GIS Applications in Forest Operations and Road Network Planning: an Overview over the Last Two Decades

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Abstract

A systematic literature review was settled to investigate the application of GIS in terms of methods, complexity and accuracy to support decision on forestry operations and forest road network planning. A comprehensive search for relevant studies was performed to retrieve as many relevant international scientific publications dealing with forestry operations and forest road network planning in the period 1996–2015.

The analysis was based on the development of a systematic literature review comprising three steps:

⇒ implementation of the database searches by well-defined search terms

⇒ identification of all the publications meeting the requirements of the search terms by abstract

⇒ choice of the most relevant publications analysis of the contents.

In this review, »GIS and forest operations« includes all the descriptors dealing with GIS applied to support forest operations decision and analysis, while »GIS and forest roads« includes all the papers dealing with the analysis, management and planning of forest road or forest road networks. A total of 372 references and 82 publications were selected for the analysis as they were clearly in conformity with the review topics (GIS applications in forest operations and road network planning).

The analysis showed that GIS has also been applied successfully and unambiguously to harvesting and transportation engineering in forest operations management. Further to the prevailing use concerning applications to support tactical planning, a significant number of recent publications have turned successfully to GIS applied at operational level. Again, despite the prevailing use concerning applications to support tactical planning, a significant number of recent publications have also turned successfully to GIS applied at operational level with the topics of Forest Operations Management in terms of optimization, productivity and safety analysis.

By considering the recent evolution and improvement of GIS technology and the increasing availability of spatial data, as well their improvement in quality and resolution, the application of GIS in forest harvesting and transportation engineering as well as in forest operations management will expand in the near future.

Keywords: systematic review, GIS, forest operations, forest road network, spatial analysis, IUFRO

1. Introduction

Nowadays the application of logical and numerical modelling and statistical methods to spatial data is almost routine thanks to the Geographical Information System – GIS (Burrough and McDonnell 1998). The application of GIS for spatial analysis is well known. GIS has the primary means of storing, viewing and analysing spatial data as well integrating a range of different spatial data and information. Spatial information can be obtained from map digitizing, field data collection (generally by Global Navigation Satellite System, GNSS), aerial photogrammetry, remote sensing and/or Computer Aid Design (CAD) (Malczewski 1999).

GIS started to support environmental decisions in the middle of the seventies (Worral 1991). One of the first GIS applications in natural resources dealt with planning and management of a forest recreation area in western Maryland (Becker 1976). Again, first GIS applications on harvesting operations focused on strategic harvesting planning to minimise site disturbance (Reisinger and Davis 1986) and on harvesting visual impact assessment in landscape design (Dunningham and Thompson 1989).

Over the last decades, the use of GIS in forestry has been increasingly expanding and widely applied in many fields in forest engineering at professional level as well as at academic and research level (Li et al. 2007). GIS application in forest engineering has also generated considerable recent research interest by highlighting different analytical approaches (Bettinger et al. 2009).

Typically, the GIS covers the range from the application of essential functions of spatial analysis to the application and development of statistical modelling and mathematical modelling (Longley et al. 2011). The choice of the analytical approach depends on the aim of the GIS or spatial analysis. To support decisions on the identification of the most suitable harvesting systems or on the evaluation of forest accessibility, morphology (largely slope, roughness analysis, etc.) and distance (largely straight line or Euclidean distance and cost distance) parameters are the most common spatial analysis applications (Reisinger and Davis 1986, Pentek et al. 2008, Cavalli and Grigolato 2010, Hayati et al. 2012, Dupire et al. 2015, Mologni et al. 2016, Sitzia et al. 2016). Further, spatial analysis essential functions (as Euclidean distance or cost path calculation) integrated in a multi-criteria model can be considered an advanced spatial analysis approach that can be used to support decisions on harvesting planning by introducing diverse criteria for selecting the most suitable harvesting techniques (Kuhmaier and Stampfer 2010, Synek and Klimánek 2014) or the energy wood supply management (Kühmaier et al. 2014), to define forest road maintenance priorities (Pellegrini et al. 2013) as well as new forest road alignment (Babapour et al. 2014, Hayati et al. 2013).

The development of complex mathematical modelling in GIS environment or comparable spatial analysis tool can enable forest engineers to design unequivocally a forest road network layout (Stückelberger et al. 2007, Najafi et al. 2008, Bont et. al. 2015), to optimize cable road layout (Bont and Heinimann 2012), to define the best skidding trail according to tree position (Sterenczak and Moskalik 2014), to support the decision on forest road upgrading (Karlsson et al. 2006), as well as to understand environmental impact generated by forest operations (Proto et al. 2016).

It is currently excessively expensive to collect information on the relevant forest characteristics (as terrain morphology and/or forest growth parameters) by means of field inventories (Maltamo et al. 2014). Light Detection and Ranging (LiDAR) technologies system, aircraft-mounted (Airborne Laser Scanner – ALS) or ground-based (Terrestrial Laser Scanner, TLS), is a cost-efficient means to obtain data with high spatial resolution and high positional accuracy (Akay et al. 2009, Pirotti et al. 2012). GIS and LiDAR thus seem to be a prominent integration for most forest engineering topics e.g. the use of high resolution terrain and stand information to support forest road network planning and designing or to analyse forest operations and forest machine performance. The increasing accuracy of spatial information and a suitable spatial resolution on forest cover and terrain has resulted in the integration of GNSS and GIS technologies (McDaniel et al. 2012). Accurate analyses, based mainly on essential functions of spatial analysis, are proposed for extracting forest-yield maps by combining accurate spatial data and harvester information (Olivera and Visser 2016), as well for proving forest machine efficiency (Alam et al. 2012, Strandgard et al. 2014) or for identifying factors, such as terrain and volume distribution, machine production efficiency and time element identification (Pellegrini et al. 2013, Grigolato et al. 2016, Macrì et al. 2016, Olivera et al. 2016).

Again, at small scale of application, essential spatial analysis commonly used in GIS environments has been used to evaluate spatial distribution of soil disturbance by forest machines by integrating high resolution data, such as micro-DEM derived from light detection and ranging (LiDAR) technologies (Koreň et al. 2015) or photogrammetry methods (Haas et al. 2016, Pierzchała et al. 2014, Pierzchała et al. 2016).

Clearly, in the last years, the forest engineering community has shown great interest in GIS and spatial analysis. As a consequence, a systematic review is currently a prerequisite to highlight the importance of the subject and help to understand the main questions that have driven this interest. Further, the same result can also be useful to encourage future interest and development.

A key motivation for this review is to identify the progress of the last two decades that can contribute to improving the knowledge and the application of GIS in the traditional forest engineering topics and in particular in forest operations and road network planning. The three main questions are: what have been the main spatial analysis techniques applied? What has been the complexity of the applied methods? What has been the accuracy of the data?

2. Materials and methods

2.1 Systematic review

To synthesize and discuss different approaches, issues and findings of GIS application in forest operations and forest road network planning, a review of the existing literature was conducted. A systematic review is the procedure of identifying and evaluating multiple studies on a topic using a clearly defined methodology (Wolf et al. 2016). An evidence-based approach to scoping reviews (Khalil et al. 2016) was thus adopted by:

⇒ defining and refining research search terms
⇒ identifying databases and search engines
⇒ querying database using the search terms
⇒ creating and applying the inclusion and exclusion criteria filters
⇒ verifying the representation of the sub-selections.

A comprehensive search for relevant studies was thus performed to retrieve as many relevant scientific publications dealing with GIS application in forest operations and forest road network planning in the period 1996–2015 (20 years). The papers were gathered up in September 2016.

The systematic literature review thus comprised three main steps. In Step 1, search terms and their various combinations were defined to seek for articles relevant from the perspective of GIS and Forest Operations and Forest Road Network. In this case, the literature search was achieved for peer-reviewed articles and conference proceedings within the Scopus (www.scopus.com) database.

Scopus Database is one of the largest multidisciplinary peer-reviewed literature database also including cited references for citation searching. For citation analysis, Scopus database also offers a higher coverage than other peer-reviewed literature databases. The main constraint of the Scopus database is the limitation in covering articles published before 1995 (Falagas et al. 2007). In this study, this limitation will not influence the results as the search for relevant studies was fixed to retrieve scientific publications in the period 1996–2015.

The search terms were so defined and combined using Boolean operators (AND, OR) and wild-cards representing any group of characters, including no character. The search string for GIS application in forest operations and forest road network planning was thus compiled as follows:

TITLE-ABS-KEY (»GIS« OR »G.I.S.« OR »Geographic information system«) AND TITLE-ABS-KEY (»Forest operation*« OR »forest mechanisation« OR »forest road*« OR »forest road network*« OR »Skid* trail*« OR »logging« OR »cable« OR »yarder«) AND TITLE-ABS-KEY (»Forest*«) AND (PUBYEAR > 1995 AND PUBYEAR < 2016) AND TITLE-ABS-KEY (»forest*«).

The additional inclusion criteria were then defined: language: »English«; subject area: »Forestry, Agriculture and Environmental Science« or »Engineering«; document type: »article«; source type: »Journal« or »Conference proceeding«.

In Step 2, the abstracts of the articles were examined to identify the papers meeting the main requirements of the research. In the subsequent Step 3, the whole contents of the articles selected in Step 2 were studied to identify their main research approach and vision.

To better understand the rising in number of publications in »GIS and Forest operation/Forest roads«, the number of papers identified by the systematic search was also compared with the total number of publications (also indexed into Scopus database) identified by the search terms: TITLE-ABS-KEY (»GIS« OR »G.I.S.« OR »Geographic information system«).

2.2 Data organization and inclusion criteria

Each identified reference in Step 1 was imported into Mendeley Desktop (Mendeley® Ltd.) library and thus re-organised into an external spreadsheet in the form of a database. The database consisted of three parts:

⇒ mandatory fields about the reference
⇒ categorization of the subject according to the IUFRO 3.00.00 Division and its unit subjects
⇒ fields on main GIS data type and quality as well on GIS analysis.

The following mandatory field were thus compiled in order to fully describe the reference as well its current impact: »Authors«, »Article title«, »Year«, »Journal/conference title«, »Number of citations«, »Type«, »Language« and »Abstract«.

For the purpose of the analysis, the main subjects were associated with the designation of the eight Units of the IUFRO 3.00.00 Division »Forest operations engineering and management« as follows: »Harvesting and transportation engineering«, »Stand establishment and treatment«, »Forest ergonomics«, »Forest operations management«, »Forest operations ecology«, »Forest operations in mountainous conditions«, »Forest operations in the tropics« and »Small-scale forestry«.

»Harvesting and transportation engineering« was sub-divided into three sub-subjects »Road networks and transportation«, »Road engineering and management« and »Harvesting and processing systems«. »Forest operations management« was also sub-divided into two sub-subjects »Operations systems analysis and modelling« and »Supply chain management«.

When the papers could not be clearly identified under the Unit of the IUFRO 3.00.00 Division, an additional field annotated them to the most appropriate IUFRO Division or eventually excluded them when they were not relevant for the subject review.

Step 2 consisted of selecting relevant documents by application of inclusion criteria. Inclusion criteria were first applied to the document title, then to the abstract and in the final phase, to the whole document. Each paper was thus screened according to the following four categories:

⇒ paper with the subject clearly in conformity with the review topics (GIS applications in forest operations and road network planning)

⇒ paper with the subject partially in conformity with the review subjects (GIS application concerns mainly forest planning, forest management and/or forest landscape and less forest operations and road network planning)

⇒ subject slightly conforming to the review subjects (GIS applications are not the main aims of the paper and slightly related to forest operations and road network planning)

⇒ paper not related to GIS application neither to forest operations or forest road network planning.

In Step 3, the whole contents of the articles selected as paper with the subject strictly conforming to the review topics (GIS applications in forest operation and road network planning) were analysed.

The database was thus complied by including the following mandatory fields:

⇒ planning level (strategic level, tactical level, operational level)

⇒ main type of input data (raster data, vector data, aerial photograph; satellite image; miscellany)

⇒ limiting spatial data resolution in case of image and raster data (greater than 10 m; between 10 m to 1 m; smaller than 1 m)

⇒ complexity of GIS analysis (static analysis; dynamic analysis)

⇒ outputs:

✓ cartographic models (temporally static, combined spatial)

✓ spatial-temporal models (dynamics in space and time, time-driven processes)

✓ network models (modelling flow and accumulation over a road network).

3. Results and discussions

3.1 Scientific literature and time distribution

In presenting the findings of the literature research, a simple chronology of the publications gathered in the first step is presented. In line with the broad focus of the review, peer reviewed publications on GIS applications in forest operations and road network planning have steadily risen over the past two decades with a rapid increase (Fig. 1), particularly since 2005. The identification process (Step 1) gathered 372 studies for the period 1996–2015. The average number of publications per year was 18.6 when calculated for the entire period 1996–2015. The average number of publications resulted statistically different

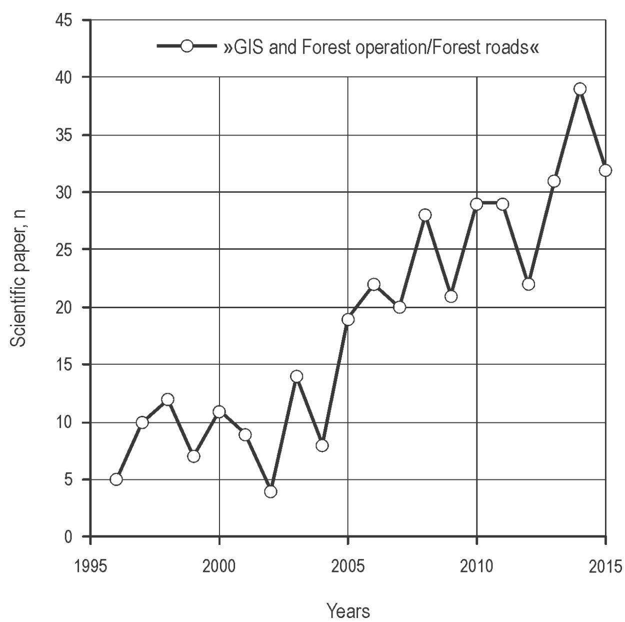

Fig. 1 Publications on »GIS and Forest operations/Forest roads« gathered from Scopus database in the period 1996–2015

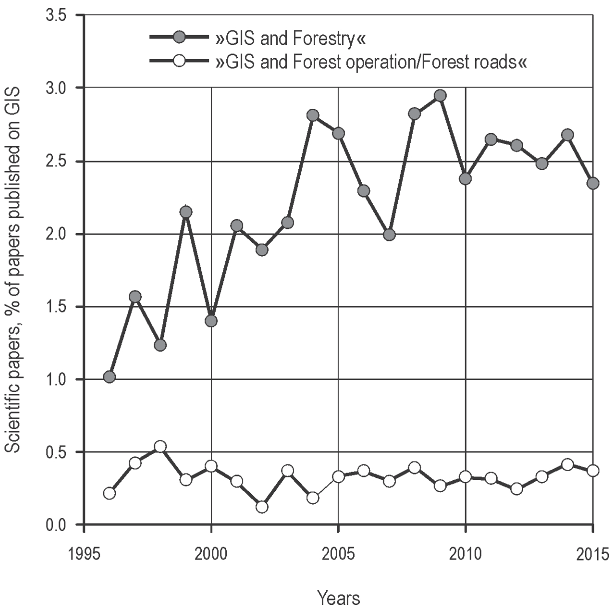

Fig. 2 Peer reviewed publications on »GIS and Forest operations/Forest roads« and on »GIS« and »Forestry« during the period 1996–2015 normalized for the total number of peer reviewed publications focusing on »GIS« published during the same period

(Paired *t*-test, α=0.05) for the first decade 1996–2005 (9.8 publications per year) if compared with the second decade 2006–2015 (27.3 publications per year).

Scientific publications in »GIS and Forest operation/Forest roads« thus seem to be constant in time (Fig. 2) when compared to the total number of publications focusing on GIS application and GIS development published during the same period. This is confirmed by the analysis of the period 1996–2015 divided in two sub-periods corresponding to two decades 1996–2005 and 2006–2015, in which the percentage of publications on »GIS and Forest operations/Forest roads« related to the total publications on GIS application and development shows that the results are comparable (0.31% in the period 1996–2005 and 0.33% in the period 2006–2015) (Paired *t*-test, α=0.05). In contrast, the yearly »GIS« publications related to »forestry« in general (search terms: TITLE-ABS-KEY (»GIS« OR »G.I.S.« OR »Geographic information system«) and TITLE-ABS-KEY (»Forest*«) seem to increase with time (Fig. 2).

The 372 collected papers have been published in 132 different scientific journals or conference proceeding (6.4% of the retrieved publications) and written by 156 different first authors from 60 different countries. The papers covered a broad range of scientific disciplines (20), of which the most represented were Environmental Science and Agricultural and Biological Sciences both accounting for 56% of the papers. About 13% (37) of the papers were published in just three journals: Croatian Journal of Forest Engineering, Forest Ecology and Managements and Biomass Bioenergy.

In terms of impact, 69.6% of the papers were also cited at least one time during the same period, with a maximum of 406 citations for a paper (Curran et al. 2004) focusing on logging in tropical forest and only partially concerning the use of GIS to support forest operations or forest road network analysis. In total, the 372 papers generated 5299 citations in 20 years with an average of 265 citations on average per year and an average of 14.2 citations per publication.

Most common keywords were: GIS (included »Geographic Information System«, »G.I.S«) with 7% and »Forest road« (including »Forest road«, »Forest road network«) with 5%.

3.2 Application of inclusion criteria

The application of inclusion criteria (Step 2) first identified 33 publications not strictly related to GIS

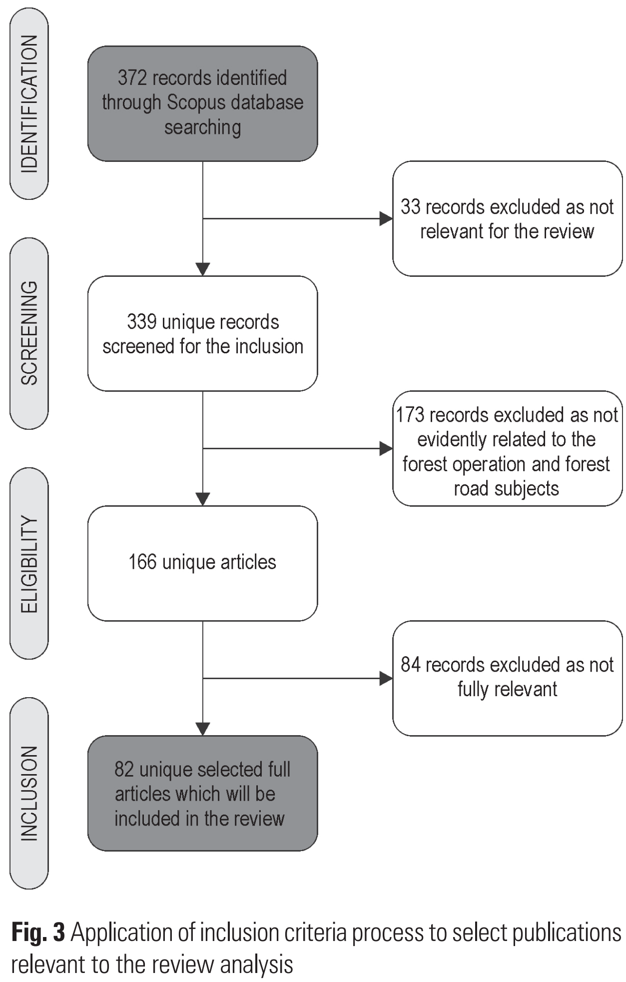

Fig. 3 Application of inclusion criteria process to select publications relevant to the review analysis

application nor to forest operations or forest road network planning.

Secondly, other 173 publications were excluded from the analysis because they only partially conformed to the review subjects (GIS application concerns mainly forest planning, forest management and/or forest landscape and less forest operations and road network planning) or just slightly conformed to the review subjects (GIS applications are not the main aim of the paper and slightly related to forest operations and road network planning).

The remaining 166 unique peer reviewed publications were analysed in detail to identify the most relevant and appropriate publications for the reviews. As a final point, 82 unique peer reviewed publications proved to be eligible for the detailed review analysis. In order to clearly determine the review decision process, Fig. 3 summarized, in the form of a flow chart, the logic of the inclusion criteria process used in this review.

3.3 Relevant publications

3.3.1 Subjects distribution

Across the entire period covered, the number of relevant peer reviewed publications with the subject clearly in conformity with the review topics (GIS applications in forest operations and road network planning) resulted in 82 unique papers after the application of the criteria section.

The average number of publications per year was 4.05, when calculated for the entire period 1996–2015. The average is statistically different (Paired *t*-test, α=0.05) when it is calculated separately for the first decade 1996–2005 (1.1 publications per year) and for the second decade 2006–2015 (7.0 publications per year).

The 82 unique publications were published into 53 different scientific journals or conference proceedings (7.3% of the selected publications) written by 67 different first authors.

In terms of impact, 70.7% of the publications were cited at least one time across the entire period covered. Within the same period, 82 publications generated 874 citations in 20 years with an average of 43.7 citations per year in total and an average of 10.6 citations per publication.

About 58% (48) of the relevant peer reviewed publications were strongly related to forest road and/or forest road planning subject, while 39% (31) were assigned to subject of forest operations. The remaining 2% (2) consisted of publications focusing mainly on assessing hydrologic integration of extensive logging-road network with the stream network (Wemple et al. 1996, Murphy et al. 2007) as crucial information to improve forest operations planning, road layout and construction, culvert location and size and off-road drive. Consequently, the publications were associated to a third subject, entitled »water control«.

Peer reviewed publications related to »Harvesting and transportation engineering« accounted for 60% (49), while publications related specifically to »Forest operations management« accounted for the remaining 40% (33).

The analysis of each reference related to »Harvesting and transportation engineering« through the tree sub-subjects »Road networks and transportation«, »Road engineering and management« and »Harvesting and processing systems« reported that »Road networks and transportation« was the most frequent description accounting for 36 (73%) out of 49 publications, while »Road engineering and management« and »Harvesting and processing systems« accounted, respectively, for 11 (22%) and for 2 (4%) out of 49 publications (Table 1). The high number of publications on »Road networks and transportation« also highlighted that this sub-subject was very attractive for the researchers, as it was absolutely the most recurring with 44 publications out of 82 publications (44% of the total). It highlighted the strong interest of the researchers in designing efficient forest road networks and wood transportation systems within the investigated period.

Within the subject »Forest operations management«, »Operations systems analysis and modelling« overlooked the sub-subject »Supply chain management«. In total »Operations systems analysis and modelling« accounted for 24 (73%) publications out of 33, while »Supply chain management« accounted for 9 (11%) publications. It should also be emphasised that »Operations systems analysis and modelling« was the second most frequently occurring sub-subject among all the selected publications.

3.3.2 Planning level

In forestry, planning and decision making is traditionally performed at strategic, tactical or operational level depending on the time scale to which they are applied (D'Amours et al. 2008). From the selected publications, the GIS application in forest operations and road network planning seemed to support all the planning levels. It should be noted that almost 50% of the publications reported GIS application to support tactical planning.

In the case of »Road networks and transportation«, GIS was extensively used to support tactical analysis

Table 1 Selected publications in the period 1996–2015 broken down according to their main subjects

Subjects and sub-subjects	n.	% $_{subject}$	% $_{total}$
Harvesting and transportation engineering			
Road networks and transportation	36	73.5	43.9
Road engineering and management	11	22.4	13.4
Harvesting and processing systems	2	4.1	2.4
Sub-total	49	100	–
Forest operations management			
Operations systems analysis and modelling	24	72.7	29.3
Supply chain management	9	27.3	11.0
Sub-total	33	100	–
Total	82	–	100

on the existing forest road network and to provide useful information for the decision-makers on further development of road network (Table 2). For example, Pentek et al. (2005) propose one of the first approaches to analyse the quantity and quality of the existing primary forest road network in different forest management units in Croatia to support forest manager in allocating efficiently the resources to specific forest areas. Again Krč and Beguš (2013) provided a GIS model to support tactical decision on identifying inaccessible forest areas by density of forest roads. In this case, the model is based on the analysis of distances between the existing network of public and forest roads and inaccessible forest areas. At tactical level, GIS also focused on road maintenance (Karlsson et al. 2006, Pellegrini et al. 2013, Talebi et al. 2015).

Some examples focused on the use of GIS to support decisions on solving issues related to the increment of volume of heavy trucks and the related rise of costs for road maintenance (Millot et al. 2006, Dowdle and Douglas 2007, Grigolato et al. 2013). Different applications were also related to transportation and logistics used for energy wood supply chains (Ranta 2005, Kanzian et al. 2009, Emer at al. 2011, Friso et al. 2011, Röser et al. 2011, Tahvanainen and Anttila 2011, Zambelli et al. 2012). They were also used for roundwood logistics (Gerasimov et al. 2008) and to support analysis on speed and fuel consumption (Holzleitner et al. 2010, Holzleitner et al. 2011, Sosa et al. 2015).

GIS used to assist in tactical planning and scheduling adapted to forest operations issues was also investigated. Kuhmaier and Stampfer (2010) provided a Decisions Support System (DSS) based on GIS and specifically designed to support timber harvesting decisions by comparing harvesting systems considering stakeholders interests and environmental circumstances. Synek and Klimánek (2014) proposed the use of GIS for multi-criteria evaluation of environmentally friendly skidding technologies.

Despite the prevailing use of applications to support tactical planning, a significant number of recent publications have also turned to the possibility of applying GIS successfully at operational level. In particular, the GIS applications focused on forest operations management in terms of optimization, productivity and safety analysis (Alam et al. 2012, Sterenczak and Moskalik 2014, Hiesl et al. 2015), as well as on forest road networks and transportation in

Table 2 Selected publications in the period 1996–2015 broken down according to their main subjects related to planning level

Subjects and sub-subjects	Strategic, n. (%)	Tactical, n. (%)	Operational, n. (%)	Total, n. (%)
Harvesting and transportation engineering				
Road networks and transportation	5 (13.9)	23 (63.9)	8 (22.2)	36 (100)
Road engineering and management	–	4 (36.4)	7 (63.6)	11 (100)
Harvesting and processing systems	1 (50.0)	–	1 (50.0)	2 (100)
Sub-total	6 (12.2)	27 (55.1)	16 (32.7)	49 (100)
Forest operations management				
Operations systems analysis and modelling	6 (25.0)	10 (41.7)	8 (33.3)	24 (100)
Supply chain management	5 (55.6)	3 (33.3)	1 (11.1)	9 (100)
Sub-total	11 (33.3)	13 (39.4)	9 (27.3)	33 (100)
Total	45 (73.2)	21 (9.7)	16 (17.1)	82 (100)

terms of single road design and in terms of decision support (Bont and Heinimann 2012, Contreras et al. 2012, Ciesa et al. 2014, Craven and Wing 2014).

3.3.3 GIS approach, analysis and outputs

GIS analyses are commonly based on process models. These can be static, such as defining the roughness index by a Digital Elevation Model (DEM), or dynamic in time and space as with a wildfire simulation model. The identified publication reported only GIS static model. According to Table 3, in the topics »Harvesting and transportation engineering« and »Forest operations management«, GIS model is not adequately applied in approaching the analysis by dynamic reiteration process through time and space.

As a result, simple GIS simulations, just based on changing model inputs or parameters to obtain different outputs in time and space, are more common. Again in the in the period 1996–2015, GIS models and derived applications were mainly based on deterministic variables and functions and rarely included random/stochastic variables as found in Dean (1997) and in Najafi and Richards (2013).

Most of the described and applied models were cartographic models (about 2.05 publications per year for the entire covered period and about 3.7 publications per year in the period 2006–2015) based on numerical operations combining temporally static data with spatial data (Table 3). Most of them were mainly spatial elaborations aimed at calculating the distance from the forest road network and terrain slope only based on vector analysis (Pentek et al. 2010, Pičman et al. 2011, Hayati et al. 2012), either integrated raster or vector analysis (Kluender et al. 1998, Najafi et al. 2008, Pentek et al. 2008, Cavalli et al. 2011, Emer et al. 2011, Nakahata et al. 2014) to provide harvesting and extraction map indicating the most suitable technology or consideration about the efficiency in terms of layout and location of the primary and/or secondary forest road network.

A consistent number of publications (almost 11%) showed interest in combining GIS tools and multicriteria decision analysis to provide Decision Support System to improve forest road planning and maintenance (Abdi et al. 2009, Norizah and Hasmadi 2012, Çalişkan 2013, Pellegrini et al. 2013, Tampekis et al. 2015) and to evaluate the most suitable harvesting system (Mihelič and Krč 2009, Kuhmaier and Stampfer 2010, Enache et al. 2013).

Examples of publications, where GIS was used in conjunction with equations involving different variables and constraints, were proposed by Contreras and Chung (2007) to determine the optimal landing location for ground-based timber harvesting by minimising total skidding and spur road costs, or by Epstein et al. (2006) to find a design of the road network that minimises the cost of installation and operation of harvest machinery, road construction, and timber transport. Again Stückelberger et al. (2006) provided a GIS model integrating different mathematical procedures to estimate accurately the spatial variability of road life-cycle costs, based on terrain surface properties as well as geological properties of the subsoil. Later, Stückelberger et al. (2007) proposed a mathematical

Table 3 Selected publications in the period 1996–2015 broken down according to their main subjects in relation to the type of GIS analysis and type of model output

	Model			
	Cartographic, n. (%)	Spatial-temporal, n. (%)	Network, n. (%)	Total, n. (%)
Harvesting and transportation engineering				
Road networks and transportation	19 (52.8)	13 (36.1)	4 (11.1)	36 (100)
Road engineering and management	6 (54.5)	3 (27.3)	2 (18.2)	11 (100)
Harvesting and processing systems	–	1 (50.0)	1 (50.0)	2 (100)
Sub-total	25 (51.0)	17 (34.7)	7 (14.3)	49 (100)
Forest operations management				
Operations systems analysis and modelling	14 (58.3)	8 (33.3)	2 (8.3)	24 (100)
Supply chain management	2 (22.2)	–	7 (77.8)	9 (100)
Sub-total	20 (60.6)	4 (12.1)	9 (27.3)	33 (100)
Total	60 (73.2)	8 (12.1)	14 (17.1)	82 (100)

graph model to be integrated into GIS to derive a road network that is optimal in terms of its construction costs.

3.3.4 Data structure and data

Only 5% of the publications did not explicitly define the type of data used in the elaboration. 33% of the publications used exclusively raster data, while 20% used only vector data, while 43% used both types of data.

In the case of raster data, 16% of the publications reported a cell size larger than 10 m and only in 8% of cases equal to or lower than 1 m. However, the growing availability of LiDAR data is contributing to increase the use of high accuracy Digital Elevation Model, as well as the use of Digital Canopy Model for pinpointing tree crowns and stems. Heinimann and Breschan (2012) explored a LiDAR-data-based approach to improve the sourcing of stands to be harvested by integrating the Airborne Laser Scanner information into a GIS system and by characterizing the tree attributes that were required for stand bucking optimization. Again, Sterenczak and Moskalik (2014) reported that combining the high-accurate Digital Elevation Model and Digital Canopy Model with GIS is appropriate for determining the optimal or near-optimal locations of forest skid trails. Recently, Strandgard et al. (2014) have shown the possibility to analyse the impact of slope on productivity of a self-levelling processor by inputting into a GIS the data obtained from the GNSS system of the machine and a Digital Elevation Model derived from LiDAR data.

4. Conclusions

It is well recognized that considerable scope exists for the application of GIS technology to aid planning, design and management of forestry. The literature review conducted for this study showed that GIS has also been applied successfully and unambiguously to harvesting and transportation engineering as well as to forest operations management.

High accuracy 3D model dataset of terrain and canopy by Aerial Laser Scanner or Terrestrial Laser Scanner, as well as photogrammetric technology, are nowadays available at lower cost than in the past. The perspective to use 2.5D or 3D spatial analysis is nowadays a reality in forestry (Vauhkonen et al. 2014) and in forest engineering applications (Alam et al. 2012, Strandgard et al. 2014, Koreň et al. 2015).

Besides the advantage of the availability and use of high resolution data, a prominent future development of GIS applications in forest operations and road network planning could be a fully integrated 4D spatial dataset and Virtual Reality (VR) system (Roßmann et al. 2013 and Roßmann et al. 2016). In fact, the evolution of GIS techniques and the improvement of data resolution, in conjunction with the skill of researcher to integrate complex mathematical model and VR, could provide new development opportunities for the forest engineering community.

5. 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.

Akay, A.E., Oguz, H., Karas, I.R., Aruga, K., 2009: Using LiDAR technology in forestry activities. Environmental Monitoring and Assessment 151(1–4): 117–125.

Alam, M.M., Strandgard, M.N., Brown, M.W., Fox, J.C., 2012: Improving the productivity of mechanised harvesting systems using remote sensing. Australian Forestry 75(4): 238–245.

Babapour, R., Naghdi, R., Salehi, A., Ghajar, I., 2014: A decision support system for allocation of mountain forest roads based on ground stability. Arabian Journal for Science and Engineering 39(1): 199–205.

Becker, R.H., 1976: Computer visualizations as aids to forest recreation management. Journal of Forestry 74(12): 820–823.

Bettinger, P., Boston, K., Siry, J.P., Grebner, D.L., 2009: Forest management and planning. Academic Press, New York, 331 p.

Bont, L.G., Heinimann, H.R., Church, R.L., 2015: Concurrent optimization of harvesting and road network layouts under steep terrain. Annals of Operations Research 232(1): 41–64.

Bont, L., Heinimann, H.R., 2012: Optimum geometric layout of a single cable road. European Journal of Forest Research 131(5): 1439–1448.

Burrough, P.A., McDonnell, R., 1998: Principles of geographical information systems. Oxford university press, 333 p.

Çalişkan, E., 2013: Planning of forest road network and analysis in mountainous area. Life Science Journal 10(2): 2456–2465.

Cavalli, R., Grigolato, S., 2010: Influence of characteristics and extension of a forest road network on the supply cost of forest woodchips. Journal of Forest Research 15(3): 202–209.

Cavalli, R., Grigolato, S., Pellegrini, M., 2011: Determination of the forest road network influence on the supply chain for firewood production by Discrete Event Simulation. Journal of Agricultural Engineering 42(4): 41–48.

Ciesa, M., Grigolato, S., Cavalli, R., 2014: Analysis on vehicle and walking speeds of search and rescue ground crews in mountainous areas. Journal of Outdoor Recreation and Tourism 5–6: 48–57.

Contreras, M., Aracena, P., Chung, W., 2012: Improving Accuracy in Earthwork Volume Estimation for Proposed Forest

Roads Using a High-Resolution Digital Elevation Model. Croatian Journal of Forest Engineering 33(1): 125–142.

Contreras, M., Chung, W., 2007: A computer approach to finding an optimal log landing location and analyzing influencing factors for ground-based timber harvesting. Canadian Journal of Forest Research 37(2): 276–292.

Craven, M., Wing, M.G., 2014: Applying airborne LiDAR for forested road geomatics. Scandinavian Journal of Forest Research 29(2): 174–182.

Curran, L.M., Trigg, S.N., McDonald, A.K., Astiani, D., Hardiono, Y.M., Siregar, P., Caniago, I., Kasischke, E., 2004: Lowland forest loss in protected areas of Indonesian Borneo. Science 303(5660): 1000–1003.

D'Amours, S., Rönnqvist, M., Weintraub, A., 2008: Using operational research for supply chain planning in the forest products industry. INFOR: information systems and operational research 46(4): 265–281.

Dean, D.J., 1997: Finding optimal routes for networks of harvest site access roads using GIS-based techniques. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 27(1): 11–22.

Dowdle, L., Douglas, R., 2007: Log truck transportation on public roads in New Zealand: regional network analysis with geographic information systems. Transportation Research Record 1989(1): 34–40.

Dunningham, A., Thompson, S., 1989: Use of geographic information systems in New Zealand forestry applications. Commonwealth Forestry Review 68(3): 203–213.

Dupire, S., Bourrier, F., Monnet, J.-M., Berger, F., 2015: Sylvaccess – A model for automatically mapping accessibility to forests. Revue Forestière Française 67(2): 11–126.

Emer, B., Grigolato, S., Lubello, D., Cavalli, R., 2011: Comparison of biomass feedstock supply and demand in Northeast Italy. Biomass Bioenergy 35(8): 3309–3317.

Enache, A., Kühmaier, M., Stampfer, K., Ciobanu, V.D., 2013: An integrative decision support tool for assessing forest road options in a mountainous region in Romania. Croatian Journal of Forest Engineering 34 (1): 43–60.

Epstein, R., Weintraub, A, Sapunar, P., Nieto, E., Sessions, J.B., Sessions, J., Musante, H., 2006: A Combinatorial Heuristic Approach for Solving Real-Size Machinery Location and Road Design Problems in Forestry Planning. Operations Research 54(6): 1017–1027.

Falagas, M.E., Pitsouni, E.I., Malietzis, G.A., Pappas, G., 2007. Comparison of PubMed, Scopus, Web of Science, and Google Scholar: strengths and weaknesses. The FASEB Journal 22(2): 338–342.

Friso, D., Grigolato, S., Cavalli, R., 2011: Energetic and exergetic analysis of steam production for the extraction of coniferous essential oils. Biomass Bioenergy 35(9): 4045–4056.

Gerasimov, Y., Sokolov, A., Karjalainen, T., 2008: GIS-Based decision-support program for planning and analyzing shortwood transport in russia. Croatian Journal of Forest Engineering 29(2): 163–175.

Grigolato, S., Pellegrini, M., Cavalli, R., 2013: Temporal analysis of the traffic loads on forest road networks. iForest – Biogeosciences and Forestry 6(4): 255–261.

Grigolato, S., Panizza, S., Pellegrini, M., Ackerman, P., Cavalli, R., 2015: Light-lift helicopter logging operations in the Italian Alps: a preliminary study based on GNSS and a video camera system. Forest Science and Technology 12(2): 88–97.

Haas, J., Hagge Ellhöft, K., Schack-Kirchner, H., Lang, F., 2016: Using photogrammetry to assess rutting caused by a forwarder — A comparison of different tires and bogie tracks. Soil and Tillage Research 163: 14–20.

Hayati, E., Majnounian, B., Abdi, E., 2012: Qualitative evaluation and optimization of forest road network to minimize total costs and environmental impacts. iForest – Biogeosciences and Forestry 5(3): 121–125.

Hayati, E., Majnounian, B., Abdi, E., Sessions, J., Makhdoum, M., 2013: An expert-based approach to forest road network planning by combining Delphi and spatial multi-criteria evaluation. Environmental Monitoring and Assessment 185(2): 1767–1776.

Heinimann, H.R., Breschan, J., 2012: Pre-harvest assessment based on LiDAR Data. Croatian Journal of Forest Engineering 33(2): 169–180.

Hiesl, P., Waring, T.M., Benjamin, J.G., 2015: The effect of hardwood component on grapple skidder and stroke delimber idle time and productivity – An agent based model. Computers and Electronics in Agriculture 118: 270–280.

Holzleitner, F., Kanzian, C., Stampfer, K., 2011: Analyzing time and fuel consumption in road transport of round wood with an onboard fleet manager. European Journal of Forest Research 130(2): 293–301.

Kanzian, C., Holzleitner, F., Stampfer, K., Ashton, S., 2009: Regional energy wood logistic – optimizing local fuel supply. Silva Fennica 43(1): 113–128.

Karlsson, J., Rönnqvist, M., Frisk, M., 2006: RoadOpt: a decision support system for road upgrading in forestry. Scandinavian Journal of Forest Research 21(S7): 5–15.

Khalil, H., Peters, M., Godfrey, C.M., Mcinerney, P., Soares, C.B., Parker, D., 2016: An evidence-based approach to scoping reviews. Worldviews on Evidence-Based Nursing 13(2): 118–123.

Kluender, R., Weih, R., Corrigan, M., Pickett, J., 1998: The use of a geographic information system in harvest landing location for ground-based skidding operations. Forest Products Journal 50(3): 87–92.

Koreň, M., Slančík, M., Suchomel, J., Dubina, J., 2015: Use of terrestrial laser scanning to evaluate the spatial distribution of soil disturbance by skidding operations. iForest – Biogeosciences and Forestry 8(3): 386–393.

Krč, J., Beguš, J., 2013: Planning forest opening with forest roads. Croatian Journal of Forest Engineering 34(2): 217–228.

Kühmaier, M., Kanzian, C., Stampfer, K., 2014: Identification of potential energy wood terminal locations using a spatial multicriteria decision analysis. Biomass and Bioenergy 66: 337–347.

Kühmaier, M., Stampfer, K., 2010: Development of a multi-attribute spatial decision support system in selecting timber harvesting systems. Croatian Journal of Forest Engineering 31(2): 75–88.

Li, R., Bettinger, P., Danskin, S., Hayashi, R., 2007: A historical perspective on the use of GIS and remote sensing in natural resource management, as viewed through papers published in north american forestry journals from 1976 to 2005. Cartographica 42(2): 165–178.

Longley, P., Goodchild, M.F., Maguire, D.J., Rhind, D.W., 2011: Geographic information science and system. 4th Edition. New York: John Wiley Sons, Ltd. 496 p.

Malczewski, J., 1999: GIS and multicriteria decision analysis. New York: John Wiley Sons, Ltd. 408 p.

Vauhkonen, J., Maltamo, M., McRoberts, R.E., Næsset, E., 2014: Introduction to forestry applications of airborne laser scanning. In Maltamo, M., Næsset, E., Vauhkonen, J., Editors. Forestry applications of airborne laser scanning: concepts and case studies. Dordrecht: Springer, 1–16.

Macrì, G., Zimbalatti, G., Russo, D., Proto, A.R., 2016: Measuring the mobility parameters of tree-length forwarding systems using GPS technology in the Italian Apennines. Agronomy Research 14(3): 836–845.

McDaniel, M.W., Nishihata, T., Brooks, C.A., Salesses, P., Iagnemma, K., 2012: Terrain classification and identification of tree stems using ground-based LiDAR. Journal of Field Robotics 29(6): 891–910.

Mihelič, M., Krč, J., 2009: Analysis of inclusion of wood forwarding into a skidding model. Croatian Journal of Forest Engineering 30(2): 113–125.

Millot, M., Torre, F., Labbe, S., 2006: An evaluation of timber flows over the forest road system using a geographic information system. Application to road maintenance and logging cost assessment. Revue Forestiere Francaise 58(2): 125–140.

Mologni, O., Grigolato, S., Cavalli, R., 2016: Harvesting systems for steep terrain in the Italian Alps: state of the art and future prospects. Contemporary Engineering Sciences 9(25): 1229–1242.

Murphy, P.N.C., Ogilvie, J., Castonguay, M., Meng, F.R., Arp, P.A., 2007: Verifying calculated flow accumulation patterns of mapped and unmapped forest streams by culvert location. Forestry Chronicle 83(2): 198–206.

Najafi, A., Richards, E.W., 2013: Designing a forest road network using mixed integer programming. Croatian Journal of Forest Engineering 34(1): 17–30.

Najafi, A., Sobhani, H., Saeed, A., Makhdom, M., Mohajer, M.M., 2008: Planning and assessment of alternative forest road and skidding networks. Croatian Journal of Forest Engineering 29(1): 63–73.

Nakahata, C., Uemura, R., Saito, M., Kanetsuki, K., Aruga, K., 2014: Estimating harvest costs and projecting quantities of logging residues for small-scale forestry in Nasushiobara, Tochigi Prefecture, Japan. Journal of Forestry Research 25(4): 965–974.

Norizah, K., Mohd Hasmadi, I., 2012: Developing priorities and ranking for suitable forest road: Allocation using Analytic Hierarchy Process (AHP) in peninsular Malaysia. Sains Malaysiana 41(10): 1177–1185.

Olivera, A., Visser, R., 2016: Development of forest-yield maps generated from Global Navigation Satellite System (GNSS)-enabled harvester StanForD files: preliminary concepts. New Zealand Journal of Forestry Science 46(1): 1–10.

Olivera, A., Visser, R., Acuna, M., Morgenroth, J., 2016: Automatic GNSS-enabled harvester data collection as a tool to evaluate factors affecting harvester productivity in a Eucalyptus spp. harvesting operation in Uruguay. International Journal of Forest Engineering 27(1): 15–28.

Pellegrini, M., Grigolato, S., Cavalli, R., 2013: Spatial multi-criteria decision process to define maintenance priorities of forest road network: An application in the italian alpine region. Croatian Journal of Forest Engineering 34(1): 31–42.

Pellegrini, M., Ackerman, P., Cavalli, R., 2013: On-board computing in forest machinery as a tool to improve skidding operations in South African softwood sawtimber operations. Southern Forests: a Journal of Forest Science 75(2): 89–96.

Pentek, T., Nevečerel, H., Dasović, K., Poršinsky, T., Šušnjar, M., Potočnik, I., 2010: Analysis of secondary relative openness in hilly areas as a basis for selection of winch rope length. Sumarski list 134(5–6): 241–248.

Pentek, T., Nevečerel, H., Poršinsky, T., Pičman, D., Lepoglavec, K., Potočnik, I., 2008: Methodology for development of secondary forest traffic infrastructure cadastre. Croatian Journal of Forest Engineering 29 (1): 75–83.

Pentek, T., Pičman, D., Potočnik, I., Dvorščak, P., Nevečerel, H. 2005: Analysis of an existing forest road network. Croatian Journal of Forest Engineering 26(1): 39–50.

Pičman, D., Pentek, T., Nevečerel, H., Papa, I., Lepoglavec, K., 2011: Possibilities of application of relative openness in secondary forest opening of slope forests in Croatia. Croatian Journal of Forest Engineering 32(1): 417–427.

Pierzchała, M., Talbot, B., Astrup, R., 2014: Estimating soil displacement from timber extraction trails in steep terrain: application of an unmanned aircraft for 3D modelling. Forests 5(6): 1212–1223.

Pierzchała, M., Talbot, B., Astrup, R., 2016: Measuring wheel ruts with close-range photogrammetry. Forestry 89(4): 383–391.

Pirotti, F., Grigolato, S., Lingua, E., Sitzia, T., Tarolli, P., 2012: Laser Scanner Applications in Forest and Environmental Sciences. Italian Journal of Remote Sensing 44(1): 109–123.

Proto, A.R., Grigolato, S., Mologni, O., Macrì, G., Zimbalatti, G., Cavalli, R., 2016: Modelling noise propagation generated by forest operations: a case study in Southern Italy. Procedia – Social and Behavioral Sciences 223: 841–848.

Ranta, T., 2005: Logging residues from regeneration fellings for biofuel production-a GIS-based availability analysis in Finland. Biomass and Bioenergy 28(2): 171–182.

Reisinger, T.W., Davis, C.J., 1986: A map-based decision support system for evaluating terrain and planning timber harvests. Transactions of the ASAE-American Society 29(5): 1199–1203.

Röser, D., Sikanen, L., Asikainen, A., Parikka, H., Väätäinen, K., 2011: Productivity and cost of mechanized energy wood harvesting in Northern Scotland. Biomass and Bioenergy 35(11): 4570–4580.

Roßmann, J., Hoppen, M., Bücken, A., 2013: Semantic world modelling and data management in a 4D forest simulation and information system. ISPRS – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-2/W2, 65–72.

Roßmann, J., Bücken, A., Hoppen, M., Priggemeyer, M., 2016. Integrating Virtual Reality, Motion Simulation and a 4D GIS. Research in Urbanism Series 4(1): 25–42.

Sitzia, T., Campagnaro, T., Grigolato, S., 2016: Ecological risk and accessibility analysis to assess the impact of roads under Habitats Directive. Journal of Environmental Planning and Management 59(12): 2251–2271.

Sosa, A., McDonnell, K., Devlin, G., 2015: Analysing performance characteristics of biomass haulage in ireland for bioenergy markets with GPS, GIS and fuel diagnostic tools. Energies 8(10): 12004–12019.

Sterenczak, K., Moskalik, T., 2014: Use of LIDAR-based digital terrain model and single tree segmentation data for optimal forest skid trail network. iForest – Biogeosciences and Forestry 8(5): 661–667.

Strandgard, M., Alam, M., Mitchell, R., 2014: Impact of slope on productivity of a self-levelling processor. Croatian Journal of Forest Engineering 35(2): 193–200.

Stückelberger, J.A., Heinimann, H.R., Burlet, E.C., 2006: Modeling spatial variability in the life-cycle costs of low-volume forest roads. European Journal of Forest Research 125(4): 377–390.

Stückelberger, J., Heinimann, H.R., Chung, W., 2007: Improved road network design models with the consideration of various link patterns and road design elements. Canadian Journal of Forest Research 37(11): 2281–2298.

Synek, M., Klimánek, M., 2014: Proposal of using GIS for multi-criteria evaluation of environmentally friendly use of skidding technologies in forestry. Journal of Forest Science 60(2): 51–60.

Tahvanainen, T., Anttila, P., 2011: Supply chain cost analysis of long-distance transportation of energy wood in Finland. Biomass and Bioenergy 35(8): 3360–3375.

Talebi, M., Majnounian, B., Abdi, E., Tehrani, F.B., 2015: Developing a GIS database for forest road management in Arasbaran forest, Iran. Forest Science and Technology 11(1): 27–35.

Tampekis, S., Sakellariou, S., Samara, F., Sfougaris, A., Jaeger, D., Christopoulou, O., 2015: Mapping the optimal forest road network based on the multicriteria evaluation technique: the case study of Mediterranean Island of Thassos in Greece. Environmental Monitoring and Assessment 187(11): 1–17.

Wemple, B.C., Jones, J.A., Grant, G.E., 1996: Channel Network Extension By Logging Roads in Two Basins, Western Cascades, Oregon. Journal of the American Water Resources Association 32(6): 1195–1207.

Wolf, C., Klein, D., Weber-Blaschke, G., Richter, K., 2016: Systematic review and meta-analysis of Life Cycle Assessments for wood energy services. Journal of Industrial Ecology 20(4): 743–763.

Worral, L., 1991: Spatial analysis and spatial policy using Geographic Information Systems. London: Belhaven press.

Zambelli, P., Lora, C., Spinelli, R., Tattoni, C., Vitti, A., Zatelli, P., Ciolli, M., 2012: A GIS decision support system for regional forest management to assess biomass availability for renewable energy production. Environmental Modelling and Software 38: 203–213.

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