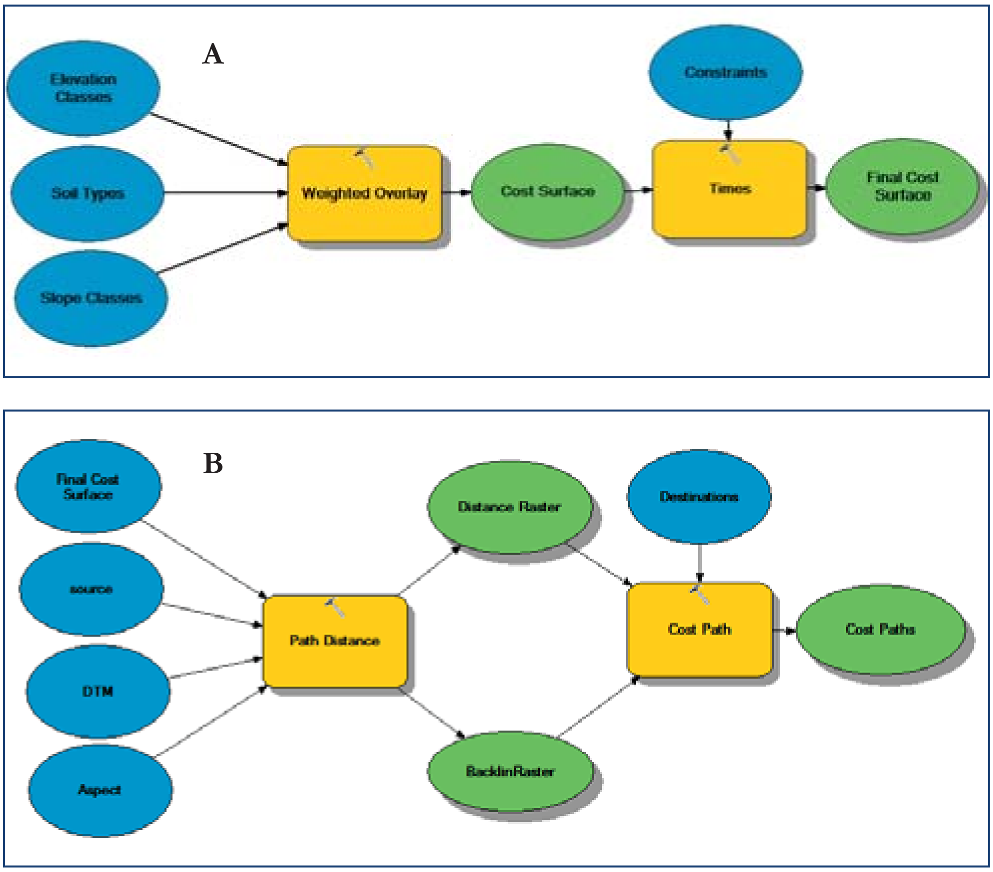


Figure 4.
Model overview: A) application of the Path Distance tool and the Cost Path tool for distance analysis, B) creating a 'Cost Surface' using the Weighted Overlay function in Model Builder.

SENSITIVITY ANALYSIS

In order to evaluate the sensitivity of the model with respect to the weights applied to each of the factors, a sensitivity analysis was performed by increasing the slope importance to 50% and decreasing the elevation weight to 30%, while the soil type level of importance was not changed due to its inaccuracy.

EVALUATION OF THE SUGGESTED ROUTES IN REALITY

The suggested route layouts, created in shape format, were transferred into a GPS device in order to examine the accuracy of the model's route design in real condition of the two study areas. Visiting the study areas occurred in May 2011.

Results

STUDY AREA 1, SCENARIO 1

Figure 5 illustrates how the model planned the least costly routes from the destinations to the source while compensating for surface distance and horizontal factor, which is the orientation of slope. As explained earlier, there was a wetland 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 while going beyond this restricted part. Figure 6 demonstrates different views of the 3D visualization of the suggested routes in ArcScene 10 environment.

STUDY AREA 1, SCENARIO 2

In this scenario, three different possibilities of building bridges in the area were evaluated. Locations 1 and 3 were natural overpasses while location 2 was the suggested place for constructing a bridge over the wetland. This wetland was considered as a barrier in the first scenario. How the model adjusted the route alignment with the new condition is demonstrated in 2D and 3D maps (Figure 7 and Figure 8).

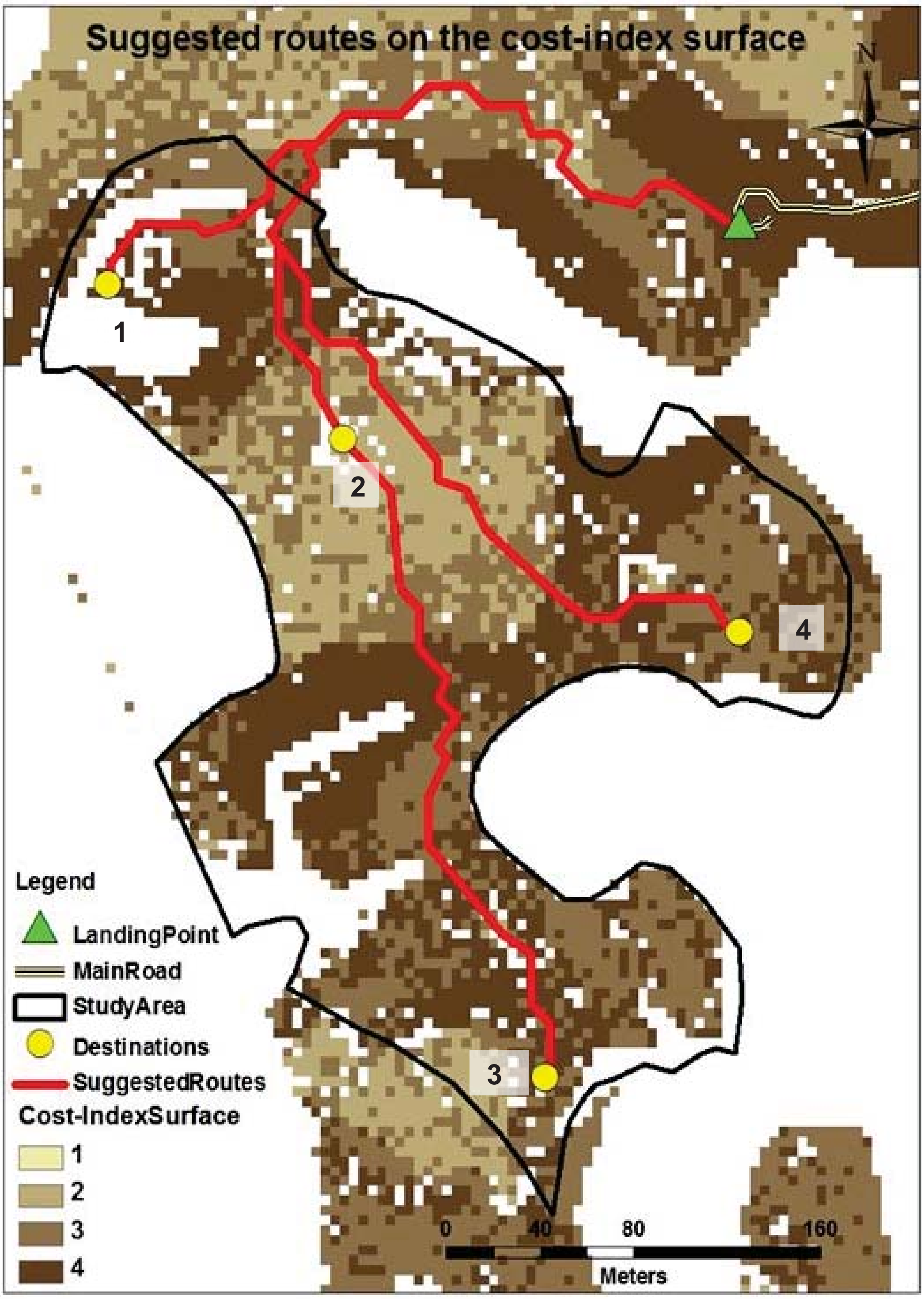


Figure 5.
Least-costly routes suggested by the model for Study area 1, Scenario 1.

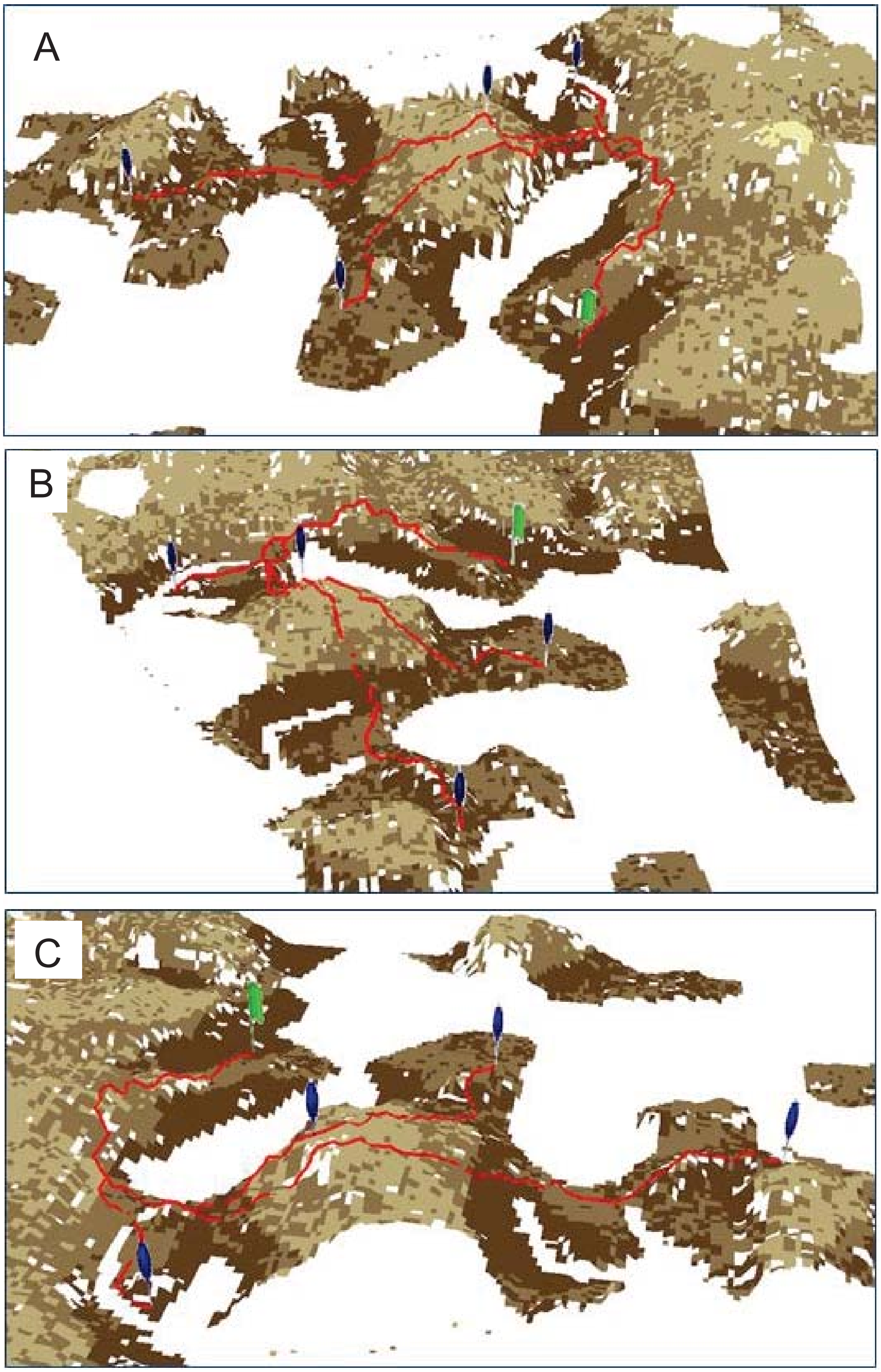


Figure 6.
3.D view of the model's route suggestion for Study area1, Scenario 1,
A) right view, B) front view and C) left view.

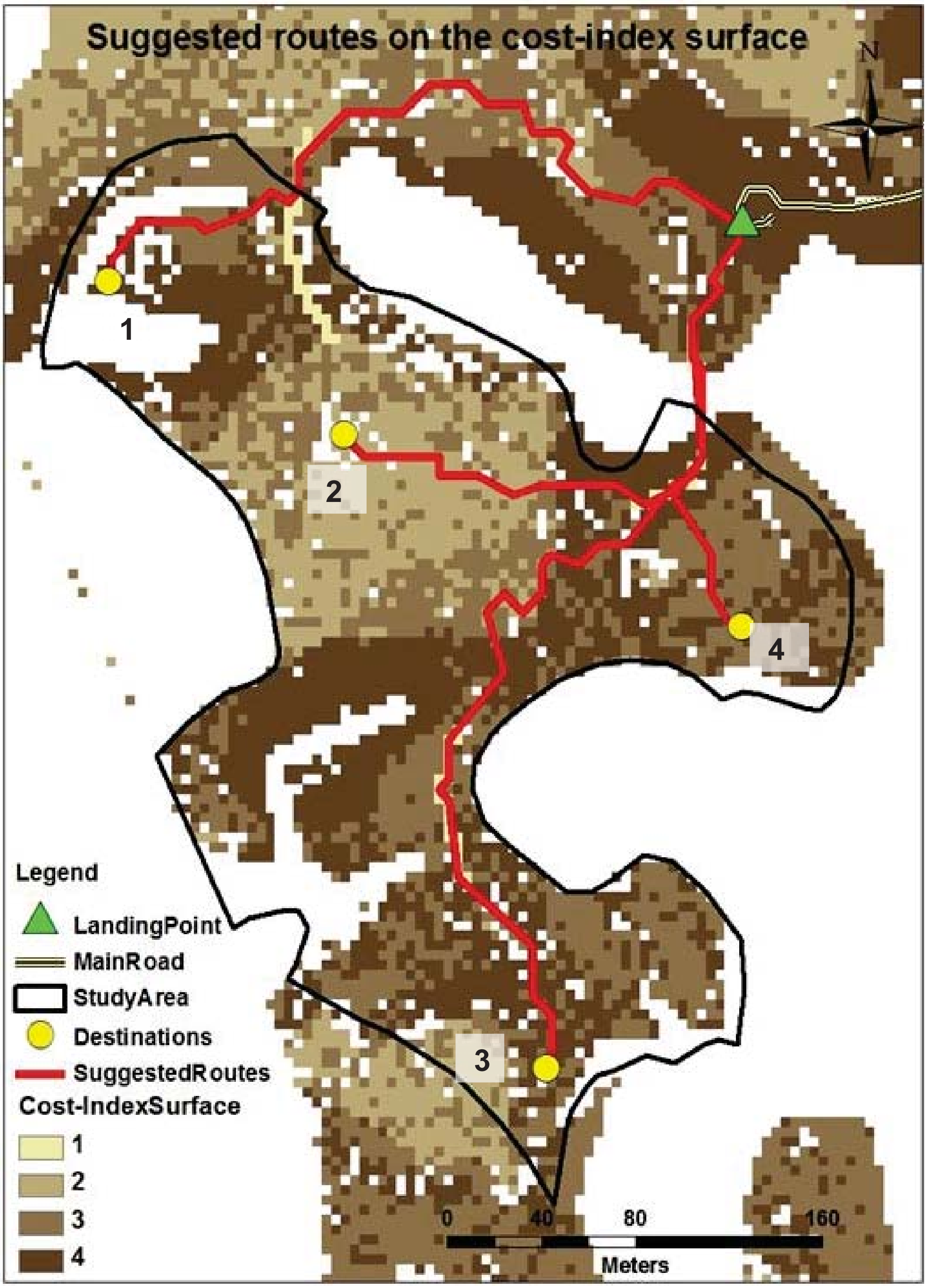


Figure 7.
Least-costly routes suggested by the model for Study area 1, Scenario 2.

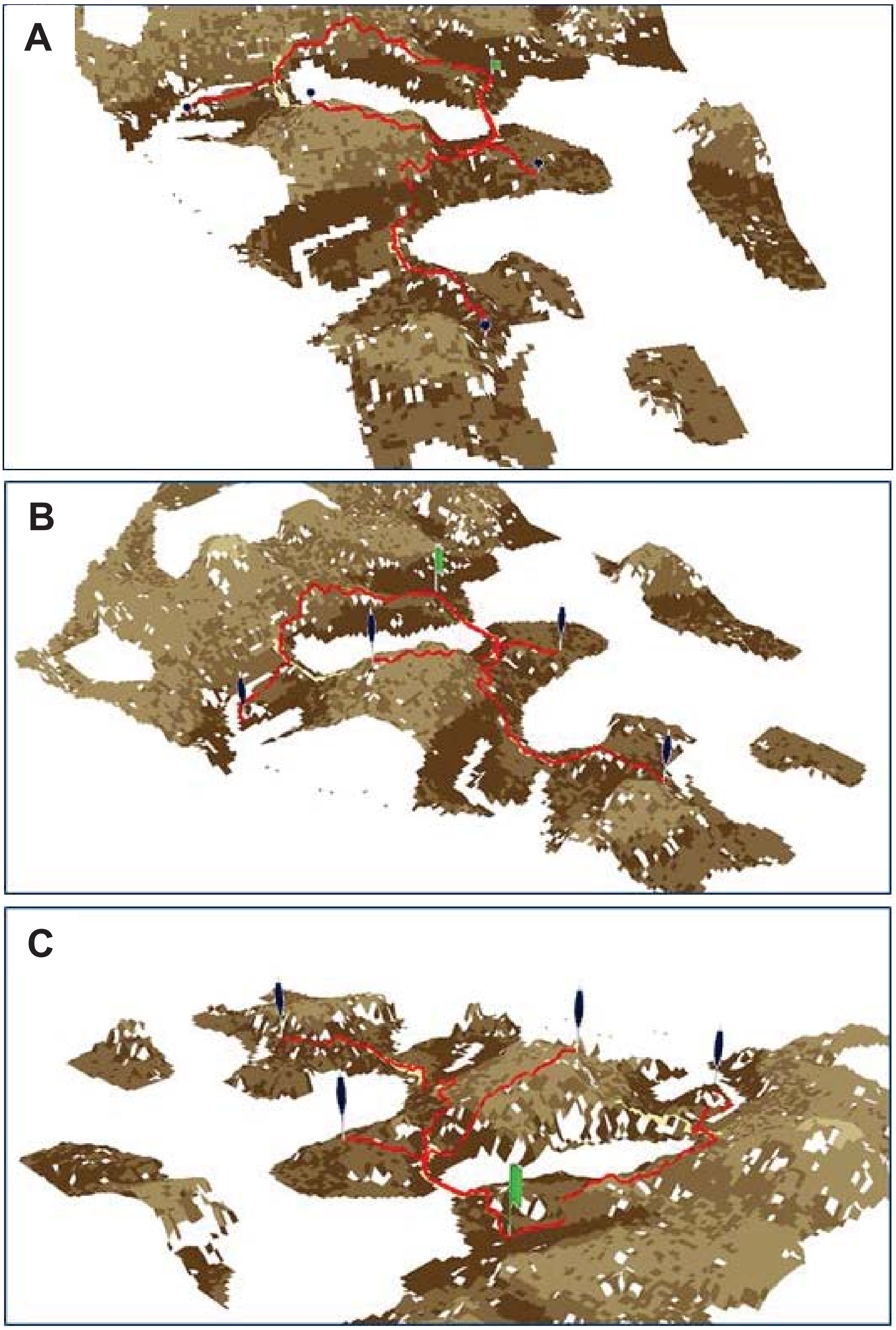


Figure 8.
3D view of the model's route suggestion for Study area1, Scenario 2,
A) front view, B) left view and C) right view.

COMPARING THE TWO SCENARIOS OF STUDY AREA 1

In Scenario 1, the total length of the suggested routes to reach destinations 2, 3 and 4 in the harvesting site was **1,616 m** while after constructing the bridge, the total length of the routes for reaching to these points was reduced to **929 m.** Assuming the maximum possible load for a forwarder as 20 tons, having **1 572.67** tons of woods to be collected through this bridge illustrated in Appendix 1, Figure 1, almost **79** full forwarder loads would be required for collecting all the trees stands, and would thus contribute to **158** passes of the route by forwarders. Taking into account the knowledge from Skogforsk experts about the maximum possible velocity of forwarders as 0.8 m/s, and the cost of forwarder operations as **850** SEK per hour, following the route pattern in Scenario2 and taking the routes over the bridge number 3, this would contribute to **858.75 s = 0.24 h** per each one way route saving in time and a total of **32 232 SEK** saving in terms of money. Comparing this value with the cost of constructing the bridge as **5 000 SEK**, estimated by experts at Skogforsk and consisting of the cost of 3 hours' work of the harvester and the cost of timber, certifies that making a bridge over the wetland area not only could preserve soil and water conditions at the wetland, but also would contribute a remarkable reduction in cost of the forwarder operation at the site. The calculation procedure is described in Appendix 1.

STUDY AREA 2, SCENARIO 1

For this area, the location of the existing main roads around the study area provided three possibilities for landing points and collecting the tree stands. Two of the landing points were located north of the harvesting site, and the third one was located in the southern part.

In Scenario 1, all the tree landing points were inserted into the model as sources. Figure 9 illustrates how destination points were connected to the cheapest source along the least costly paths. Figure 10 illustrates the 3D view of the routes and the cost surface imposed on the DTM layer.

STUDY AREA 2, SCENARIO 2

In Scenario 2, the southern landing point was removed from the source layer, providing just the two landing points in the northern part. Destinations 5 and 6 ere replaced by destination 5*, located near the southern border of the site, to provide access to the whole area to be harvested.

Figure 11 demonstrates how the destination points were distributed between the two landing points, located north of the study area. The 3D view of the suggested routes is illustrated in Figure 12.

COMPARING THE TWO SCENARIOS OF STUDY AREA 2

At Study area 2, different scenario conditions resulted in different route designs. In Scenario 1, the model connected destination 6 to the land point located at the southern part, along a rather short road section of **353 m**, which would be used to collect **584.5 tons** of wood at this part, (Appendix 1, Figure 2). In Scenario 2, the wood would be collected from a longer distance of **655 m**.

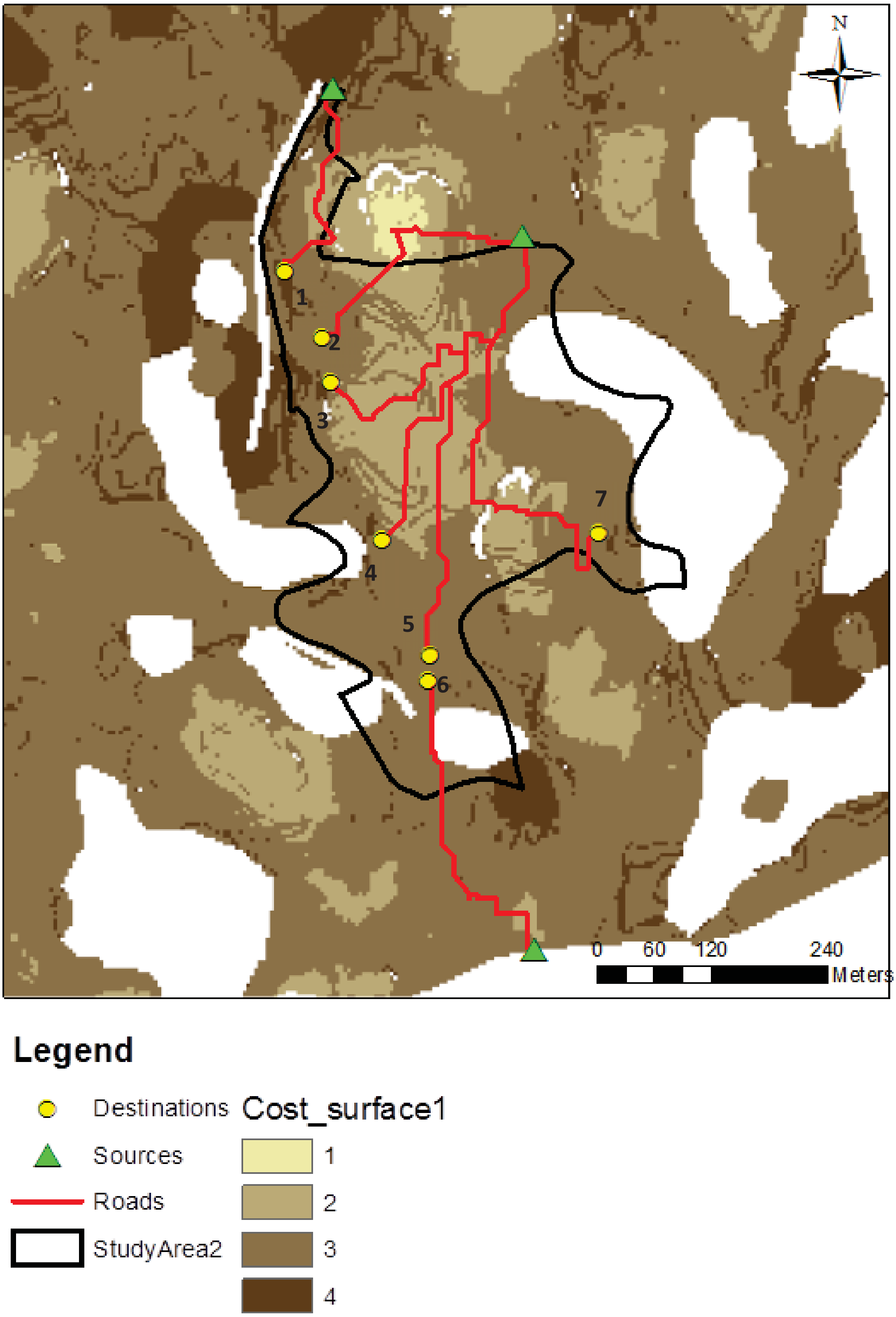


Figure 9.
Least-costly routes suggested by the model for Study area 2, Scenario 1.

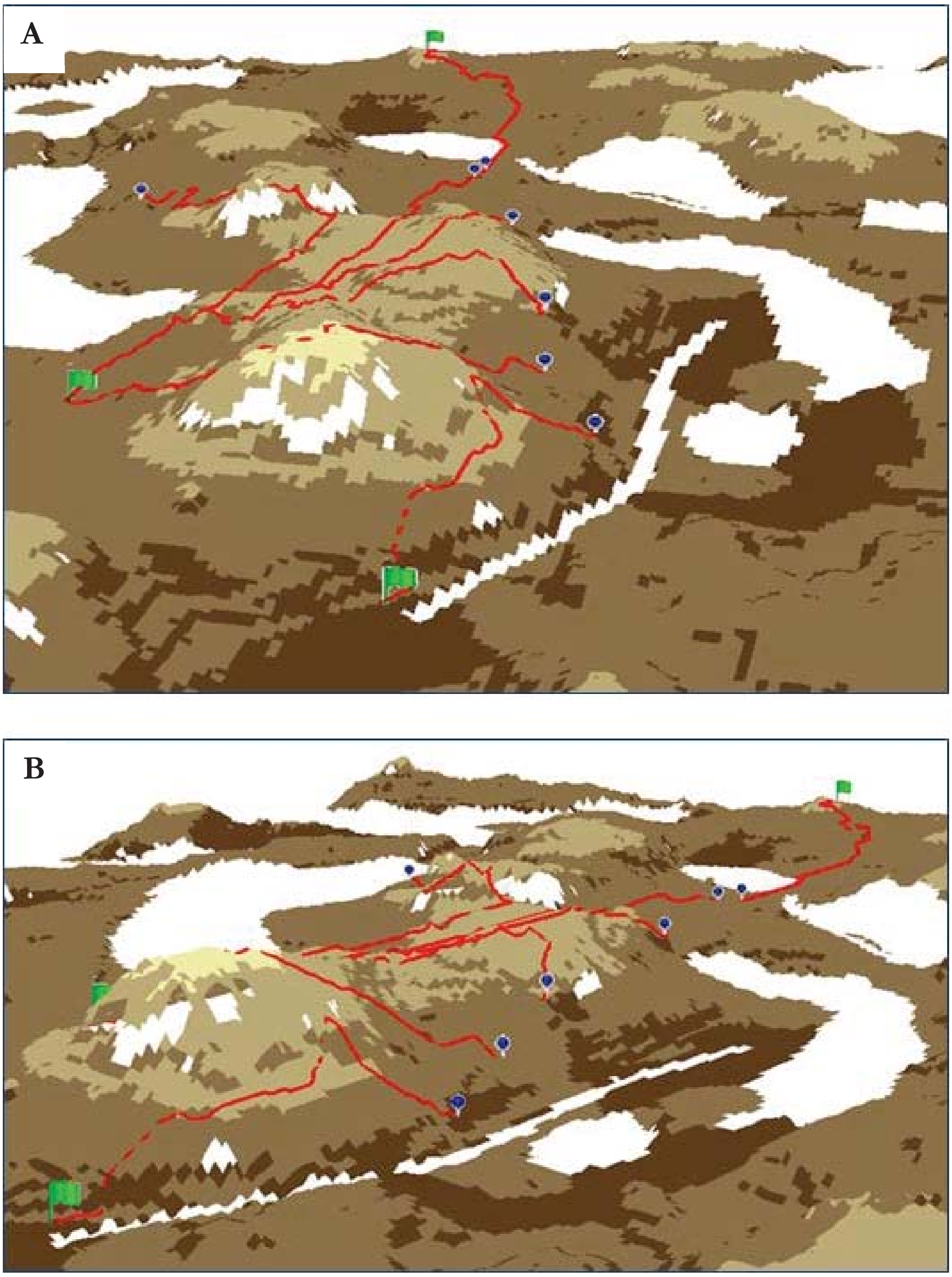


Figure 10.
3D view of the model's route suggestion for study area 2, scenario 1, A) back view, B) right view.

Assuming the same characteristics for forwarders, having maximum load capacity as 20 tons and average velocity as 0.8 m/s, utilization of the southern landing point in Scenario 1 could contribute to **377.5 s = 0.1 h** savings in time and **5 100 SEK** cost. Calculation procedure is described in Appendix 1.

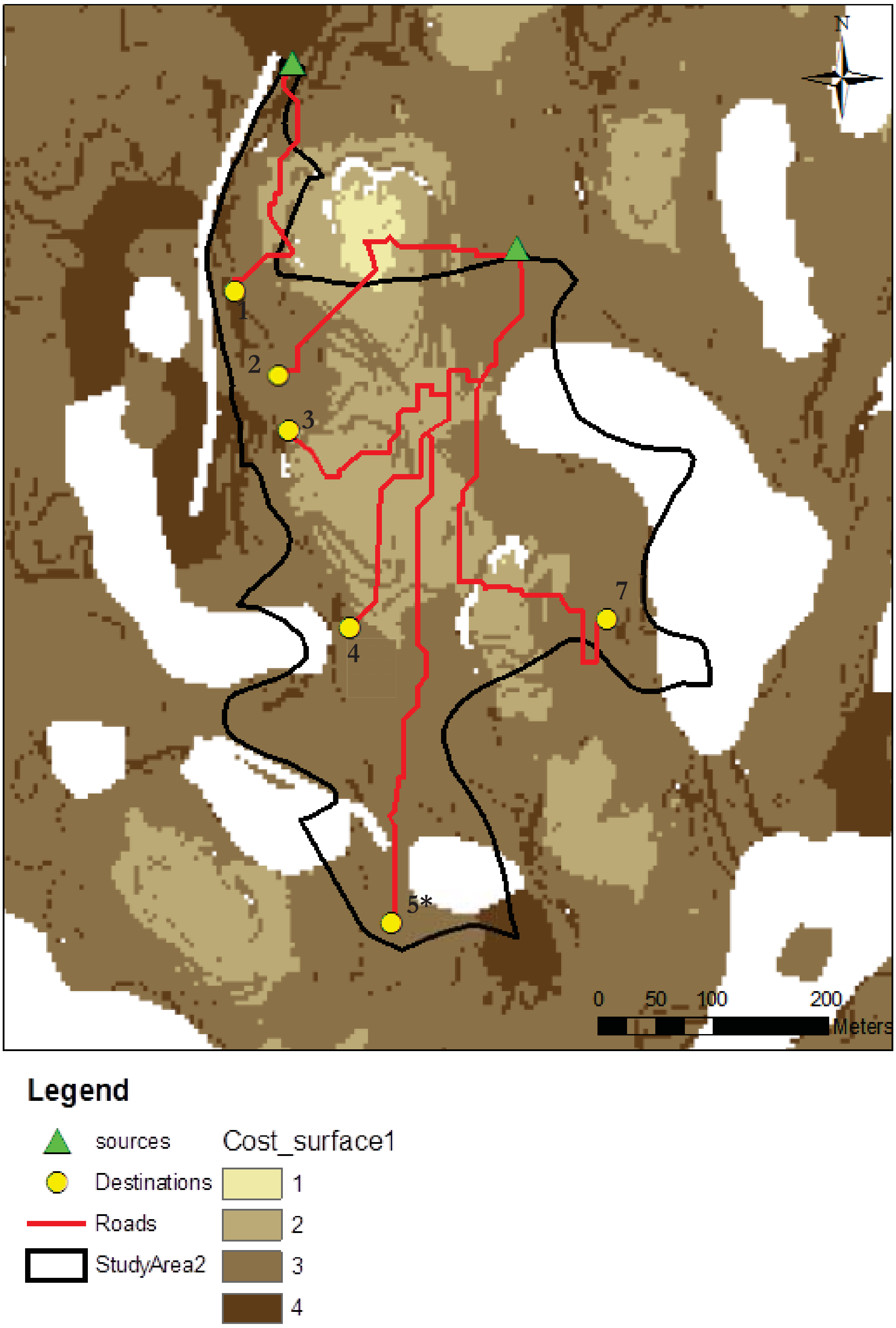


Figure 11.
Least-costly routes suggested by the model for Study area 2, Scenario 2.

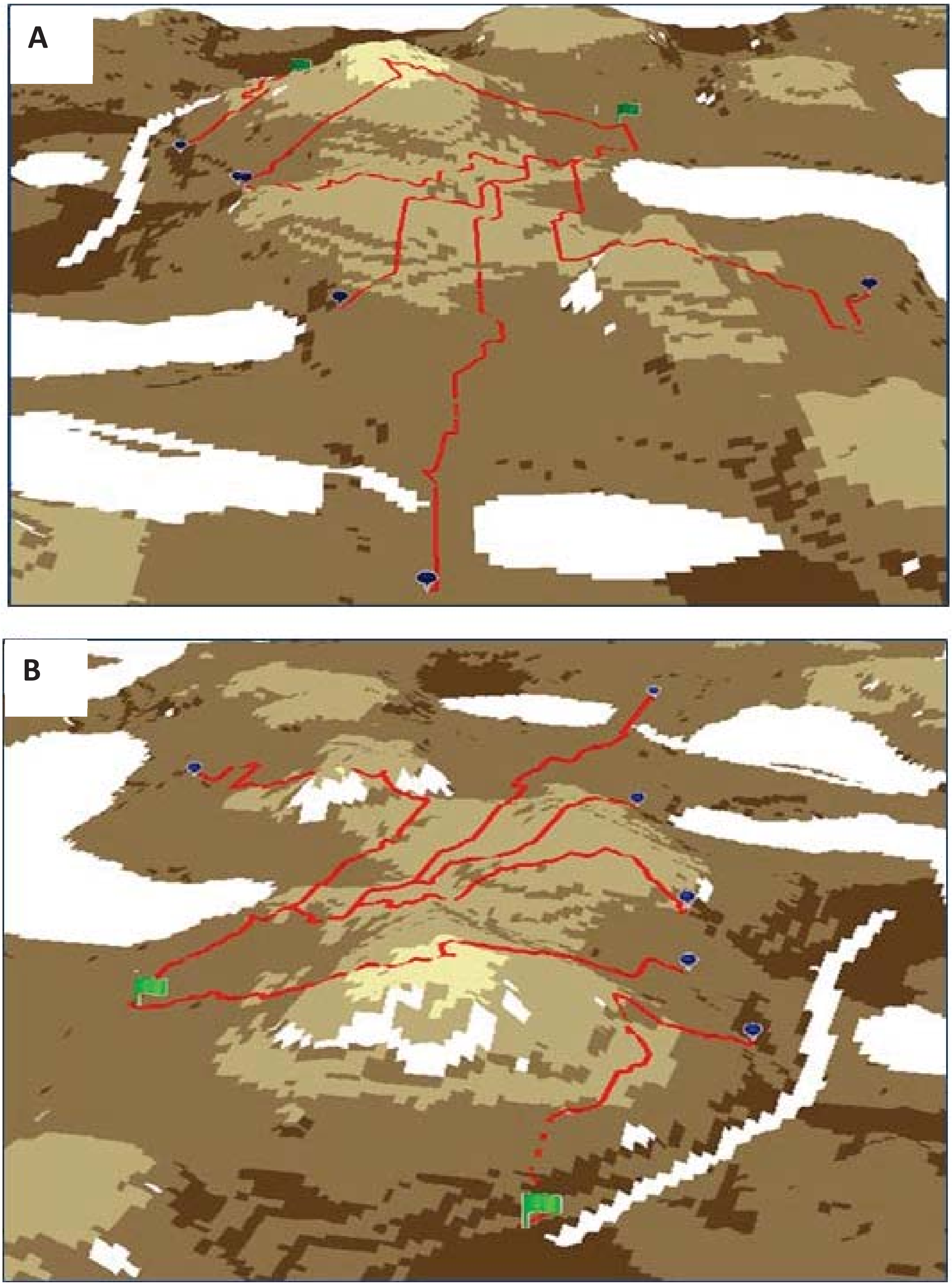


Figure 12.
3D view of the model's route suggestion for study area 2, scenario 2,
A) front view, B) back view.

SENSITIVITY ANALYSIS

The results of the sensitivity analysis for all scenarios of Study area 1 and 2 together with the primary route layouts with the first set of applied weights are illustrated in Figure 14 and Figure 15 respectively. The red lines represent the suggested routes with the first set of applied weights, which considered elevation as the most important factor, and thus having 50% of influence in the cost surface cell values. The green routes are the model's new suggestion after assigning 50% weight to the slope layer, and reducing the elevation influence to 30%. Soil type influence did not cause any change in this analysis.

EVALUATION OF THE SUGGESTED ROUTES IN REALITY

Following the designed routes with the GPS device showed that the model had been successful in finding the optimum routes by avoiding disturbing the wet lands, ditches, nature reserves and other restricted parts, following the elevated regions with higher bearing capacity, wherever exist any, and aligning properly with respect to the slope direction of the ground.

Discussion

At Study area 1, the presence of a wetland in the way of connecting the landing point to the destinations in the harvesting site, steered the model to the solution of reaching all the destinations from the northern part. In Scenario2, after inserting the layer containing possible bridge locations with minimum cost-index as 1 into the cost surface, it could be seen that the route pattern was mainly changed due to the suggested bridge number 3. Destinations 2, 3 and 4 would reach the landing point through the route layouts that passed bridge number 3, while destination 1 would follow almost the same pattern as the previous scenario with minor adjustments at the natural overpass 1.

At Study area 2, the configuration of the main forestry roads around the harvesting site provided three different possibilities for locating landing positions. In Scenario1, destination 6 was connected to the cheapest landing point located in the south, based on the accumulated cost factors and the distance raster layer (the DTM layer). In Scenario 2 destination 5* had just two possible landing points to choose and reach to the outer boarder of the harvesting area. Here again, based on the above mentioned parameters, destination 5* was connected to the most appropriate landing point, which was the source located in north-east of the study area.

SENSITIVITY ANALYSIS

At Study area 1, changing the weights of influence for considered factors did not change the outline of the suggested roads, except in very small sections (Figure 13). It can be conceived that in this region there are significant flat areas that are located on high elevated regions and thus different applied weights to these two factors did not cause any outstanding changes in the final result. In contrast, at Study area 2, it is seen that the route outline showed significant changes in connecting the destinations 1 and 7 to their corresponding sources (Figure 14). This could be interpreted as in this study area, all the elevated areas were not necessarily located on less steep slopes, and thus assigning different level of importance to each of these criteria would result in different road suggestions for the harvesting site.

Making decision about distributing weights of importance among different factors could be decided by planners of the forest companies at the harvesting site after examining other important natural condition at the site.

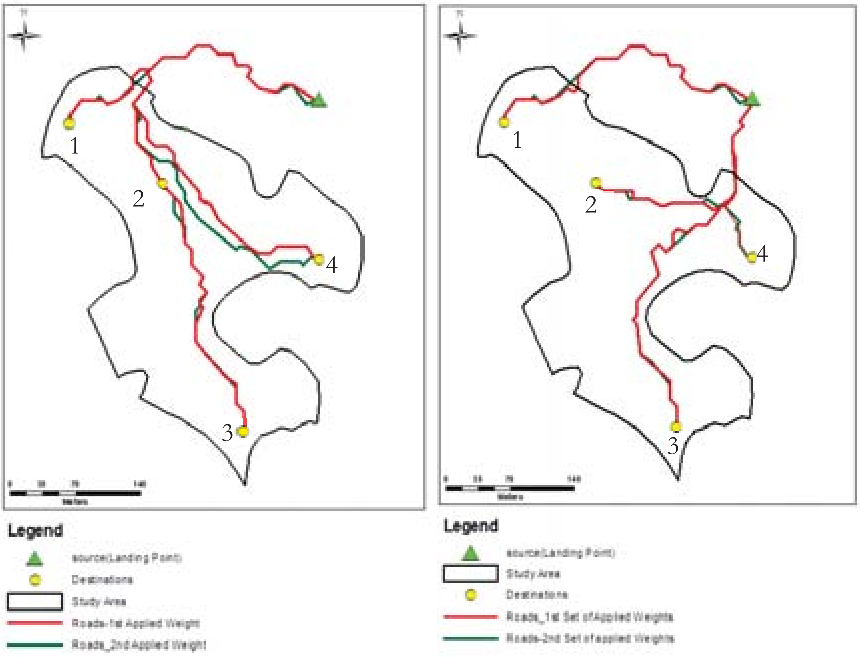


Figure 13.
Model route suggestion with elevation as the most important factor (red routes) and slope as the most important factor (green routes) for study area 1, Scenario1 (left) and Scenario 2 (Right).

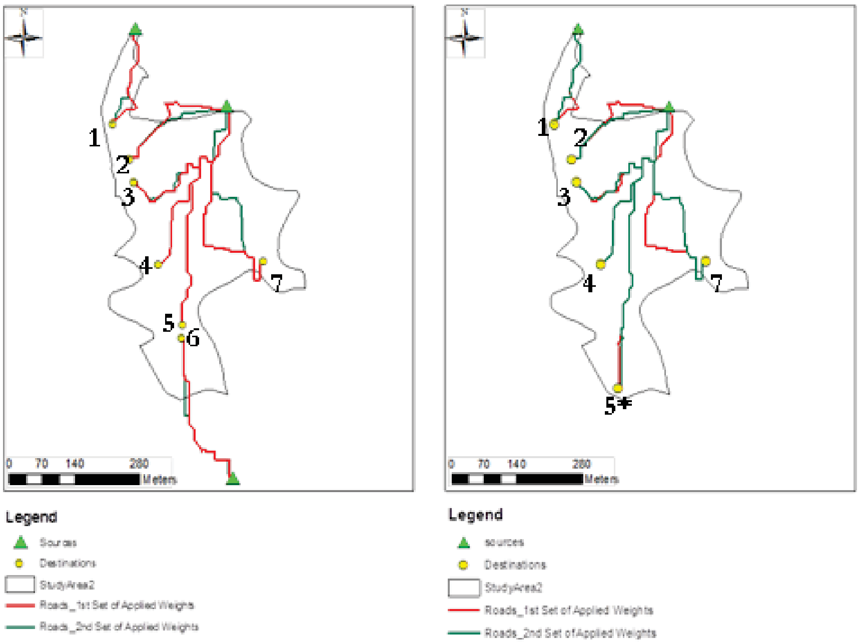


Figure 14.
Model route suggestion with elevation as the most important factor (red routes) and slope as the most important factor (green routes) for study area 2, Scenario1 (left) and Scenario 2 (Right).

Conclusions

Forests are natural resources that provide various vital services for diverse groups of consumers from human beings to native biotopes. Recent human exploitation of this natural environment as a wood resource has brought about the issue of avoiding severe environmental damages to soil and water which threatens growth, reproduction and biodiversity in forest lands. These adverse impacts could be avoided or minimized through informed and comprehensive preplanning by applying the knowledge and technology that already exist.

The aim of this study was to provide decision support for protecting soil and water during harvesting activities. In order to achieve this goal, there were plenty of important elements that could be taken into account to determine suitability of the terrain for supporting off-road trafficabilty, however the scope of this study was narrowed down to elevation of the ground, soil type, slope and its direction. These factors were assessed following an MCDA procedure. Weighted linear combination was the applied rule for prioritizing and rescaling the considered factors and integrating them to a single map of suitability, called a Cost-Index Surface.

GIS was found as quite an applicable tool, with great potential for visualizing the problem, exploring available data layers and evaluating possible solutions for every single designed scenario. Using the 'Path Distance' and 'Cost Path' tools within the 'Model Builder' environment, a model was created to design main access off-routes within the harvesting sites. The designed model suggested the cheapest access routes, regarding the cost-index values, while accounting for the actual distance to pass in the terrain. It was also designed to compensate for lateral inclination more than 5 degrees with respect to the slope directions on the harvesting site. 3D visualizations of the suggested routes as illustrated in the Results section fully displayed how much the model have been successful in this task. Moreover, validation of the results in the harvesting sites using a GPS device to follow the route pattern and orientation, especially on the slopes, also proved the accuracy of the final results. All the constrained regions were assigned the value of 'No Data' and were removed from the cost surface area. This meant that these areas were regarded as barriers by the model and this functionality assures complete preservation of environmentally sensitive areas in these kinds of models. The ArcGIS environment provided the opportunity to define different complexes of possible landing points and available surfaces to design unique route layouts, evaluate them from environmental and economic point of view to make the most appropriate decision in each scenario of possibilities.

Further work

In continuation of this study, further important factors such as macro and micro-topography, obstacles, vegetation types, topographic wetness index and meteorological information such as snow levels could be added to the evaluated criteria to assure a more comprehensive and secure model that meets the objectives of the forestry planners in more detail.

References

Abdi, E., Majnounian, B., Darvishsefat, A., Mashayekhi, Z. & Sessions, J., 2009. A GIS-MCE based model for forest road planning. Journal of forest science, 55 (4): 171–176.

Bishop, K., Allan, C., Bringmark, L., Garcia, E., Helsten, S., Högbom, L., Johanson, K., Lomander, A., Meili, M., Munthe, J., Nilson, M., Polvati, P., Skyllberg, U, Sorensen, R., Zetterberg, T. & Åkerbolm, S., 2009. The Effects of Forestry on Hg Bioaccumulation in Nemoral/Boreal Waters and Recommendations for Good Silvicultural Practices. Ambio. 38 (7): 373–379.

Cowen, D. 1988. GIS versus CAD versus DBMS: what are the differences. Photogrammetric Engineering and Remote Sensing, 54: 1 551–1 555.

Eastman, J.R., Jiang, H. & Toledano, J. 1998. Multi-criteria and multi-objective decision making for land allocation using GIS. In : Beinat,E., Nijkamp, P. MultiCriteria Analysis for Land Use Management , Kluwer Academic Publisher, 227–247.

Eliasson, L. 2005. Effects of Forwarder Tyre Pressure on Rut Formation and Soil Compaction. Silva Fennica. 39 (4): 549–557.

Fredricsson, J. & Dahlin, B. 1995. Computer-Assisted Forest Road Planning- A Proposed Interactive Model With Spatial Emphasis on Private Forest Land. Journal of forest engineering .6 (2): 35–39.

Lubello, D. 2008. A rule-based SDSS for integrated forest harvesting planning. PhD thesis. Padova: Universita Degli Studi di Padova.

Malczewski, J. 1999. GIS and Multi Criteria Decision Analysis. New York, USA: John Willey & Sons.

Malczewski, J. 2006. GIS-based multicriteria decision analysis: a survey of literature. International Journal of Geographic Information Science. 20 (7): 703–726.

Mellgren, P.G. 1980. Terrain Classification for Canadian Forestry. Montreal: Canadian Pulp and Paper Association.

Rogers, L. 2005. Automating Contour-Based Road Projection for Preliminary Forest Road Designs Using GIS. Master of Science. University of Washington. p 87.

Rongzu, Q. & Mikkonen, E. 2004. GIS-based decision support system for wood logistics. Forestry Studies in China. 6 (4): 29–33.

Suvinen, A. 2006. A. GIS-based Simulation Model for Terrain Tractability. Journal of Terramechanics .43: 427–449.

Wu, C., Ayers, P.D. & Anderson, A.B. 2007. Validating a GIS-based multi-criteria method for potential road identification. Journal of Terramechanics. 44 (3): 255–263.

Other references

ArcGIS Resource Center Desktop 10, 2010. Aspect (Spatial Analyst),online, (updated at:12/11/2010), available at: [http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//009z000000tr000000.htm], viewed 8 February 2011.

ArcGIS Resource Center Desktop 10, 2010. Slope (Spatial Analyst), online, (updated at:12/11/2010), available at: [http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//009z000000v2000000.htm], viewed 8 February 2011.

ArcGIS Resource Center Desktop 10, 2010. Understanding path distance analysis, online, (updated at:12/11/2010), available at: [http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//009z00000022000000.htm], viewed 10 February 2011.

Barth, Andreas: Skogforsk. Discussion on criteria selection and evaluation of the result, (Group meetings, January, February, March, April 2011).

Bergkvist, Isabelle: Skogforsk. Discussion on criteria selection and evaluation of the results, (Group meetings, January, February, March, April 2011).

ESRI 2011, What is GIS, online, available at: [http://www.gis.com/content/what-gis], viewed 4 April 2011.ESRI Info, ESRI History, online, available at: [www.esri.com/about-esri/about/history.html],viewed 5 April 2011.

Jönsson, Petrus: Skogforsk. Discussion on criteria selection and evaluation of the results, (Group meetings, January, February, March, April 2011).

Sonesson, Johan: Skogforsk. Discussion on criteria selection and evaluation of the results, (Group meetings, January, February, March, April 2011).

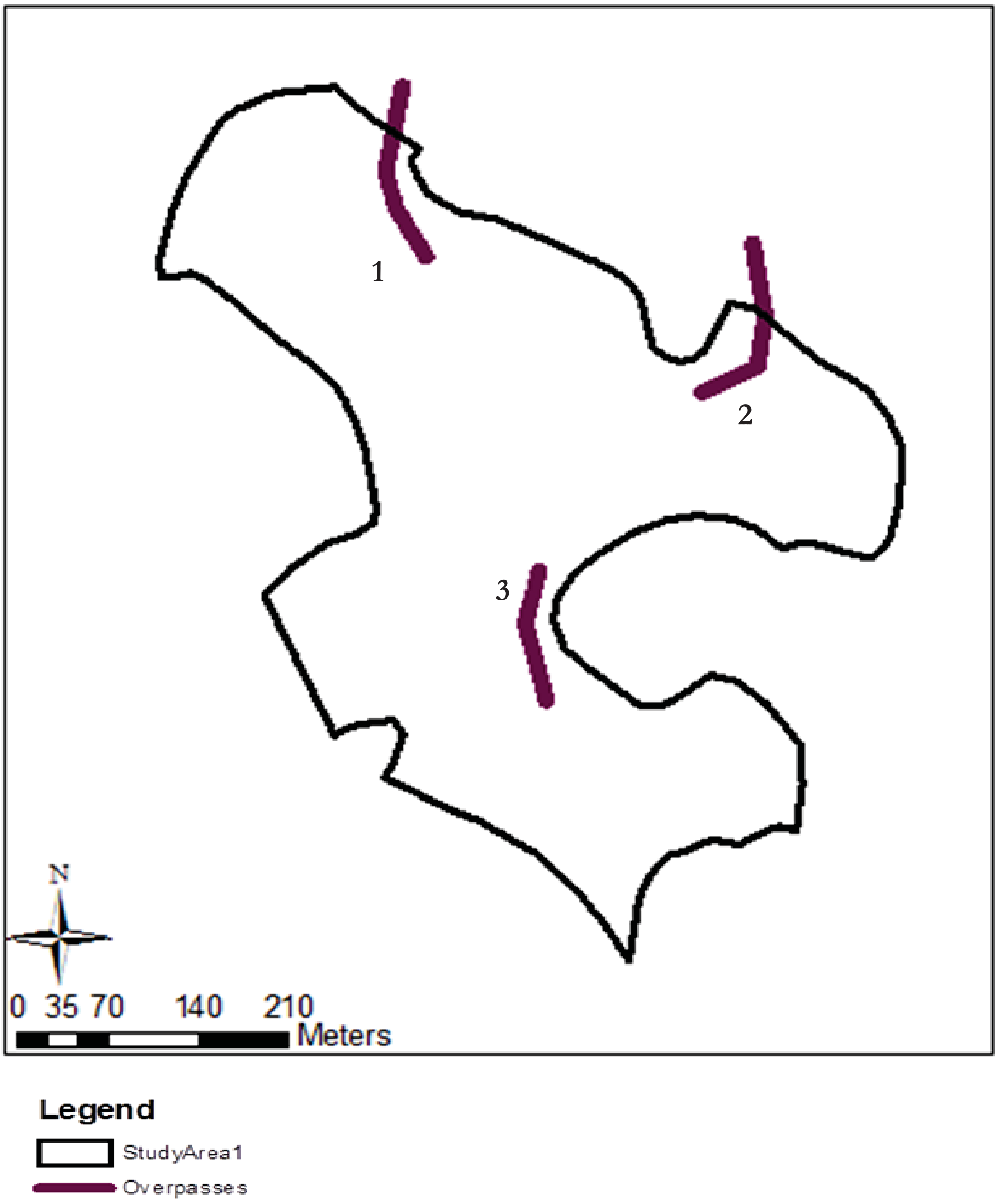
Sweden's Environmental Objectives in Brief, 2008. Swedish Environmental Objective Council, online, [http://www.naturvardsverket.se/Documents/publikationer/978-91-620-8324-3.pdf], viewed 3 December 2010.

The Swedish Forestry Act, Skogsstyrelsen, online, available at:[http://www.skogsstyrelsen.se/en/forestry/The-Forestry-Act/The-Forestry-Act/], viewed 2 December 2010.

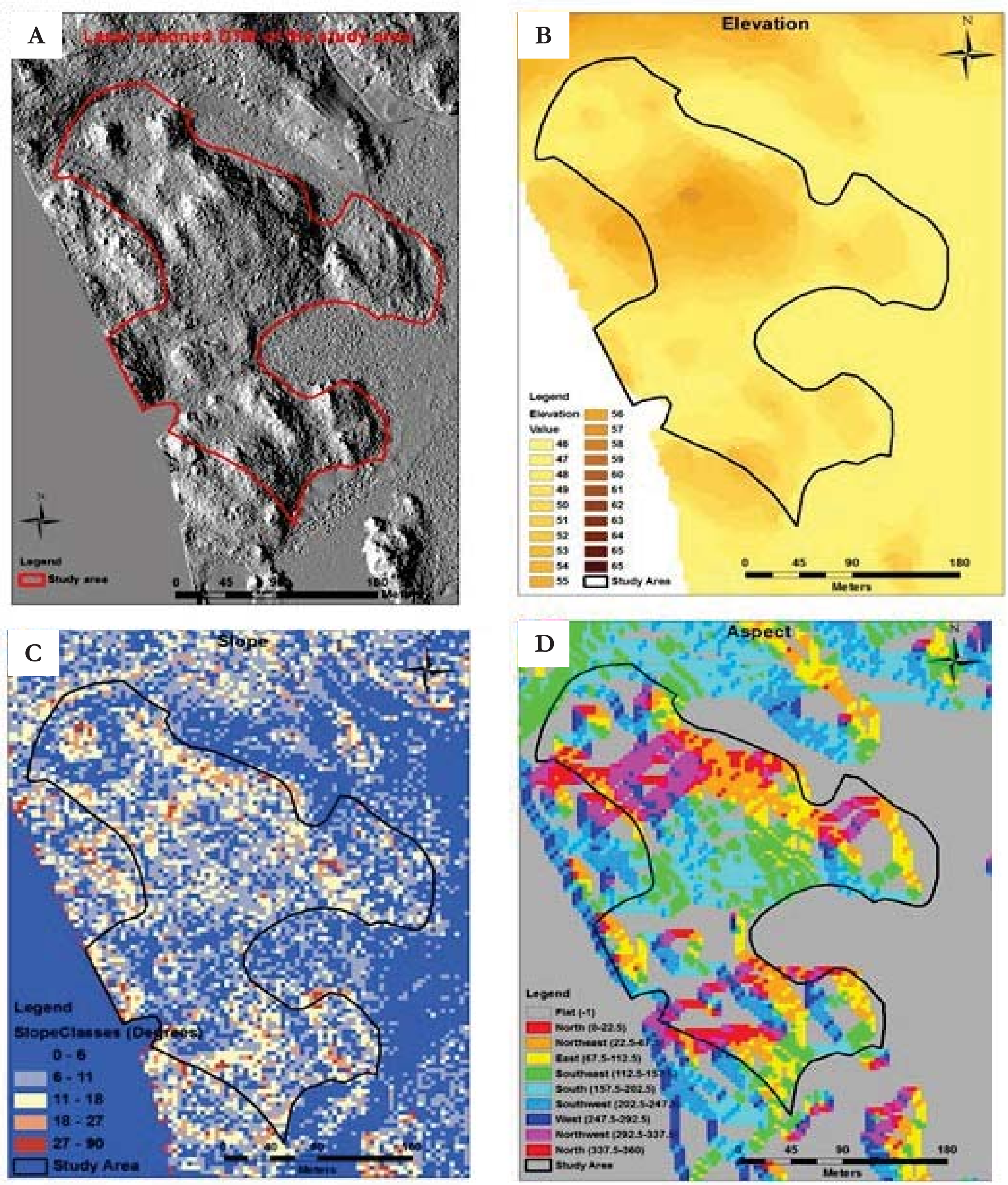
Thor, Magnus: Skogforsk. Discussion on criteria selection and evaluation of the results, (Group meetings, January, February, March, April 2011).

Mörk, Anders: Skogforsk. Discussion on designing route distribution in harvesting sites, (Group meetings, March, April 2011).

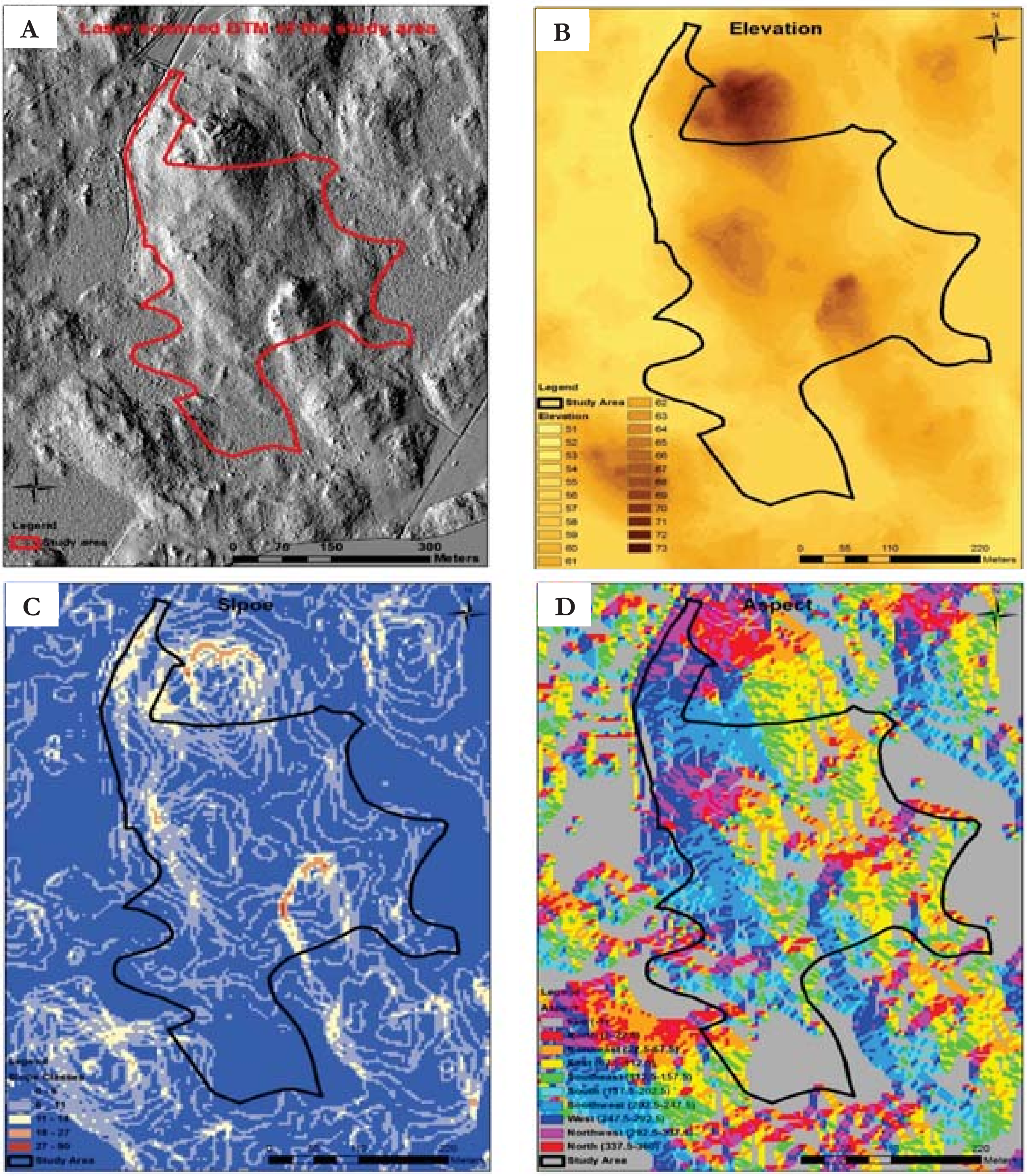
Appendix 1



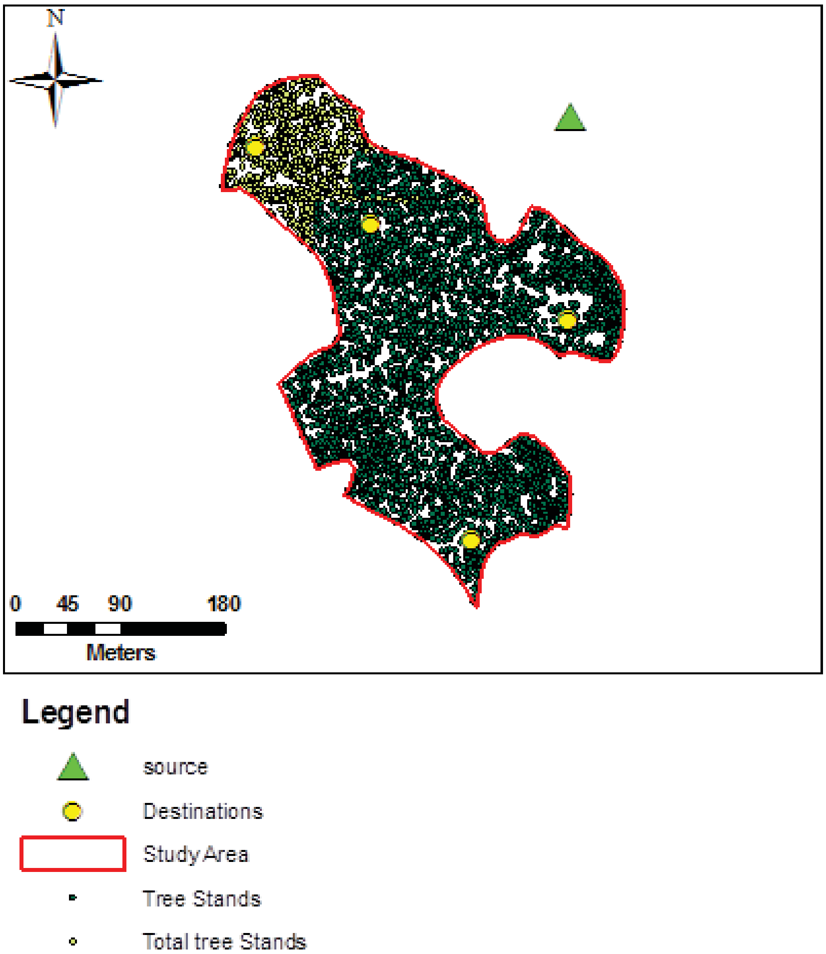
Appendix Figure 1.
Suggested over passes for the Study area 1, Scenario 2. 1 and 3 are natural overpasses while 2 is the suggested location for building a bridge over the restricted wetland.



Appendix Figure 2.
Main input data layers of the model at Study area1: A) DTM, B) elevation, C) slope, D) aspect.



Appendix Figure 3.
Main input data layers of the model at Study area2: A) DTM, B elevation, C) slope, D) aspect.



Appendix Figure 4.
Visualization of the tree stands of the study area1. Light green represents total tree stands; Dark green represents the trees to be collected over the bridge on the wetland.

Economic evaluation of Study area 1:

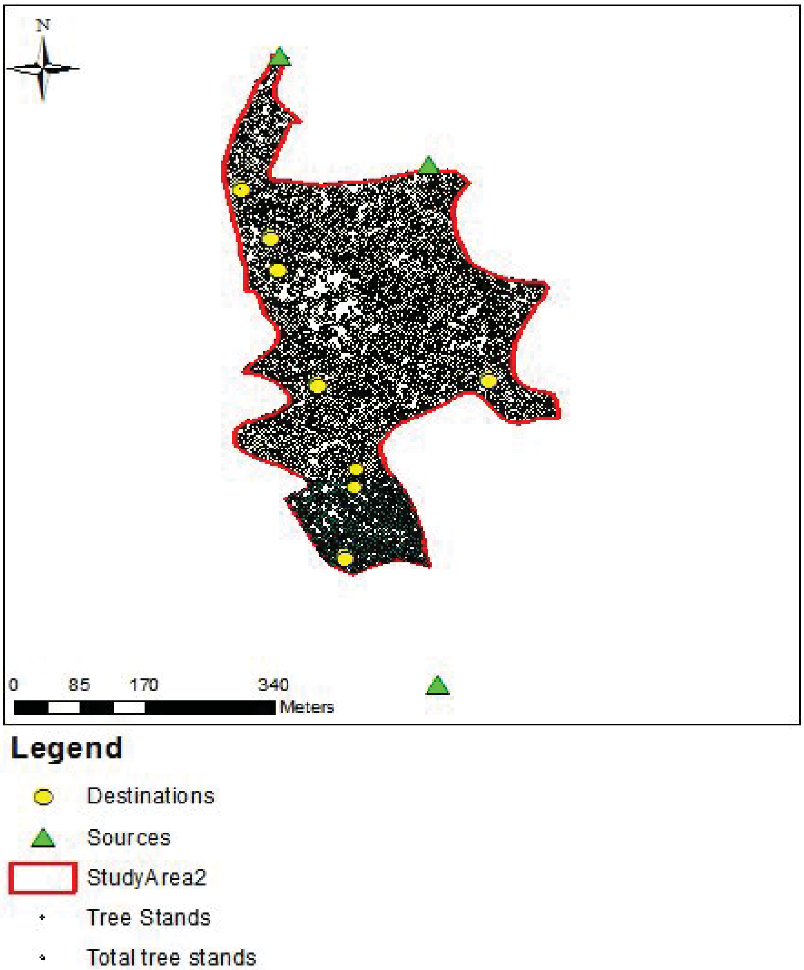
- Route length (m) Scenario 1-Route length(m) Scenario 2 =
  1 972-1 285 = 687 m.

- Assuming maximum velocity of forwarders as: 0.8 m/s
  687 (m) / 0.8 (m/s) = 858.75 s = 0.24 h.

- Tree volumes to be collected from destinations 2, 3, 4 =
  2 526.38 m^3SK = 2096.8954 (m^3 solid under bark) = 1572.67155 tons.

- Assuming maximum possible load of forwarders as 20 tons:
  1 572.6 (tons of tree stands) /20 (Possible tons of load/forwarder) =
  78.63 number of loaded forwarder contribute to almost 158 times passage of forwarders.

- Assuming cost of forwarder as 850 SEK/h:
  0.24 × 158 × 850 = 32 232 SEK.



Appendix Figure 5.
Visualization of the tree stands of the study area 2. Light green represents total tree stands; dark green represents the trees to be collected from either destinations 5 and 6 in Scenario 1 or destination 5* in Scenario2.

Economic evaluation of Study area 2:

- Difference of route section 5 and section 5* =
  655–353 = 302 m.

- Assuming maximum velocity of forwarders as: 0.8 m/s
  302 (m)/0.8 (m/s) = 377.5 s = 0.1 h.

- Tree volume =
  939.02 m^3SK = 779.3866 (m^3 solid under bark) = 584.5 tons.

- Assuming maximum possible load of forwarders as 20 tons:
  584.5 (tons of tree stands) /20 (Possible tons of load/forwarder) =
  29.2 number of loaded forwarders which contribute to almost 60 times of passages by forwarders.

- Assuming cost of forwarder as 850 SEK/hour, finally the amount of saving in money:
  60 × 0.1 × 850 = 5 100 SEK.

Arbetsrapporter från Skogforsk fr.o.m. 2010

2010	
Nr 700	Hannerz, M. & Cedergren, J. 2010. Attityder och kunskapsbehov – förädlat skogsodlingsmaterial. 56 s.
Nr 701	Rytter, R.M. 2010. Detektion av röta i bokved – resultat av mäthöjd, riktning och tidpunkt. 10 s.
NR 702	Rosvall, O. & Lundström, A. 2010. Förädlingseffekter i Sveriges skogar - kompletterande scenarier till SKA-VB 08. 31 s.
Nr 703	von Hofsten, H. 2010. Skörd av stubbar – nuläge och utvecklingsbehov. 18 s.
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