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SPATIAL MODELING OF A NEW TECHNOLOGICAL TYPIFICATION IN FORESTRY BASED ON MULTICRITERIA EVALUATION OF SKIDDING TECHNOLOGIES

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Abstract

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The study describes a new system of technological typification in forestry based on multicriteria evaluation of environmentally friendly use of common skidding technologies. A farm tractor, skidder, cable system, forwarder, and forwarder in combination with harvester were selected as model skidding technologies. The proposed model determines one of the four categories in terms of their environmentally friendly use: 1) Fully suitable, 2) Suitable, 3) Unsuitable – not excluded and 4) Unsuitable for every forest stand and individual skidding technology. The Saaty matrix was used to define weights of input parameters for multicriteria evaluation. The selected input parameters included: slope inclination, ground bearing capacity, risk of logging-transportation erosion hazard, presence and size of obstacles, skidding distance, terrain shape and age of stands. Stocking and areal representation of selected tree species were added to the evaluation of forwarder-harvester combination. Different equipment (standard tires, low-pressure tires, wheel tracks) and climatic conditions (dry, wet) were also taken into account in the evaluation of the model. A multicriteria evaluation was carried out by means of GIS tools in SW ESRI ArcGIS Desktop. The model was applied to the selected experimental territory in the upper part of the basin of the Oskava river and it was verified in different forest stands and terrain conditions in the northern part of the Mendel University Training Forest Enterprise Křtiny. Verification of model results was carried out in randomly selected stands with the overall area representing more than 10% of the total forest area in the experimental territory and more than 8% of the total forest area in the verification territory.

Keywords: multicriteria evaluation, skidding technologies, digital terrain model, technological typification, technological optimization

INTRODUCTION

Utilization of GIS application and method of remote sensing in forestry has a long tradition in the Czech Republic. Forestry has been one of the first pioneers in putting GIS applications and methods of remote sensing into practice. These technologies became a standard tool for acquiring, updating, analyzing, and presenting spatial data.

Both in the world and in the Czech Republic, several technical papers and studies focused on utilization of GIS technologies for the evaluation of forestry transportation network or for the selection of a suitable skidding technology. Two main approaches used to be applied in modeling the process of making forests accessible. The first approach is based on solutions for model conditions which are generally applicable for all situations. These procedures are based on theoretical models. The aim of these models is the creation of generally applicable model which should be independent on real conditions of the territory which are usually simplified in these models. The second approach represents solutions which take into account real conditions of the territory, mainly the terrain characteristics. These solutions have gradually prevailed thanks to quick developments in the field of the hardware, software, databases, and commercial geographic information systems. Use of the digital terrain model (DTM) has enabled modeling real terrain conditions in these models. This category include for example the models of TERDAS (Shiba, 1996), PLANEX (Epstein *et al.*, 2001) or models for evaluation of skidding and forwarding distance created using the AML programming language (Pacola *et al.*, 1999; Tuček *et al.*, 2003). In some new works LIDAR data are used to optimizing terrain transportation (Søvde *et al.*, 2011) or to carry out forest transportation survey (Sačkov *et al.*, 2014).

GIS is also an integral part of models for automatic localization of new forest roads in forests not yet accessible. These solutions are usually based on economic assessment of their design. The most applied parameters for evaluation of suitability of particular designs are costs, profit, mean skidding and forwarding distance, and exploitation index. There are many methods for searching an optimal design of forest road network in forests not yet accessible. GIS are used for assessment of costs and multicriteria evaluation. Earlier studies on this topic include studies by Liu and Session (1993) or the model of ROADPLAN (Newnham, 1995). Among the more recent studies we can mention models by Contreras and Chung (2006), Kühmaier and Stampfer (2010), Mohtashami (2012), Jourgholami *et al.* (2013) or Krč *et al.* (2013). Also these models have recently used LIDAR data. Saito *et al.* (2013) have developed an automatic forest road design model which is based on a LIDAR highly accurate DTM and shallow landslide risk maps.

For completeness, in relation to the overview of using GIS in forest transportation accessibility, we have to mention models solving terrain and technological typification. One of the first studies on this topic was a study by Davis and Reisinger (1990) who classify terrain by slope inclination, ground bearing capacity, and presence of obstacles. These three parameters are also used in later models. Owende *et al.* (2001) based their classification on similar parameters, namely soil conditions (mainly ground bearing capacity), roughness of the terrain (presence of obstacles, such as stones and grooves), and slope inclination. Simanov *et al.* (1993) proposed a new system of terrain and technological typification for conditions of the Czech Republic. Basic parameters of the terrain classification are slope inclination and edaphic categories derived from forest types. The edaphic category is a source of information on presence of obstacles, ground bearing capacity, and presence of landslide areas. There are 23 terrain types derived from the combination of input parameters. The last two terrain types are based only on the parameter of slope inclination (over 50%). Suitable skidding technologies are subsequently assigned to each terrain type. Pentek *et al.* (2008) based terrain typification on three factors: terrain slope, extraction distance and breast height diameter in order to determine environmentally sound harvesting system.

One of the last studies focusing on terrain and technological typification is a study by Slančík *et al.* (2008). Terrain typification is carried out on the basis of four parameters: slope inclination, presence of obstacles, ground bearing capacity, and risk of logging-transportation erosion development.

MATERIAL AND METHODS

An area in the upper part of the Oskava river basin, where forests are administrated by The Forests of the Czech Republic, state enterprise, the experimental territory was selected. The altitude of the area ranges from 340 to 960 meters above sea level. The experimental territory is suitable for multicriteria evaluation of environmentally friendly skidding technologies due to its geomorphological variability, high percentage of forest cover and high variability of forest types. There are 65 forest types in 16 edaphic categories, including steep slope forest types are represented in the experimental territory. With regard to its variety, the experimental territory is well accessible using skidding roads of the density of 19.7 m.ha^{-1}.

The proposed model was subsequently verified in different stand and terrain conditions in a northern part of the Mendel University Training Forest Enterprise Křtiny. The verification territory was chosen because there are deep valleys with long steep slopes, forest types different from those in the experimental territory with beech prevailed in the stands.

The latest ESRI ArcGIS Desktop, version 10.2.1 was selected for construction of the model for multicriteria assessment of environmentally friendly skidding technologies. Input parameters were selected based on a literature research and with regard to the aim of the study to build a universal dynamic system which will be applied for the whole area of the Czech Republic. The selected parameters have either a nationwide digital layer or can be derived from another nationwide digital layer:

1. Terrain conditions:
   a) Slope inclination;
   b) Terrain shape (concave, convex, combined, flat);
   c) Presence of obstacles (including singularities).
2. Soil parameters:
   a) Ground bearing capacity;
   b) Risk of logging-transportation erosion development.
3. Stand:
   a) Areal representation of spruce and fir;
   b) Age;
   c) Stocking.

4. Technology:
   a) Climbing ability;
   b) Nominal ground pressure;
   c) Ground clearance;
   d) Skidding and forwarding distance.

Intervals are defined with regard to environmentally friendly use of selected technology for the selected input parameters. These intervals have the following classification:

1. Fully suitable;
2. Suitable;
3. Unsuitable – not excluded;
4. Unsuitable.

Not all the input parameters have the same weight for a particular skidding and forwarding technology. Weights of input parameters for multicriteria evaluation were defined by means of Saaty matrix and geometric mean of rows (Saaty, 1977).The final weights serve to objectification of basic values of the input parameters (value vs. weight). An independent layer was derived for every defined skidding and forwarding technology. Every stand is classified into one of the categories of environmentally friendly use based on multicriteria evaluation of the input data (Tab. I).

I: *Categories of environmentally friendly use*

Category	Description
< 1.50	Fully suitable
1.51–2.50	Suitable
2.51–3.50	Unsuitable – not excluded
> 3.50	Unsuitable

Terrain Conditions

Input parameters as slope inclination and terrain shape were derived from a DTM. Altitudinal data from the Fundamental Base of Geographic Data (ZABAGED) were used, based on the study by Klimánek (2006), as input for DTM creation. Vertical contour line interval was 2 m and in a small part of the experimental territory 5 m. Apart from contour lines, also more ZABAGED data layers were used for the DTM construction: altitude points, edges, terraces, roads and water bodies. Singularities, local maxima and local minima were located during the field survey by GPS Trimble Geo XT 2008. After post processing, these data were used as a further input data layers to make the DTM more accurate. The DTM was constructed as TIN due to taking into account singularities as compulsory edges. Data layers of slope inclination and curvature were derived from the DTM and subsequently transformed to the raster presentations with resolution of 5 m. The layer of curvature was reclassified then by means of statistical characteristics included in the function of Zonal Statistics. The result of the reclassification was that every stand has only one prevailing terrain shape: flat, convex, concave, or combined. The methodology of terrain shape determination has been subsequently changed according to results of the model in the experimental territory. The prevailing terrain shape was calculated for individual parts of forest stands in the verification territory of Křtiny. Presence of obstacles was derived from the edaphic categories of forest types according to methodology of terrain and technological typification by Simanov *et al.* (1993). The presence and size of obstacles was verified in selected edaphic categories during the field survey.

Soil Parameters

Ground bearing capacity was assessed according to the methodology by Vavříček (2011) who evaluates the ground bearing capacity on the basis of one-time pressed track of LKT 80 skidder with nominal ground pressure of 200 kPa. Ground bearing capacity is evaluated at common moisture of the class of moderately damp soils and also for sites influenced by precipitations of the class of wet soils. Vavříček (2011) defined five resistance degrees of soil in taxonomic units taking into account consistency and temporary hydric influence. The layer of soil resistance degrees was derived from the layer of forest types. Each forest type was assigned by a prevailing soil type based on which the appropriate soil resistance degree is derived. Risk of logging-transportation erosion development was assessed according to the methodology by Macků (2000) created within the project No. VaV/640/3/00 titled “System of complex assessment of forest soils”. The assessment includes two steps. The first step is creation of a data layer of the potential development of logging-transportation erosion which is derived from the data layer of forest types. In the second step this data layer is converted into a data layer of real risk of development of logging-transportation erosion according to areal representation of broadleaved and coniferous trees by means of the weight of reduction factor. Areal representation of broadleaved and coniferous trees takes into account the changing of natural soil parameters caused by forest management.

Stand

Data on age, areal representation of tree species and stocking which enter the model are taken over from the valid forest management plan for forest administration unit of Janovice. A barrier had to be used for the parameter of areal representation of spruce and fir according to model testing for the combination of harvester with forwarder. This barrier was used for the preference of stands with areal representation of spruce and fir over 60 per cent. The lowest grade 4 was replaced by grade 99.

Technical Parameters

Technical parameters of particular skidding and forwarding technologies serve in relation to terrain conditions to set the environmentally friendly use intervals:

- Climbing ability in relation to slope inclination;
- Nominal ground pressure in relation to ground bearing capacity;
- Ground clearance in relation to presence and size of obstacles.

Assessment of a climbing ability of farm tractor and skidder was taken over from the study by Slančík *et al.* (2008) without using fuzzy intervals. Assessment of climbing ability of forwarders and harvesters was carried out according to figures quoted by Neruda (2008). Figures of nominal ground pressure for farm tractor and skidder were taken over from the study by Simanov *et al.* (1993). For forwarders and harvesters, figures of nominal ground pressure determined within the project of ECOWOOD (Owende *et al.*, 2002) were used. Skidding and forwarding distances were calculated for every stand by means of a mean geometric skidding and forwarding distance. To recalculate the geometric skidding and forwarding distance into the real skidding and forwarding distance, a formula derived by Beneš (1986, in Ulrich, 2006) was used. Beneš used this formula to express skidding and forwarding distance in a basin.

$$ds = dg \times \sqrt{2}\ ,$$

ds ..... real skidding and forwarding distance [m],
dg ..... geometric skidding and forwarding distance [m].

Ten variants were assessed in the model based on combination of selected skidding and forwarding technologies with different equipment (standard tires, low-pressure tires, wheel tracks) and climatic conditions (dry, wet):

1. Farm tractor – dry soil (FT–dry);
2. Farm tractor – low-pressure tires – dry soil (FT-dry);
3. Farm tractor – low-pressure tires – wet soil (FT-wet);
4. Skidder – dry soil (SK-dry);
5. Skidder – low-pressure tires– wet soil (SK-wet);
6. Forwarder – dry soil (FW-dry);
7. Forwarder – wet soil (FW-wet);
8. Forwarder in combination with harvester – dry soil (FWHV-dry);
9. Forwarder in combination with harvester – wet soil (FWHV-wet);
10. Cable system (CS).

The variants of farm tractor and skidder both with standard tires was not considered in the condition of wet soil. Their nominal ground pressure of 160 kPa and 220 kPa resp. fails to correspond even to the highest degree of ground bearing capacity (81–120 kPa) according to Vavříček (2011).

Input parameter weights were defined by means of Saaty matrix and geometric mean of rows for selected skidding and forwarding technologies (Fig. 1).

Input parameters and their weights were at first processed by means of the function of *Weighted sum*. Parameters of areal representation of spruce and fir, stocking, age, terrain shape, skidding and forwarding distance were directly defined or converted for particular stands or their parts. Other parameters entered the analysis without this conversion for stands. The final raster was reclassified to categories of environmentally friendly use. This raster was subsequently processed by means of the function of *Zonal statistics* to final values of categories of environmentally friendly use for selected skidding and forwarding technologies for particular stands. Scheme of the model is described in Fig. 10.

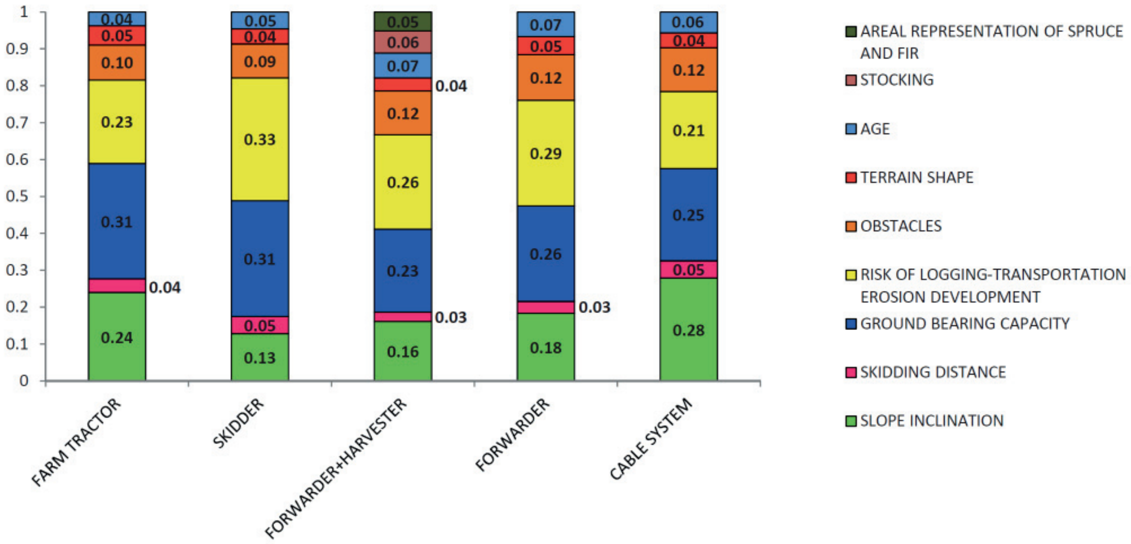
RESULTS AND DISCUSSION

The model was applied at the experimental territory of 3.660 ha and subsequently tested in the different stand and terrain conditions of the verification territory with a total forest area of 3.148 ha. A regular grid of points in spacing 1×1 km was randomly created to verify the results of the model in the both territories. A buffer zone was then created around every point with a diameter of 30 m. Stands for verification of results were selected using spatial intersections of these buffer zones with data layer of the stands or their parts. Area of the selected stands represents 10.1 per cent of the total forest area within the experimental territory and 8.5 per cent of the total forest area within the verification territory.

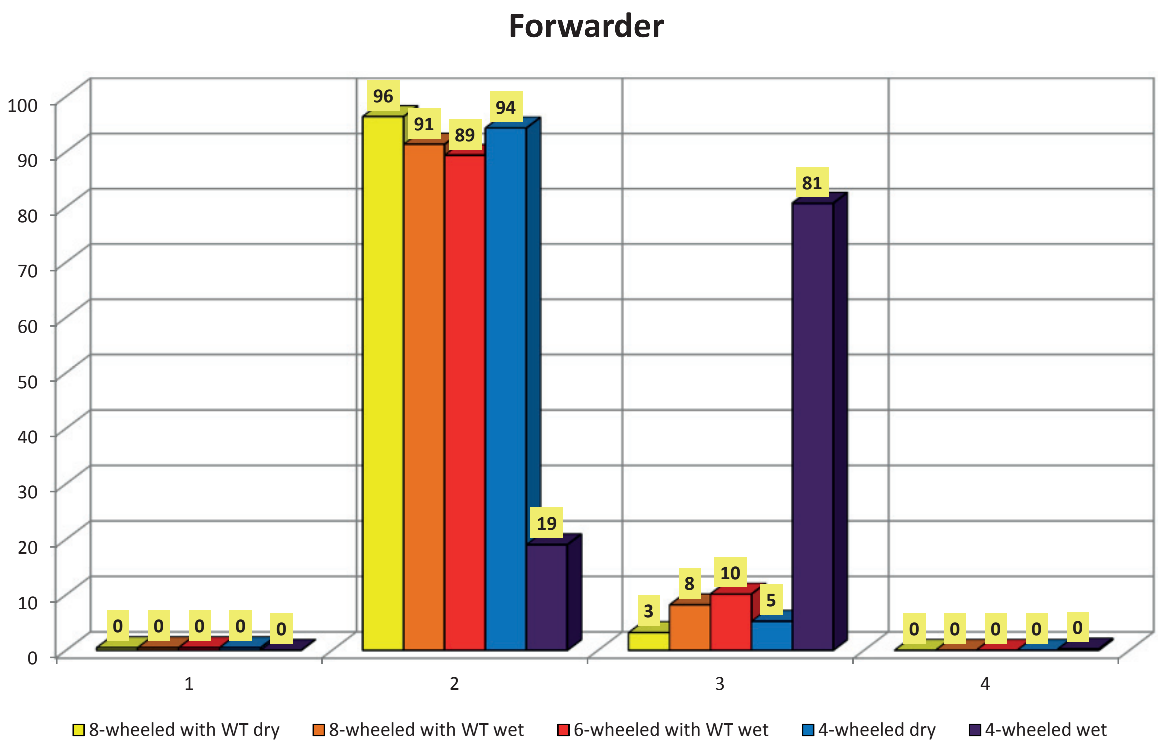
The input parameters of the model – slope inclination, edaphic category, presence of obstacles and terrain shape – were verified during a field survey in the selected stands. Evaluation of the category of environmentally friendly use for the selected skidding and forwarding technologies were also verified within the field survey.

The highest variability between model figures and field reality was found out for the terrain shape during the verification in the experimental territory. Assessment of the terrain shape was changed in 8 stands during the field survey. In other 10 stands, it was concluded that the terrain shape was assessed correctly but it was not specific enough to influence the results of the model significantly. The methodology of terrain shape determination has been subsequently changed according to results in the experimental territory. The prevailing terrain shape was calculated for individual parts of forest stands in the verification territory. This change of methodology has had a significant influence on an accuracy of terrain shape determination. Assessment of the terrain shape was changed in 4 stands during the field survey in the verification territory. In other 7 stands, it was concluded that the terrain shape was assessed correctly but it was not specific enough to influence the results of the model significantly. The assessment of the parameter of obstacles presence was changed in 5 stands in the experimental territory and in 1 stand in the verification territory. This parameter depends on the accuracy of determination of forest types in terrain and subsequently on areal representation of edaphic categories in individual stands. The median value of slope inclination in individual stands was compared with field measurements where a prevailing slope was measured by clinometer. In 10 stands in the experimental territory it was found out that there is a difference between the model values and field measurement higher than 5 per cent out of which the slope inclination derived from the DTM was lower than the prevailed slope inclination in the terrain in 7 stands. In the verification territory it was found out that there is a difference in 5 stands. The prevailed slope inclination was in 4 stands higher than the slope inclination derived from DTM.

The assessment verification of the environmentally friendly use categories for the selected skidding and forwarding technologies showed differences depending only on the accuracy of input parameters determination. If model

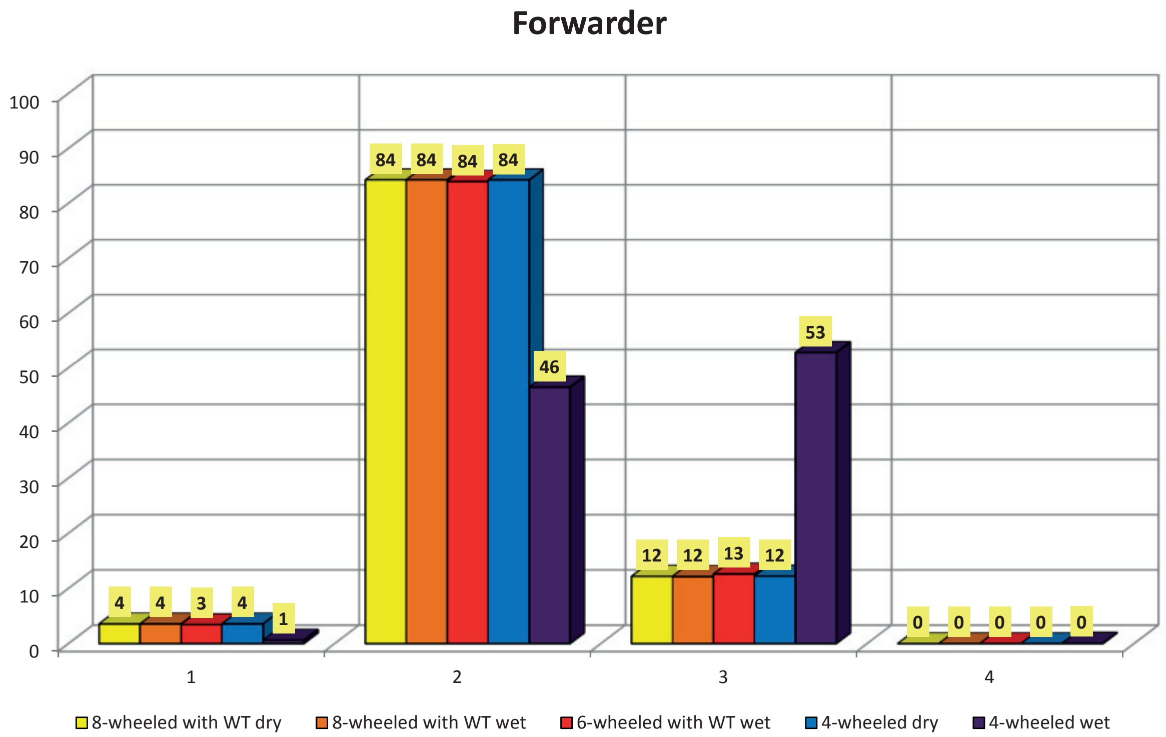


1: *Input parameter weights for selected skidding and forwarding technologies*

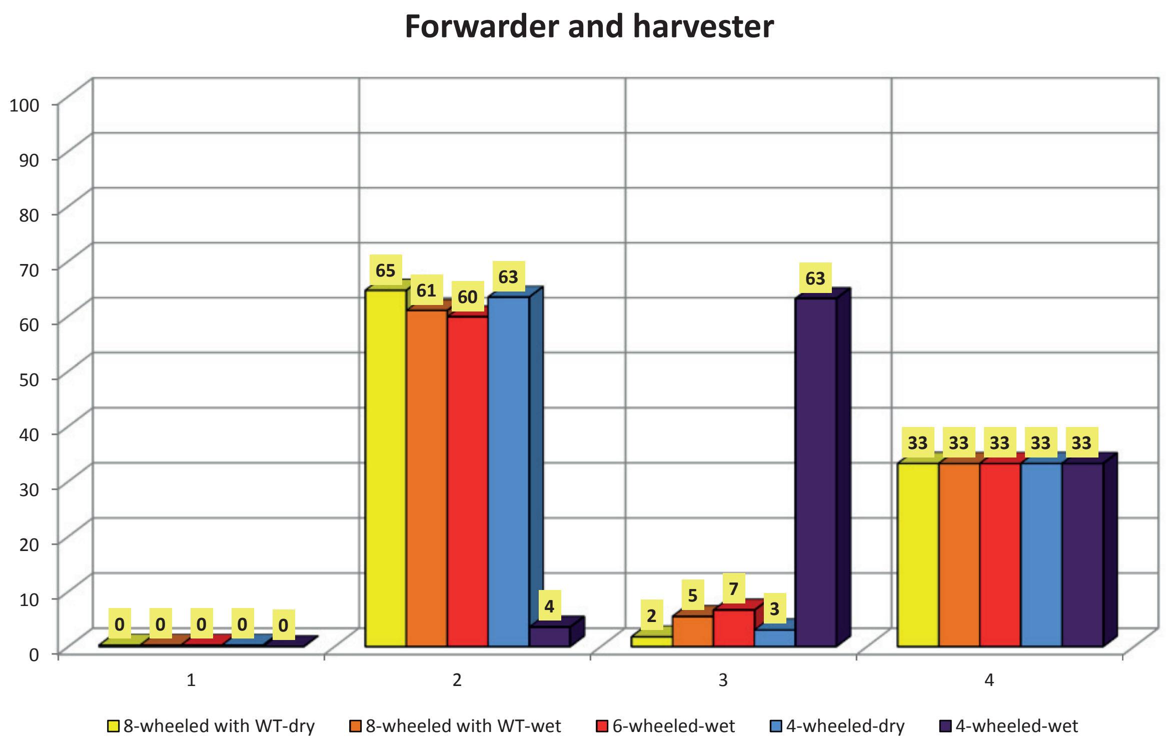


2: *Forwarder – experimental territory*

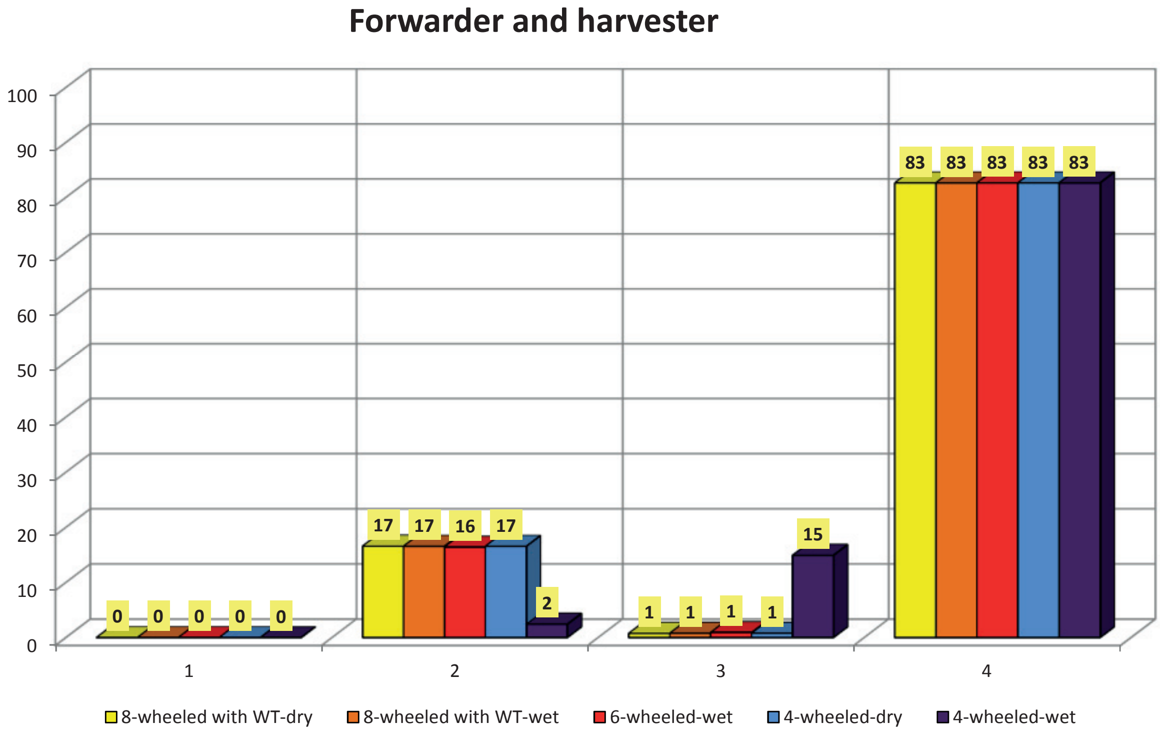
input parameters corresponded to real terrain conditions, no significant errors in classification of the environmentally friendly use categories for the selected skidding and forwarding technologies were recorded. Results for the selected skidding and forwarding technologies were processed for two variants. The whole stands were taken into account in the first variant and parts of individual stands were taken into account in the second variant. The second variant has given more accurate results, these



3: *Forwarder – verification territory*

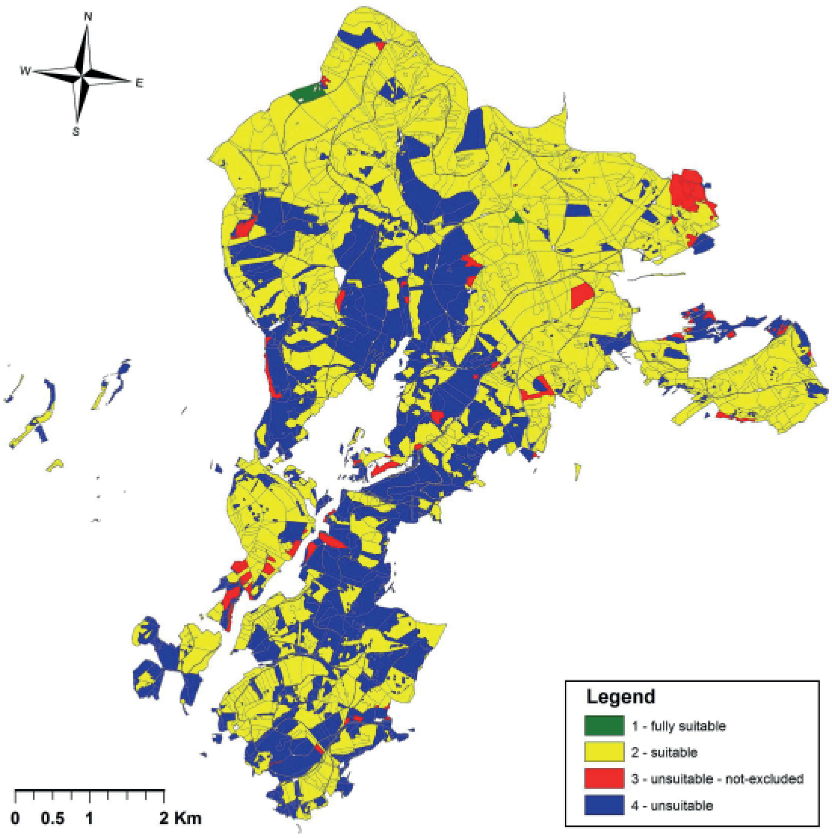


4: *Forwarder and harvester – experimental territory*

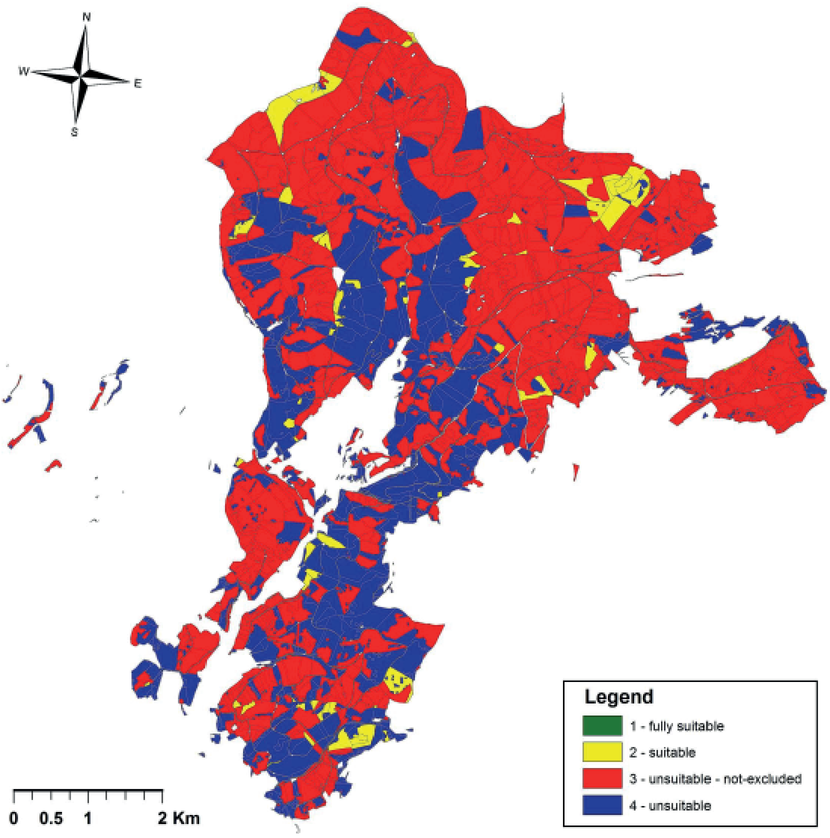


5: *Forwarder and harvester – verification territory*

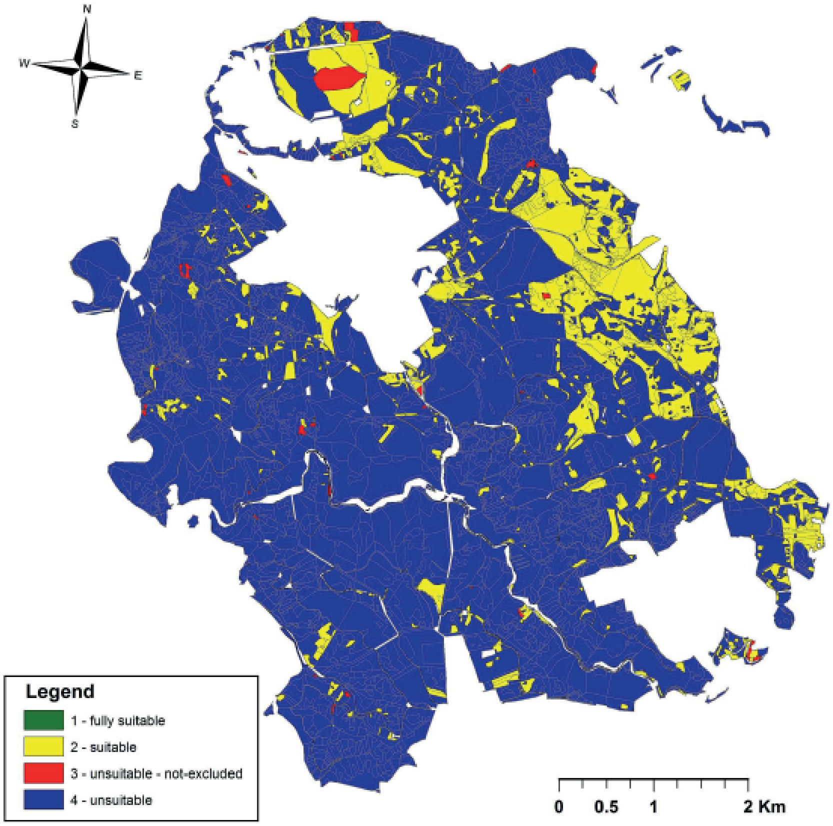
results for both territories and selected skidding technologies are quoted in graphs (Figs. 2–5). As expected, the most environmentally friendly skidding technology, the eight-wheeled forwarder with suitable wheel tracks, has the highest areal representation in the categories of environmentally friendly use 1 and 2 in the experimental territory. Application of this forwarder is suitable in almost 91 per cent of the forest area under wet conditions and in almost 96 per cent of forest area under dry conditions. Likewise, just a small difference is between using this type of forwarder with an eight-wheeled harvester with suitable wheel tracks. It is 65 per cent of forest area under dry conditions and 61 per cent of forest area under wet conditions. There is a big difference in using four-wheeled forwarder under wet or dry conditions. Using this type of forwarder is suitable in almost 94 per cent of forest area in the experimental territory under dry conditions but only in 19 per cent of forest area under wet conditions. Using a combination of four-wheeled forwarder with a four-wheeled harvester is suitable in 63 per cent of forest area under dry conditions (Fig. 6) but only in 4 per cent of forest area under wet conditions (Fig. 7). Different results we have had in the verification territory. Eight-wheeled forwarder with suitable wheel tracks has the same areal representation in the categories of environmentally friendly use 1 and 2 under dry and wet conditions and it is 88 per cent. The biggest difference was also found in using four-wheeled forwarder but the difference is not as high as in the experimental territory. Using this forwarder is suitable in 47 per cent of the forest area under wet conditions and in 88 per cent of forest area under dry conditions. The smaller difference between dry and wet conditions is mainly caused by higher areal representation of bearable soils but on the other hand, there is higher areal representation of steep slopes and obstacles in the verification territory which caused lower suitability in dry conditions in contrast to the experimental territory. Prevailing beech stands are a main reason for low suitability of the combination the eight-wheeled forwarder with the eight-wheeled harvester both with suitable wheel tracks in the verification territory. The areal representation in the categories of environmentally friendly use 1 and 2 under dry and wet conditions comprises 17 per cent. The four-wheeled combination of forwarder with harvester is suitable in 17 per cent of forest area under dry conditions (Fig. 8) but only in 2 per cent of forest area under wet conditions (Fig. 9) within the verification territory. Significant differences are also in the environmentally friendly use of a farm tractor depending on equipment and climatic conditions. Using a farm tractor with standard tires is suitable in 53 per cent of forest area within the experimental territory under dry conditions. Suitability of using a farm tractor with low pressure tires is much higher under dry conditions, namely 79 per cent of forest area. However, under wet conditions, even though using low pressure tires, suitability of using a farm tractor drops to only 15 per cent of forest area. Different results we have had in the verification territory mainly as a result of different



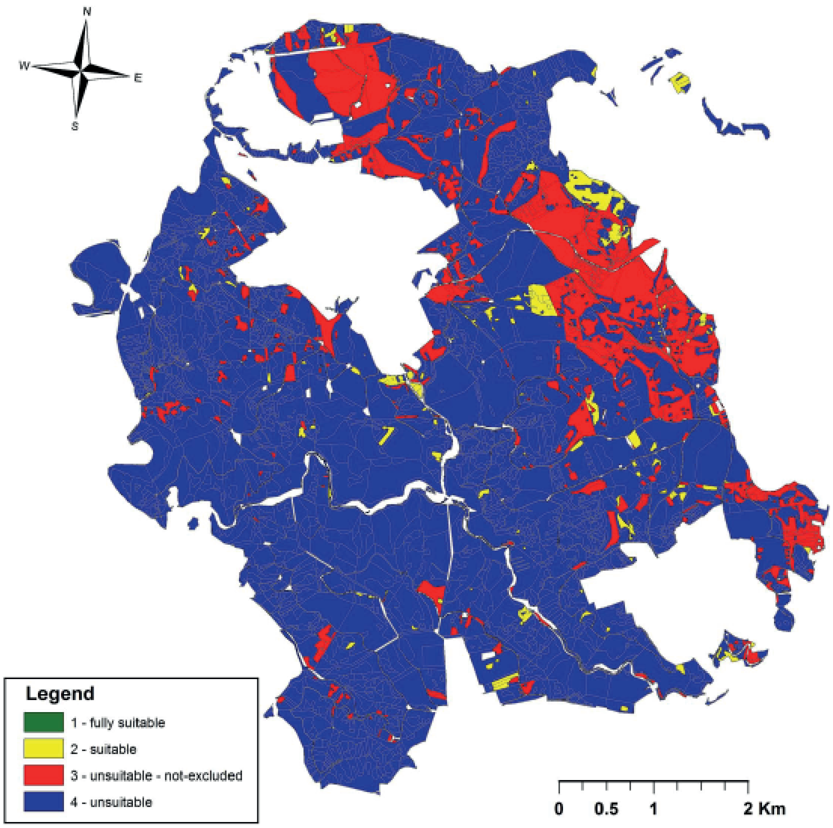
6: *Experimental territory – Forwarder+Harvester 4-wheeled – dry*



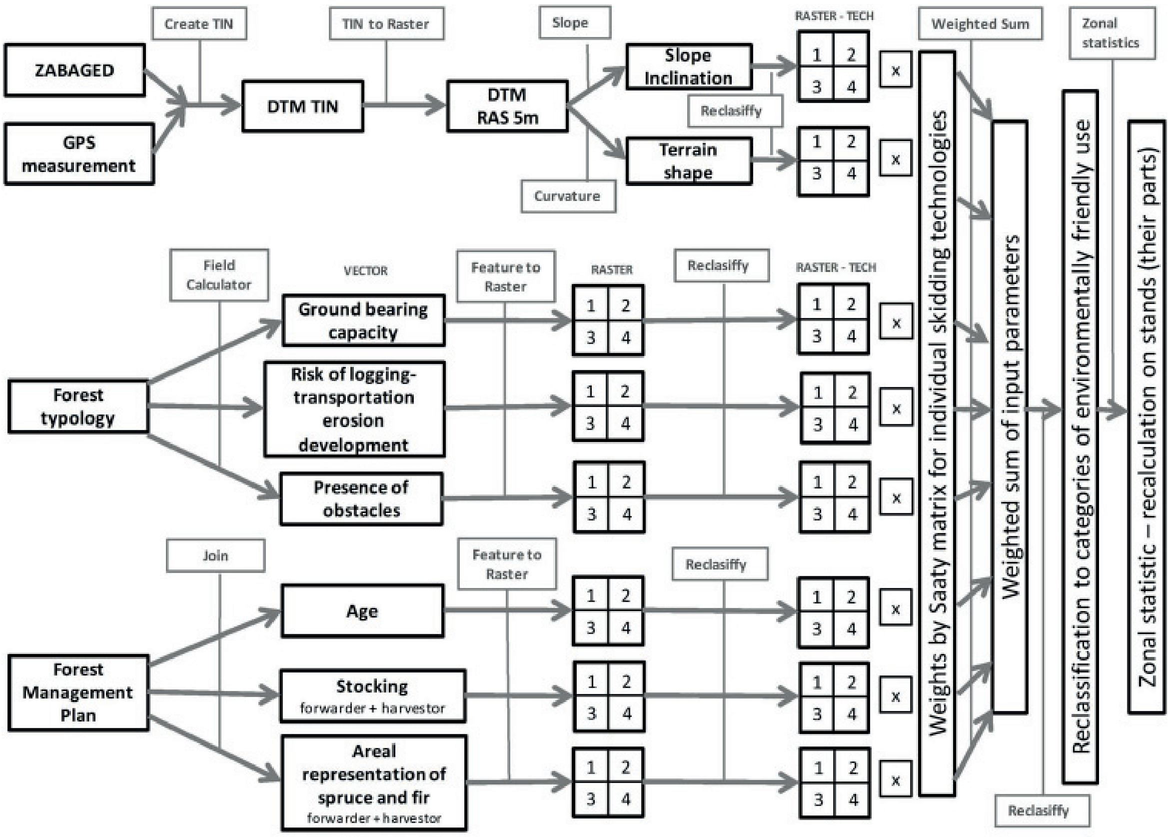
7: *Experimental territory – Forwarder+Harvester 4-wheeled – wet*



8: *Verification territory – Forwarder+Harvester 4-wheeled – dry*



9: *Verification territory – Forwarder+Harvester 4-wheeled – wet*



10: *Scheme of the model*

soil and terrain conditions. The farm tractor with standard tires is suitable in 68 per cent of forest area under dry conditions. Suitability of using a farm tractor with low pressure tires is in 78 per cent of forest area under dry conditions and in 46 per cent of forest area under wet conditions. Significant differences were also recorded in environmentally friendly use of a skidder depending on equipment and climatic conditions. Using a skidder with standard tires is suitable in 64 per cent of forest area in the experimental territory under dry conditions and only in 32 per cent of forest area under wet conditions, despite of using low pressure tires. Suitability of using a skidder is higher in the verification territory. Areal representation in the categories of environmentally friendly use 1 and 2 is 87 per cent under dry conditions and using low pressure tires 66 per cent under wet conditions. The model for assessing the environmentally friendly use of a cable system is designed to promote stands where slope inclination, ground bearing capacity, presence of obstacles or combination of these parameters do not allow using wheeled technologies in terms of their environmentally friendly use. Based on these conditions, cable systems are suitable only in 3 per cent of forest area within the experimental territory. This low cable system suitability has been one of the reasons to verify model in different terrain and soil conditions. Suitability of using a cable system has reached 13 per cent of forest area in the verification territory.

CONCLUSION

The aim of the study was to create and verify a model for selection of environmentally friendly skidding technologies based on multicriteria evaluation by means of GIS tools in the selected experimental territory. Verification of model results was carried out in randomly selected stands with the overall area representing more than 10 per cent of the total forest area in the experimental territory and more than 8 per cent of the total forest area in the verification territory. The terrain shape showed the lowest level of reliability among all the input parameters of the model in the experimental territory but its determination has been changed in verification territory and this methodology change has had a positive impact on determination accuracy. Weight of terrain shape ranged from 3 to 5 per cent in the final multicriteria evaluation, and therefore the incorrect determination of this parameter has a very low influence on the final results of the model. Next accuracy improvement of the terrain shape as well as determination of the slope inclination is possible in the next development of the model by using a more accurate DTM. Digital Terrain Model of the Czech Republic – 4th generation (DMR 4G) and later Digital Terrain Model of the Czech Republic – 5th generation (DMR 5G) will be suitable sources for derivation of these two parameters. These two models will be created from LIDAR data. Thanks to this technology both models will have substantially higher altitude accuracy as well as more accurate detection of singularities which have significant influence on determination of the terrain shape. After adjustment, the total standard error of height in the bare terrain will amount to 0.3 m and in the forested terrain to 1 m in DMR 4G which was available in the end of 2013. After adjustment, the total standard error of height in the bare terrain will amount to 0.18 m and in the forested terrain to 0.3 m in DMR 5G which will be available in 2015. When input parameters corresponding to real terrain conditions were used, there were no significant errors in classification of the categories of environmentally friendly use for the selected skidding and forwarding technologies recorded. A small portion of the experimental and the verification territory (0.01–0.02 per cent) was classified by grade 0 for all the selected skidding and forwarding technologies. Reason for this classification is the spatial differences of input data layers. Not only this model but also all nationwide data layers and models will be more accurate after creating the unified digital cadastral map of the Czech Republic. In the next development of the model it seems to be suitable to take into account the size of the stands, mainly for cable system. It is not to select due to too small stands or parts of the stands for this type of technology. Stands, where the main reason for using the cable system is the ground bearing capacity, could be also differentiated, because it is possible to use wheeled vehicles when the ground is frozen here. The model was primarily focused on the stands. The results of the model were calculated not only for the whole stands but also for particular parts of the stands and we have got more accurate results for the categories of environmentally friendly use. In further development of the model, the categories of environmentally friendly use can be determined with higher accuracy. We propose to determine several categories of environmentally friendly use of a particular skidding technology for stands or for their parts with an area larger than 1.5 (2) ha. The reason for this division into several categories would be a continuous area of the suitability category of use larger than 0.5 ha or smaller depending on the requirements of forest management or authorities of nature protection on the size of clear-cuts. The final output of the model will be a map of potential use of selected skidding technologies where the information on environmentally friendly use of particular skidding and forwarding technologies will be directly visualized for particular stands.

The proposed model is going to be universally applicable to new types of selected skidding and forwarding technologies. Defined weights of input parameters will stay unchanged for selected skidding and forwarding technologies but a user will be able to correct intervals of environmentally friendly use (Fully suitable, Suitable, Unsuitable – not excluded, Unsuitable) of selected input parameters according to technical parameters of a particular type of skidding and forwarding technology. For example a new type of forwarder can have higher climbing ability or lower nominal ground pressure than it was set in the model so the user will be able to correct intervals of environmentally friendly use in relation to slope inclination or ground bearing capacity. The selected input parameters make it possible to use the proposed model not only in the conditions of the Czech Republic. According to published research results, these parameters and their digital geospatial layers are usually available or can be derived from existing data layers for particular chosen territories in many countries.

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