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Review

Application of Geoinformatics in Forest Planning and Management

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Abstract: Rational forest planning and management is the key to a forest's systematic construction. It is beneficial to many aspects, such as the cultivation and preservation of a forest's ecological resources, sustainability, forest fire prevention, and others. In recent years, some effective strategies and tactics for the planning and management of forests' systematic construction have been established. Among them, the application of geoinformatics in forest planning and management (AGFPM) is one of the most effective and promising strategies. Therefore, it is necessary to conduct a comprehensive summary and analysis of the current situation. AGFPM has effectively applied in logging operations, forest road development, forest material transport, and forest fire prevention. An analysis of the research results in the past 20 years showed that decision support tools are the most used solutions to problems related to forest planning and management, especially the analytic hierarchy process (AHP). Light detection and ranging (LiDAR) is the second most popular method. With the development of geoinformatics, it will play an increasingly important role in forest planning and management in the future.

Keywords: forest planning and management; forest systematic construction; AGFPM; geoinformatics

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1. Introduction

Forests are critical ecosystems, providing habitats for most of the planet's species and livelihoods for humans. For example, forested watersheds provide most of the world's accessible freshwater resources—a critical source of the water we drink and use daily. Additionally, as carbon sinks, healthy forests play a crucial role in mitigating climate change. According to the State of the World's Forests 2022, issued by the Food and Agriculture Organization of the United Nations (FAO), sustainable forestry should be adopted under which humans can generate decent incomes and conserve forests.

Forest planning and management is very important in promoting a forest's systematic construction, which can effectively promote the forest's economic development. In recent years, international researchers have paid more attention to the long-term economic benefits of forests in their research, mostly from the perspective of sustainable development. This has included, for example, research on forest fire prevention, forest road construction, rational harvesting, and so on. Laschi et al. [1] summarized the research from various countries on improving forest fire roads, such as using the entropy weighting coefficient (EWC) method for planning forest roads in fire-prone environments, using the operational difficulty index in firefighting (ODIF) to analyze the factors affecting the efficiency of firefighting, and using ring roads that allow firefighting vehicles to move along the edge of a fire more quickly. Simonenkova et al. [2] proposed an optimization method considering forest road construction and transportation costs. They used a mathematical model based on the multi-commodity flow model to solve the road network layout for an extensive forest. This method can greatly reduce the optimal path's solution time while maintaining the results' accuracy. Caliskan [3] used a convolutional neural network (CNN) method to assess the road network taken from high-resolution orthophotos to monitor forest road infrastructure continuously. Luo et al. [4] designed a mixed-integer linear programming model to maximize the benefits of a forest's supply chain. This model combines a long planning period of forest management strategy with a short planning period of sawmill operation strategy to improve the net present value of forest management and wood processing operations. Over the past few decades, heuristic techniques such as genetic algorithms (GAs), simulated annealing (SA), and Tabu search (TS) have been applied to solve forest planning issues. With their increasing computational power, researchers have started to utilize more accurate solutions such as integer linear programming and mixed-integer linear programming.

Current challenges in forest planning and management include reducing the environmental impact of forest operations, improving tree growth and increasing economic benefits. Therefore, researchers have developed various decision-making tools to address the complexities of forest planning and management from economic, ecological, and social perspectives. For example, Zhou [5] thoroughly reviewed the current situation of forest city cluster development in China. He proposed specific countermeasures for forest city cluster construction from comprehensive planning concepts, evaluation index systems, and functional zoning based on natural conditions and development needs. Through this research, regional ecological environment problems were effectively solved. Michael et al. [6] investigated methods to use forest inventory data to help manage biodiversity and to monitor, assess, and plan for it. Cammerino [7] and Woo et al. [8] investigated the application of multi-criteria decision-making in forest management and discussed the application potential of the method. Also, other researchers have focused on evaluating advanced approaches that may address ecosystem services.

In addition to the above research, more researchers have been focusing on using geoinformatics to solve the problems in forest construction. The most frequently used include geographic information systems (GIS) and remote sensing (RS), which focus on solving the issues of timeliness and spatiality in forest survey and monitoring. For example, Caliska [9] utilized GIS with spatial multi-criteria decision-making (S-MCDM) to plan forest roads by incorporating five environmental indices into the design: avalanche, river, soil, geology, and slope. This method ultimately produced the most efficient and least costly road network. Using GIS, Sanchez-García [10] and Mishra et al. [11] conducted several spatial assessments to choose forest sites. Kulimushi et al. [12] used the revised universal soil loss equation (RUSLE) with GIS and RS data to evaluate soil erosion and environmental damage. Overall, geoinformatics covers a range from spatial analysis to statistical modeling and can be used to solve different problems, thus stimulating researchers' interests.

In general, although the research on geoinformatics has been very enthusiastic in recent years and achieved many results, there is a lack of relevant literature to summarize these research results. Because geoinformatics has a broad scope, this paper primarily focuses on GIS technology and the RS technology frequently used in conjunction with it. We reviewed the relevant literature on applying these technologies for forest construction. Then, we summarized the current research progress and achievements of researchers from the perspectives of forest planning and management. The primary purpose of this review is, firstly, to provide a systematic summary and supplementation of current research. Secondly, our goal is to emphasize the importance of applying GIS and RS technologies in forest construction. Thirdly, we wish to identify current research gaps and propose focused research directions to support researchers in their future manuscripts.

2. Methods

2.1. Literature Review

This paper reviewed the literature to discuss the application of geoinformatics in forest planning and management. A systematic review identifies and evaluates multiple studies on a topic using a clearly defined methodology. We searched for relevant studies to retrieve as many relevant scientific publications dealing with geoinformatics application in forest planning and management in 2004–2023 (20 years). However, one of the challenging issues in conducting a literature review is that it is impractical to read each paper. Therefore, we followed specific guidelines and defined the search scope clearly. This paper applied the search regulations shown in Table 1. This review consists of three main steps. In Step 1, we searched terms and their combinations to seek references of GIS in forest planning and management from the Science Index (SCI), Engineering Index (EI), and China National Knowledge Network Infrastructure (CNKI) databases. In Step 2, we examined their abstracts to identify papers that met the requirements of the topic. In Step 3, we studied the full texts selected in Step 2 to obtain their central research methodology and vision.

Table 1. Search regulations.

Search Criterion	Search Scope		
Database	SCI	EI	CNKI
Language	English	English	English, Chinese
Scientific field	All		
Academic journal	All		
Article type	Journal articles, Conference papers, Book chapters		
Search for words	Title, Abstract, Keywords, Subject		
Publication date	January 2004–March 2023		
Search term	"GIS", "Forest", "Road planning", "Operations", "Forest fires", "Transport of materials", "Timber harvesting", "Forest resources", "Decision support", "Management"		

To organize the application of GIS in forest planning and management, this review presents the following research questions:

(1) How much research has been conducted to develop decision support tools or computer systems to enable forest planning and management?
(2) How many papers have used GIS in combination with three-dimensional (3D) simulation, LiDAR, and hotspot detection in forest fire prevention, forest road planning, and forest management, and do other methods exist?
(3) How many papers have used heuristic algorithms for forest planning and management?
(4) In addition to the mainstream research directions, what other aspects of forest construction have been studied by experts and scholars using GIS?
(5) What research contributions were accomplished in this manuscript?
(6) What are the current research trends, gaps, and emerging research topics within GIS for forests?

2.2. Data Collection and Inclusion Criteria

Entering the words "GIS" and "forest" into the databases yielded 12,197 results from the SCI database, 6210 from the EI database, and 374 from the CNKI database. To narrow our search, we specified the following terms in the title, abstract, or keywords of the articles: "forest road network planning", "forest fire fighting", "forest management", "forest material transport", "timber harvesting", and "forest resource". To obtain accurate information, we superimposed keywords with two or three attributes for searching. For example, we searched "forest fire" and "GIS" simultaneously so that the results would be more accurate. Finally, this manuscript referenced more than 130 papers. Figure 1 illustrates the distribution of these papers by publication year. The horizontal coordinate represents the year from 2004 to 2023, and the vertical coordinate indicates the number of papers published. The analysis in this manuscript is more biased toward papers published after 2013, as there has been a noticeable increase in the number of studies over the past 20 years, particularly since 2013.

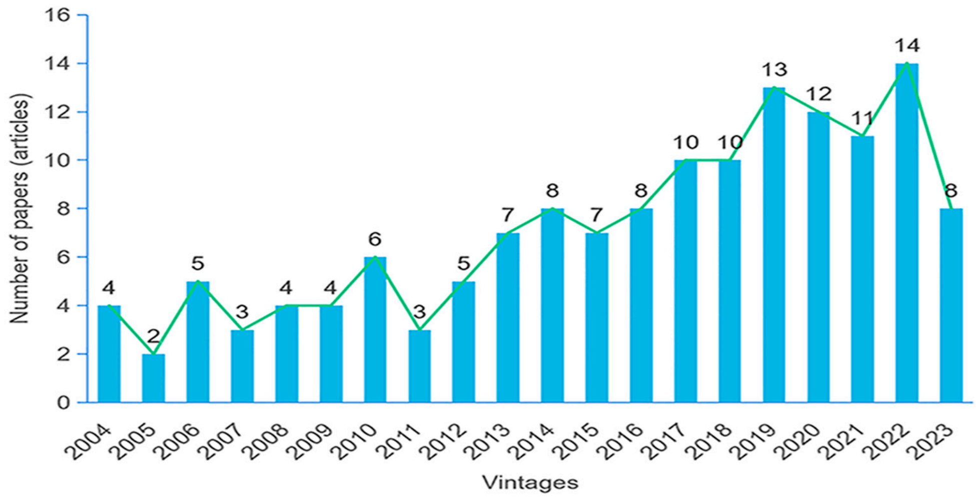


Figure 1. Number of papers published, 2004–2023.

A total of 195 keywords were listed when the literature was organized. Most of them were used only once, accounting for about 79% of all keywords. Figure 2 demonstrates the frequently occurring keywords. Ultimately, we categorized the keywords that showed up more than three times. As in Figure 3, the horizontal coordinate indicates the frequency of a keyword's usage, while the vertical coordinate shows the different keywords. With 34 occurrences, "GIS" was the most common keyword in these publications, followed by "forest roads", "forest fires", "AHP", and "forest harvesting", which were all mentioned 10^{-6} times apiece. Furthermore, we compiled some frequently used keywords under each main topic, as indicated in Table 2, because the keywords used in publications on the same subject may have changed. These keywords also indicate the current research focus.

Figure 2. Word cloud of keywords that often appear in literature searches.

The collected papers were published in 55 different scientific journals or conferences. The number of articles accounted for 28% of published articles. They mainly come from the journals "Croatian Journal of Forest Engineering", "Environmental Monitoring and Assessment", "Forests", and "Remote Sensing". These papers covered a wide range of 20 scientific disciplines. Figure 4 shows the percentage of the disciplinary categories of these journals represented. "Agricultural Science and Technology", making up 23% of the journals, was the most defined disciplinary category among them. The order of "Environmental Science", "Computer Science", "Operations Research and Management Science", and "Multidisciplinary Science" is 18%, 14%, and 10%, respectively. Regarding impact, 69.6% of the papers were cited at least once in the same period. One of the most cited papers, with 218 citations, focused on the spatial modeling of tropical forest fire sensitivity using a novel hybrid intelligence approach. These more than 130 papers generated 2132 citations over 20 years, an average of 106 citations per year and 4.3 citations per publication.

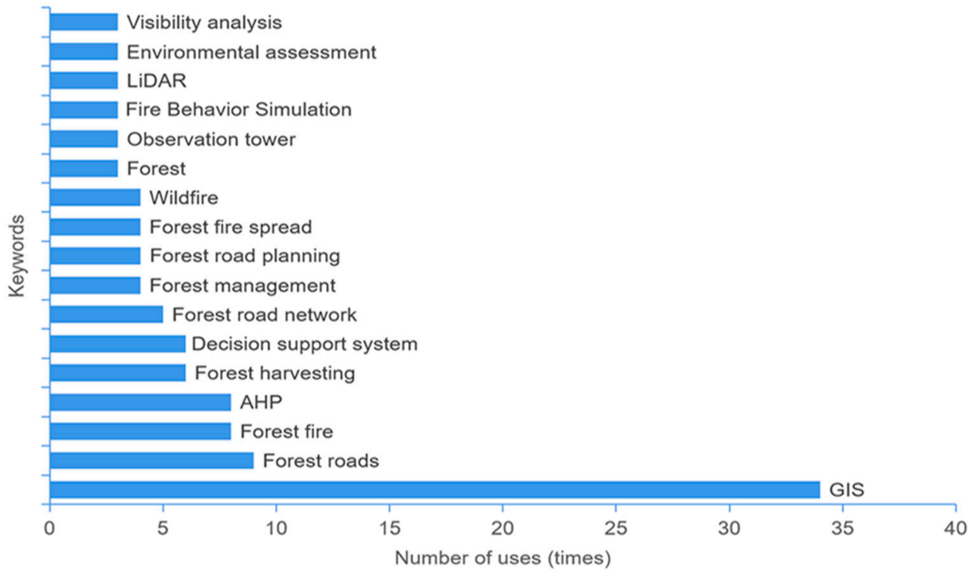


Figure 3. Main keyword count.

Table 2. Summary table of commonly used keywords for articles on various topics.

Topic of the Article	Keyword
Forest fire prevention	forest fire spread, forest fire, FARSITE, fire behavior, fire simulation, cellular automata model, Huygen's principle, three-dimensional visualization, forest firefighting, burn probability, fire risk map, prediction, fire management, fire risk index models, forest fire risk, hotspots, wildfire, fire monitoring, visibility and suitability analyses, fire lookout tower, alert system
Disaster recovery	environmental preservation, vegetation regeneration, ecosystem health modeling, earth observation, resilience, soil erosion, burn severity, dispersal drainage system, surface runoff, natural resources, sensitivity analysis
Forest planning	road network efficiency, slope analysis, GIS, remote sensing, AHP, optimum road density, road upgrading, forest road planning, Delphi method, road design, road network improvement, road network analysis, decision support system, SWOT, spatial distribution, forest network extraction, green infrastructure, algorithm, LiDAR
Forestry activities	timber harvesting, harvesting costs, harvest access planning, precision harvesting, logging residues, railway transportation, forest transportation, traffic loads
Forest management	single tree detection, digital terrain model, development pattern, investment and financing mechanism, management, species suitability map, biomass estimation, tree species identification, multi-scale remote sensing, sustainability

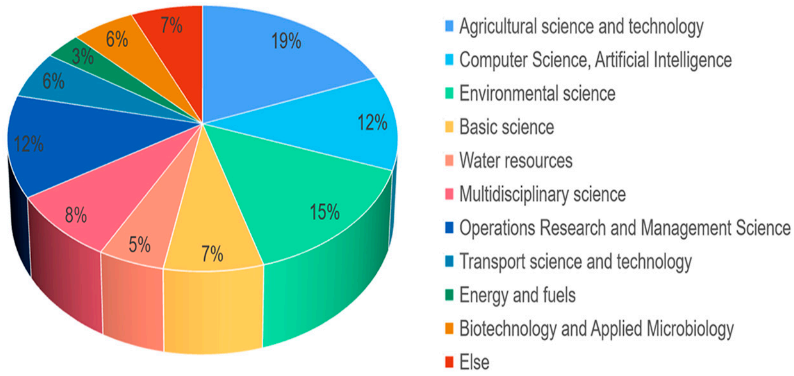


Figure 4. Proportion of subject categories of journals in the collection.

2.3. Thematic Distribution of Articles

To better assess the focus proposed by the authors of the papers, we categorized and merged the retrieved articles into two focus subjects. Figure 5 presents the themes of GIS applications in forest planning and management in different years. Between 2004 and 2023, most papers discussed forest planning, including its subthemes of forest fire planning, forest road planning, etc. This implied that designing effective forest infrastructure and forest road networks were given a lot of attention. Forest management concerned material transportation, harvesting operations, and resource distribution. In contrast, the percentage of papers with directions on disaster recovery and heuristic algorithms was not yet very high. More recently, research on forest supply chains could also be found in selected journals, with "operational systems analysis and modeling" being the second most frequent subtopic. Most academic research on forests that had currently been conducted focused more on the application level, with an emphasis on finding solutions to issues that arose to increase these areas' economic benefits further. Also, most of the published papers used GIS technology in combination with computer programs, algorithms, decision support systems, laser detection technology, etc., to solve problems. This illustrates that GIS serves more as an auxiliary technology to help some other technology perform their roles better.

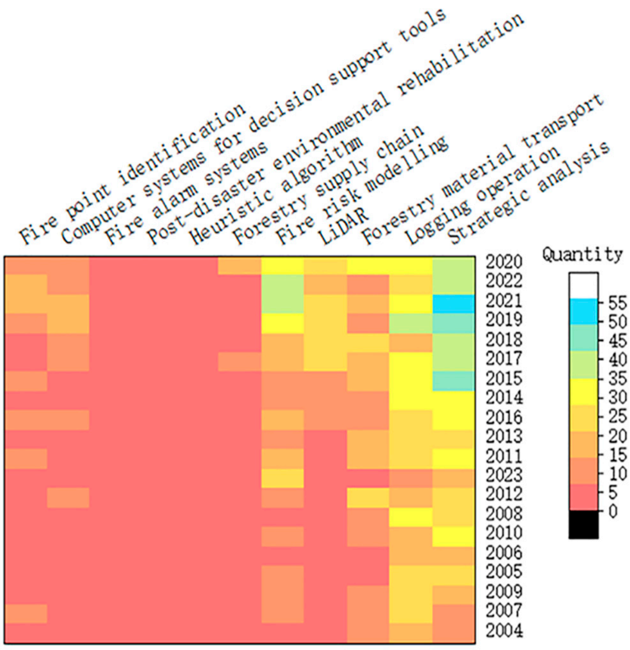


Figure 5. Chart of the number of research themes in papers by year.

3. Construction of Forests in Countries around the World

According to pertinent data, the construction of forest roads began in the 18th to 19th centuries. At that time, with the rise of the Industrial Revolution in Europe and the increasing demand for timber in the market, Austria and Germany began to build forest roads to facilitate timber transportation. Owing to the 1840s, many miners entered the forest and created a network of forest roads. In 1889, Japan began constructing forest roads to harvest natural forests. After the 20th century, the construction of forest roads in most countries entered a peak period of development, and led by Germany, Austria, and Finland, European countries joined the golden period of the timber industry. The introduction of four-wheel drive further promoted the construction of forest roads on a larger scale in Australia. In contrast, Korea's forest road construction started later, from the second half of when the 20th century began to build to the 1990s, to enter its stage of full promotion.

Due to the lack of scientific planning in the early phases of forest road construction, several nations expanded irresponsibly, which damaged the ecological environment. As the number of forest roads increased, the road density gradually reached each country's standard. The construction of new roads was curtailed into the maintenance of existing roads instead. The functions of forest roads have expanded from harvesting and transportation to forest fire prevention and forest recreation. They are also used as highways in some countries.

Therefore, various countries have formulated relevant regulations to managing forests. Tables 3–6 show the division and management of forest roads in some representative countries [13–17]. Most countries, such as Germany, France, Russia, Japan, Canada, New Zealand, and Australia, divided their forest roads into three grades. Forest roads in these countries have the same in function despite differences in specifications and definitions: Grade I forest road—a main road, which can be used by heavy trucks, is a two-lane paved road with a high transportation volume; Grade II forest road—subordinate road (or feeder road), connecting the main road and the skid road for large- and medium-sized trucks to pass, is the particular road for transporting timber, generally for two-lane or single-lane paved roads, and the transportation volume is medium; Grade III forest road—skid roads for harvesting collection and afforestation operation, including mostly single-lane dirt roads, narrow roads, only for small vehicles to pass, and the transportation volume is small.

In addition to Grade I–III forest roads, European countries such as Germany also have a small number of forest roads for public recreation. In Russia, temporary roads are used to transport timber in the winter by making use of frozen rivers or paving roads in swamps. And New Zealand also has temporary roads during afforestation. In contrast, the division of forest roads in Australia is more complicated and is divided into five grades according to specifications. Among them, grades I–III are all haul roads, grade IV is the harvesting road, and grade V is the particular road for forest firefighting, as shown in Table 4 [14,15]. The United States is more special in saving money and reducing the environmental impact; the forest roads are divided into five grades according to their function and level of maintenance, as shown in Table 5 [16,17].

The forest road was divided into four grades in China. Grade I or II forest roads are often designated as the main road and linking-up road, respectively, while other roads were selected as Grade III or IV according to specific conditions [13]. The grades, specifications, and functions of forest roads in China are shown in Table 7. However, due to the influence of natural, economic, social, and other issues, the construction of forest roads in China is seriously lagging. The average density of Chinese main forest roads is less than 1.5 m/hm^2, and in some remote areas, less than 1 m/hm^2, which is at a lower level worldwide. The low density of forest roads and their insufficient maintenance have seriously affected the development of forestry.

Table 3. The division of forest roads in the world.

Country	Total Length/km	Density/ (m/hm^2)	Grade I	Grade II	Grade III	Others	
			Main Road	**Subordinate Road**	**Skid Road**	**Temporary Road**	**Recreational Road**
Germany	1,209,000	108.90	Road width 3–4 m Slope < 10% Annual transport volumes 500–5000 m^3	Annual transport volumes < 500 m^3	Road width < 3–4 m Lower transport volumes	–	Open forest tourism areas
Austria	297,300	89.00	–	–	–	–	–
France	30,100	18.00	Slope 2%–6% Density of roads in plains 10 m/hm^2 Density of roads in mountainous 35 m/hm^2	Slope 2%–6%	Road width 4–5 m Density of plain skid roads 25 m/hm^2 Density of mountain skid roads 40–50 m/hm^2	–	–
Finland	130,000	10.50	Road width 6.5–8 m	Road width 3.6–5.5 m Speed 60 km/h	Road width 3.6–5.5 m Speed 40 km/h	–	–
Britain	26,600	32.20	Road width 7.3 m	–	–	–	–
Russia	1,618,000	1.46	Annual transport volumes > 500,000 m^3 Traffic volume 20–25 vehicles/day	Annual transport volume 150,000–500,000 m^3 Traffic volume 25 vehicles/day	–	Frozen rivers or paved roads in swamps	–
Canada	–	10.60	Road width 8–10 m Slope 10% Adverse slope 6% Speed < 80 km/h	Road width 8–10 m Slope 10% Adverse slope 6% Speed < 80 km/h	Road width 5–6 m Slope 12%–14% Adverse slope 8%–10% Speed < 80 km/h	–	Mostly located in nature reserves and forest parks
Korea	17,200	2.70	Road width 3–4 m Speed 14 km/h	Road width 3–4 m Speed 14 km/h	–	Access for large machinery, skid, and haul	–
Japan	137,000	5.40	Road width 4–5 m Speed 20–40 km/h	Road width 3 m Speed 15–30 km/h	Road width 2–3 m Speed 15–20 km/h	–	–
India	155,800	2.00	–	–	–	–	–
New Zealand	–	15–20	Plain and hill: Road width 9 m, speed 70 km/h Mountain: Road width 8 m, speed 50 km/h Traffic volume 80 vehicles/day	Road width 4.5 m Traffic volume 20–80 vehicles/day	Plain and hill: Road width 4.3 m, speed 40 km/h Mountain: Speed 30 km/h Traffic volume 80 vehicles/day	Road width 2.5 m Light four-wheel drive passing at low speeds	–

Data source: Study on Road Construction and Investment and Financing Management in Forestry Areas [13].

Table 4. The division of forest roads in Australia.

Country	Total Length/km	Density/ (m/hm^2)	Grade I	Grade II	Grade III	Grade IV	Grade V
Australia	–	15.00	Road width > 7 m Speed 50–80 km/h Traffic volume > 100 vehicles/day	Road width > 5.5 m Speed 30–70 km/h Traffic volume 30–100 vehicles/day	Road width > 4 m Speed 20–60 km/h Traffic volume 20–50 vehicles/day	Road width > 4 m Speed 40 km/h Traffic volume 20 vehicles/day	Road width > 3 m Limit the height and speed of vehicles Traffic volume 10 vehicles/day

Data source: Study on Road Construction and Investment and Financing Management in Forestry Areas [13].

Table 5. The division of forest roads in the United States.

Country	Total Length/km	Density/(m/hm^2)	Tool	Functional Classification	Maintenance Level	Length/km	Ratio (%)
America	612,000	31–50 (private forests) 7.8 (state-owned forests)	Passenger vehicle	Main road or subordinate road	3–5	138,495	23.0
			Heavy truck	Open feeder road	2	338,961	56.5
			Non-motorized vehicle	Closed feeder road	1	122,920	20.0

Data source: Study on Road Construction and Investment and Financing Management in Forestry Areas [13].

Table 6. Investment, financing, and management mechanisms of forest roads in the world.

Country	Investment Mechanism	Financing Mechanism	Management Mechanism
Germany	Management of the host state	Joint venture between forest owners and the government	Co-management by forest owners and government
Austria	Federal government, state governments, and construction bodies	Investor and government subsidies for forest road construction	Co-management by the forestry department, owners, and managers
France	Community forests are financed by the State; private forests have diverse investments such as district governments, public interest groups, etc.	Subsidy, funding, loan	Forestry departments under the districts introduce building charters for their respective areas
Finland	Direct inputs from forest owners and financial subsidies from the State	Co-financing by government and forest owners	Management, construction and renovation by the Ministry of Transport and Communications, Railway Administration, local forest centers, private forest organizations, national forest organizations, Central Forestry Development Center (Tapio), Metla Forestry Research Institute, Forest Stewardship Council (FSC), and environmental protection authorities (EPAs).
Britain	National forests: British Forestry Commission Private forests: Private forest owners	National forests: National Forestry Fund and Forestry Commission operating revenues and government grants Private forests: Private forest owners	Construction management, project quality management, and fund management
Russia	Federal Government finances main roads; Russian forest service, local forest services, and forest lessees invest in other roads	Co-financing by the federal government, local governments, and forest lessees	Harvesters
America	Special fund of the USDA, consumers, Public institutions, private sector and co-financing for individuals		Federal department of USDA Forest Service, Federal Highway Administration (FHWA), U.S. Bureau of Land Management Federal, local governments, etc.
Canada	Federal, local governments	National aid programs, local government financing plans, and IMF lending	Development of road management mechanisms and technical protocols by local governments
Japan	National forest roads: special accounts; Private forest roads: State finance, local finance, and forest road builders	National forest roads: National forest management and state financial subsidies; Private forest roads: financial aid, loans from Japan Finance Corporation and self-financing	National forest roads: bidding system; Private forest roads: forest road builders
Korea	National forest roads are built by the state; community forest roads are built by local self-governments; private forest roads are built by forest owners	The State fully finances national forest roads; private forest roads may apply for government subsidies in addition to local self-governments, forest owners, and managers.	National forest roads are managed by the forestry department; private forest roads are managed by local self-governments
India	Forestry department and the state governments	Financial revenue, funded projects	By the federal forestry department
Australia	Following the "user pays" principle, including road owners, the treasury, domestic and foreign businesses, the British royal family, the British federal government, etc.		Department of Sustainability and Environment (DSE), forestry department
New Zealand	Forest owner co-operative planning, funded by the government	New Zealand transport fund, local authorities, and loans to forest owners	Different regional and local committees, New Zealand Forest owners' association (FOA), forest owners, state forestry department

Data source: Study on Road Construction and Investment and Financing Management in Forestry Areas [13].

Table 7. The division of forest roads in China.

Parameter	Grade I	Grade II	Grade III	Grade IV
	Main Road		Subordinate Road (Feeder Road)	
Carriageway (m)	7.0	6.0	5.0	4.5
Annual transportation volume (ton)	≥100,000	≥60,000	≥40,000	<40,000
Speed (km/h)	30–60	25–40	20–30	15–20
Vehicle load	Forest—Grade 50 (Heavy vehicle)	Forest—Grade 25 (Medium-sized vehicle)	Forest—Grade 25 (Medium-sized vehicle)	Forest—Grade 25 (Medium-sized vehicle)
Turn-out lane	Two-lane	Two-lane/Single-lane (should not exceed 300 m where the roadbed width is less than 4.5 m)	<500 m	<500 m
Maximum longitudinal slope (%)	4–7	5–8	7–9 (10)	4–12 (14)
Road surface	Sub-high- or intermediate-type pavement	Intermediate-type pavement	Intermediate-type pavement or low-type pavement	Low-type pavement or none
Function	Permanent use, long-term maintenance, connecting external road networks, feeder roads, and timber lending, 5%–15% of the forest road network		Seasonal use, irregular maintenance, mainly by short-term timber vehicles, 15%–50% of the road network	Interior forest roads (excluding skidding roads), which account for the most significant proportion of the forest network, 55%–80%, have minor traffic flow, a service life of fewer than two years, a temporary road during production, the use of timely restoration of vegetation does not need to be maintained, and mainly timber short-term vehicle traffic

Data source: Technical Standards for Forestry Highway Engineering (LY5104-98) [13].

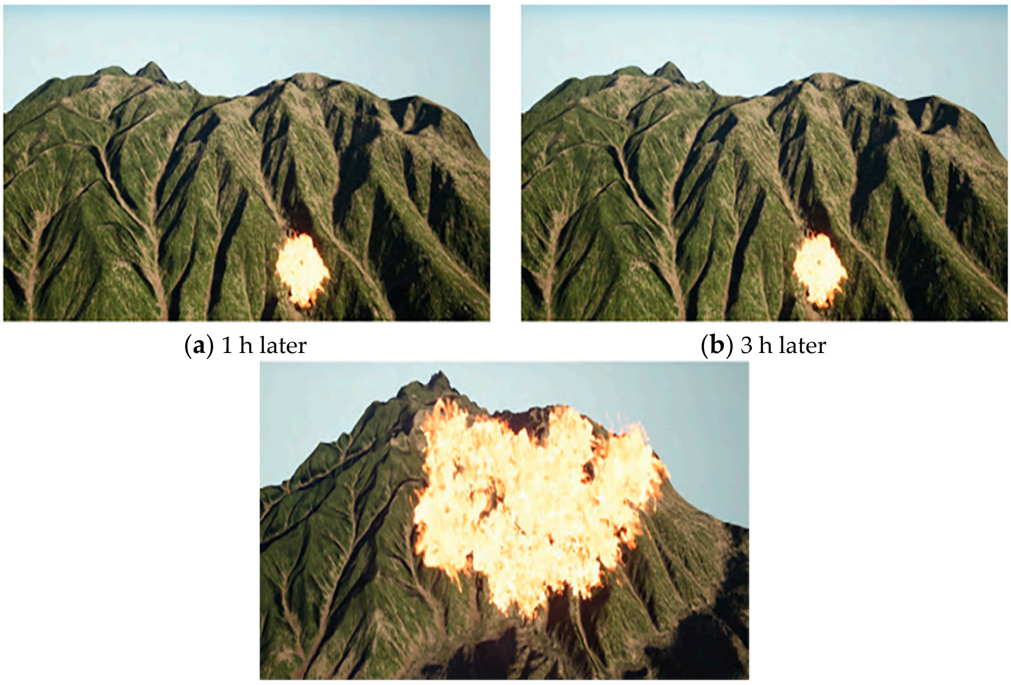
4. Application of Geoinformatics in Forest Planning

4.1. Application in Forest Fire Prevention

Fire is highly harmful to forests and the second factor leading to ecosystem degradation after agriculture and urban activities (air pollution, noise pollution, etc.). Preventing forest fires and rationally planning forest fire roads are the most important aspects of maintaining forest safety [18].

4.1.1. Simulating Fire Spreading Trends and Delineating Fire Risk Zones

It is challenging to forecast the spread of forest fires because of their multi-component character and the influence of topography and meteorology [19]. So, numerous researchers approach their research from the standpoint of maximizing the forest fire spread model. Currently, the Rothermel model of the United States, the McArthur model of Australia, the forest fire spread model of Canada, the Wang Zhengfei model of China, and the modified models based on these models are the most common application models for predicting the spread of forest fires. Cellular automata, Huygen's principle, and fractal theory have been used to solve the models. The forest fire is simulated from the three dimensions and displayed on the GIS platform. This method enables the visualization of the simulation and improves its prediction accuracy, as shown in Figure 6 [19–24]. Constraints are added in the solution process to determine the optimal firefighting position with less input and shorter time [25].



(**a**) 1 h later (**b**) 3 h later (**c**) 5 h later

Figure 6. GIS-based 3D forest fire spread simulation process.

In conclusion, the 3D simulation of forest fire spread considers the influence of combustible materials, weather, terrain, and other environmental factors. It can visually show the pattern of the fire's progress and serve as a guide for creating fire suppression tactics [26]. However, the accuracy level of this method still needs to be improved. In the future, researchers could deploy transducers in fire hazardous areas and utilize real-time data to correct the forest fire spread boundary. They could also incorporate fire suppression features for simulation.

In addition to the above methods, some researchers have chosen to use comprehensive evaluation (CE) to assess the risk of forest fires [27], including the gray fuzzy comprehensive evaluation, quadratic entropy weight method, fire risk index model, information diffusion theory, and AHP [28–31]. Statistics also have been used, including the vegetation type, roads, slope inclination, etc., to construct a fire risk model and divide fire risk zones. This can provide a reference basis for forest fire management [32–37].

4.1.2. Assisting in the Realization of Forest Fire Monitoring and Early Warning

As early as the 1990s, some researchers proposed producing fire risk maps for forest fire initiation and spread factors. Some contemporary researchers use RS technology to extract ecological indicators such as the surface water content, temperature, vegetation index, etc., for hotspot detection when collecting data, for example, satellite data such as GEOS/VAS, NOAA/AVHRR, MODIS/EOS, TM, and DMSP. Barbosa [38] interacted with satellite hotspots generated by RS and risk areas indicated in fire susceptibility maps to highlight the hotspots with the highest danger level. The outcomes are displayed in Figure 7. The advantage of this method is classification based on the susceptibility index. It can effectively detect medium and high susceptibility in low-susceptibility areas to avoid miscalculations and make forest fire detection more accurate. Salsabila et al. [39] utilized RS data to develop fire mitigation measures by identifying factors that caused fires through spatial hotspot analysis of fire locations. Jeefoo [40] proposed a mobile GIS platform that uses the Client/Server GIS framework to develop a standalone smartphone application. This application gathers fire conditions, sends them to administrators, and displays them on a network base station.

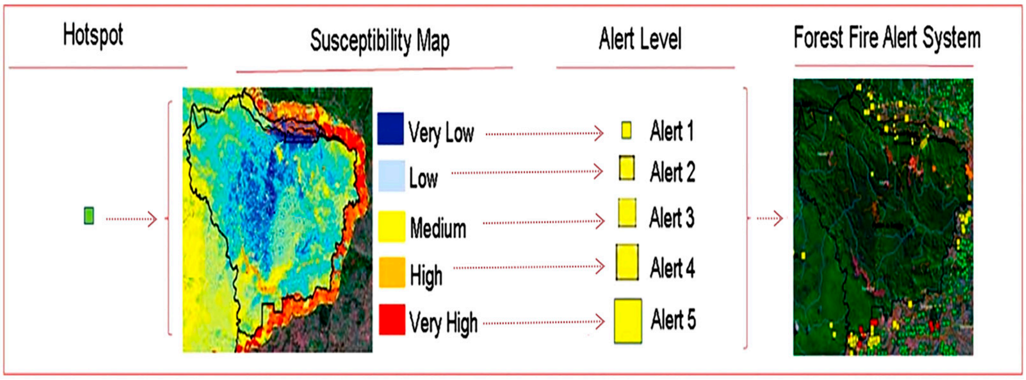


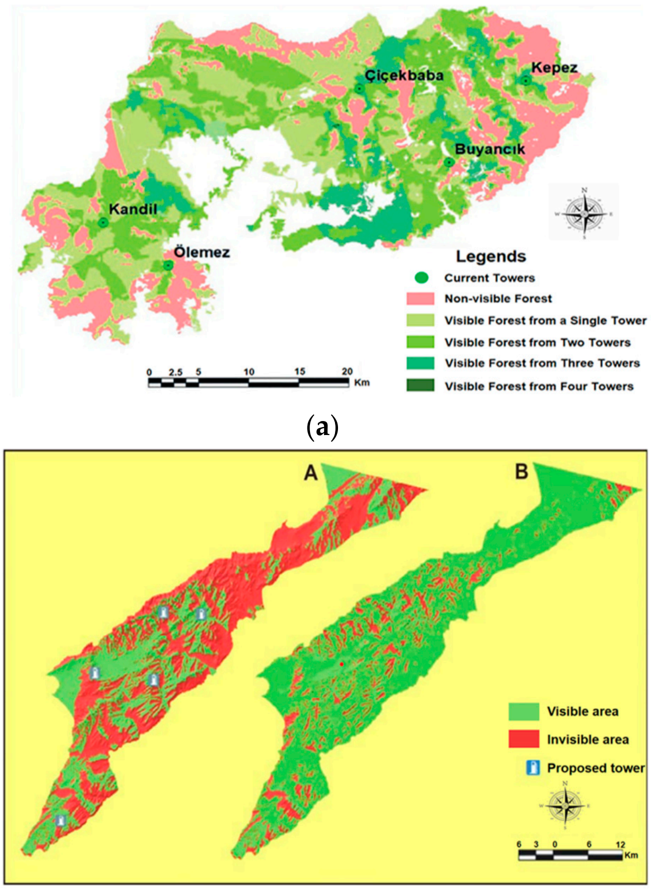
Figure 7. Schematic representation of the interaction between hotspots and sensitivity maps.

However, it is difficult to satisfy the needs of fire monitoring and localization in time and space when using RS data from a single satellite to perform fire monitoring. Multi-source RS data are used for forest resource inventory and assessment because environmental factors may limit single monitoring results, decreasing monitoring effectiveness [41]. For example, Tian [41] extracted the time series of spreading fire lines to acquire the location and time evolution of a fire by combining fire data from Sichuan Province, China, with multi-source RS satellites, namely Planet, Sentinel-2, MODIS, GF-1, GF-4, and Landsat-8. This approach can accurately calculate and analyze the area and how it changed at different times after the fire, accurately and quickly judging the direction of fire spread and solving the problem that single RS data cannot be continuously monitored. Due to the cloud passage and uncertainty of image capture, fire recognition accuracy of satellite measurement system is low; sometimes, fire recognition sensitivity lags. To solve this issue, Krishnamoorthy [42] utilized IoT technology to identify fire by sensing and measuring environmental parameters through multiple sensors. This method avoids false calls and faulty alarms caused by a single sensor.

For the early detection of forest fires, forest managers would systematically locate fire lookout towers and monitor fire-hazardous areas from these towers. Furthermore, visible analysis has been successfully applied in GIS technology over the past few decades. Each lookout tower's location can be ascertained based on GIS visibility and suitability analysis, and whether the towers can adequately cover a forest can be assessed. If not, they will overlap with the vegetation cover to create a new map to them locate additional lookout towers to increase the area of visible forest. Table 8 presents the statistical data that needed to be entered into the GIS system during the expansion of a Turkish forest lookout tower by Akay et al. Figure 8 displays the study's findings [43–45]. This approach is unique because it looked at both the suitability of lookout tower locations and the visibility capacity of the new towers. Forest managers can combat forest fires using the study's data [45].

Table 8. The required data to be entered in the attribute table of the lookout tower layer.

Lookout Tower	UTM Coordinates		Elevation (m)	Tower Height (m)	Smoke Visibility Height (m)	Horizontal View Angle (Degree)	Visibility Range (km)	Vertical View Angle (Degree)
	X	Y						
Kandil	634,852	4,085,818	860	10	100	360	15	+/−90
Ölemez	641,441	4,081,066	920	10	100	360	10	+/−90
Çiçekbaba	660,366	4,100,557	2020	10	100	360	20	+/−90
Buyancik	669,418	4,092,572	1100	10	100	360	20	+/−90
Kepez	676,921	4,101,706	1400	10	100	360	20	+/−90



(**a**)

(**b**)

Figure 8. (**a**) Woodland visible through one or more watchtowers; (**b**) Visibility analysis results of the proposed observation towers (A) and superimposed map of proposed and existing towers visibility condition (B).

4.1.3. Recovery of the Post-Disaster Environment

Forest fires can severely affect the coverage of surface vegetation. Therefore, it is necessary to gauge the amount of fire impacts by understanding post-disaster environmental recovery. The truth is that the recovery of a forest environment after a disaster varies from region to region, from years to decades. Therefore, assessing fires requires data in large spaces, which are difficult to collect from field surveys. Geoinformatics offers an alternative that provides the extent of burns from fires and monitors the degree of burns.

Image classification, the spectral vegetation index, and spectral mixture analysis are some of the most popular image analysis techniques that have been used to characterize vegetation recovery. The normalized vegetation index (NDVI) is the most popular technology. An area's vegetation recovery can be assessed by comparing the changes in NDVI values in the years before and after the disaster in GIS. This method can be utilized for post-disaster renewable evaluation [46,47]. However, RS-based vegetation indices are limited in their monitoring capabilities and cannot distinguish between the regeneration dynamics of different vegetation types. So, they cannot explain the nature of fire damage well. To address this shortcoming, some researchers have spatially simulated forest dynamics (seed growth, competition, and succession) using the forest landscape model (FLM). This approach can compensate for processes not captured by fire succession models and RS to fill data gaps. It has been effectively applied to post-disaster forest reconstruction [48]. However, it is necessary to increase research in this field in the future.

In addition, forest fires can affect soil structure, porosity, and hydraulic conductivity. Radar remote sensing also plays a role in post-fire environmental restoration [49]. Cao et al. [50] used high-definition LiDAR terrain data and a GIS-based soil erosion model to obtain the landscape location, slope, and burn severity. The results showed the effects of wildfires on road runoff, soil erosion, and sediment transport to predict on-site soil loss ratio. Dobre [51] demonstrated that terrain slopes significantly affect the amount of mineral soil exposed after a wildfire. His findings allowed forest managers to identify areas of high and sensitive post-fire erosion by relying on topographic maps of forested areas using only GIS. In the future, researchers can continue to improve prediction accuracy and focus on determining the method's applicability to larger-scale fires.

As shown in Figure 9, the application of geoinformatics in forest fire prevention has been studied from different perspectives. It includes the simulation of fire spread, monitoring, and risk zone delineation before forest fires. It can also be used in the positioning of fires, alarm system design, and watchtower optimization when forest fires occur and in the restoration of the forest environment after the fire occurs, etc. However, the following improvements should be made to make its application even better: First, the objectives and dimensions of RS research should be expanded. Presently, research on forestry RS is mainly concentrated in a small area, which does not fully exhibit the qualities of sensing data, including comprehensive coverage, quick speed, and real time. In the future, multi-dimensional essential information should be created to investigate the law of forestry development in depth [52]. Secondly, the capacity of the geographic information platform construction should be upgraded. Although some geographic information platforms have existed in recent years, such as forest resource surveys, wetland monitoring, and forest disaster monitoring, their large-scale production and application has been limited, due to the problems of network structure and resource dispersion. Thus, the integration of an already existing professional system should be performed to improve the platform's level of intelligence and networking. Thirdly, it can support medium-long-term planning of digital forestry. Integrating GIS, RS, and other geographic information technology with forest management is imperative for forest managers, providing the required data more quickly and efficiently to realize the monitoring of forest resources and the estimation of forest ecology.

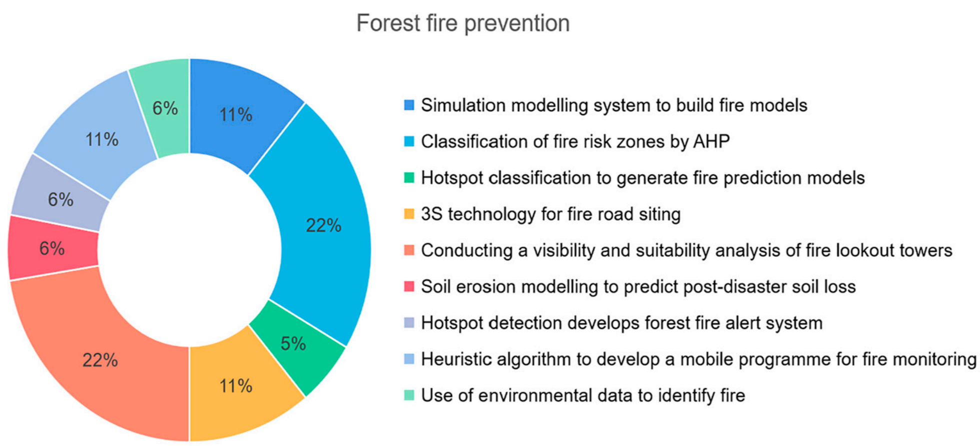


Figure 9. Forest fire theme research methodology.

4.2. Application in Forest Road Construction

4.2.1. Using LiDAR for Forest Road Engineering

The road conditions should be observed when constructing forest roads. Currently, it is costly to collect information on forest characteristics through field surveys. LiDAR in RS is a cost-effective means of obtaining data with high spatial resolution and high-precision positioning. This method provides information on forest structure and biomass composition with up to 90% accuracy [53]. Therefore, GIS and LiDAR combine technologies used in most forest engineering construction.

Unmanned Aerial Vehicles (UAV) equipped with LiDAR were employed to acquire accurate maps of surface watercourses in forests [54]. LiDAR continued to track watercourse changes after construction to support later road improvements. Even though the methodology's accuracy still needs to be verified, its results are encouraging and promising. The high accuracy requirements of forest roads require the development of automated and reliable programs to identify forest roads. According to recent research, Buján et al. [55] employed LiDAR to detect forest roads in conjunction with a new hierarchical hybrid classification tool (HyClass). It can update existing maps as long as the density of points is greater than 1 point/m^2, which prevents errors caused by steep terrain or tree cover. This method maximizes the problem of road identification discontinuities and class similarities, but fewer areas are currently applying it. Therefore, more areas must be tested to verify its accuracy.

LiDAR, digital maps, and heuristic algorithms are widely used when optimizing forest roads. For example, an optimization program created based on GIS and ALS is feasible to confirm the viability of roads and locate inaccessible places before actual construction to assess alternate roads [56]. Kweon et al. [57] used mobile laser scanning (MLS) to map 3D forest roads to overcome the limitations of ALS and TLS. The MLS's accuracy and mapping efficiency was evaluated by comparing the data obtained from GNSS and total station techniques. In conclusion, passive sensors widely used in cities are inefficiently used in forests with dense vegetation. On the contrary, LiDAR, which can provide data for areas below the canopy, is considered the best choice for detecting forest roads [55].

4.2.2. Use of Decision Assessment Tools for Forest Road Projects

Building forest road networks enables the sustainable management of forest resources, but the irreversible impacts on the forest environment should be eliminated. Therefore, forest managers must design forest road networks more efficiently and environmentally. Nowadays, GIS has become one of the most widely used tools in spatial planning and management, and it is frequently used in conjunction with decision support systems to plan forest road networks [58].

The utilized multi-criteria decision-making (MCDM) for forest road planning has been widely used. The map layers such as slope, aspect, hydrology, landslide susceptibility, etc., have been created and the AHP used to determine the weights. As illustrated in Figure 10, the weighted graph was stacked in GIS to create maps of forest potential for road construction (FPRC) [59]. In this process, the different scenarios of the road network could be obtained by evaluating its technical, environmental, and social aspects. Then, the best-designed road network was compared, as shown in Figure 11 [60].

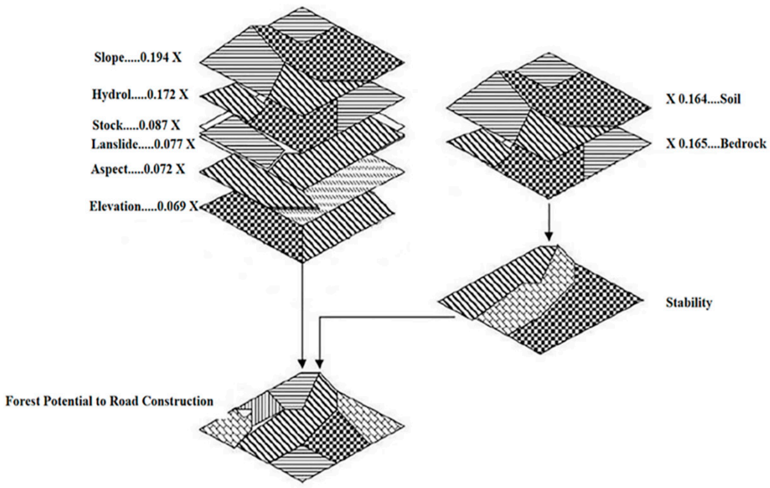


Figure 10. GIS layers used to determine forest potential for road construction.

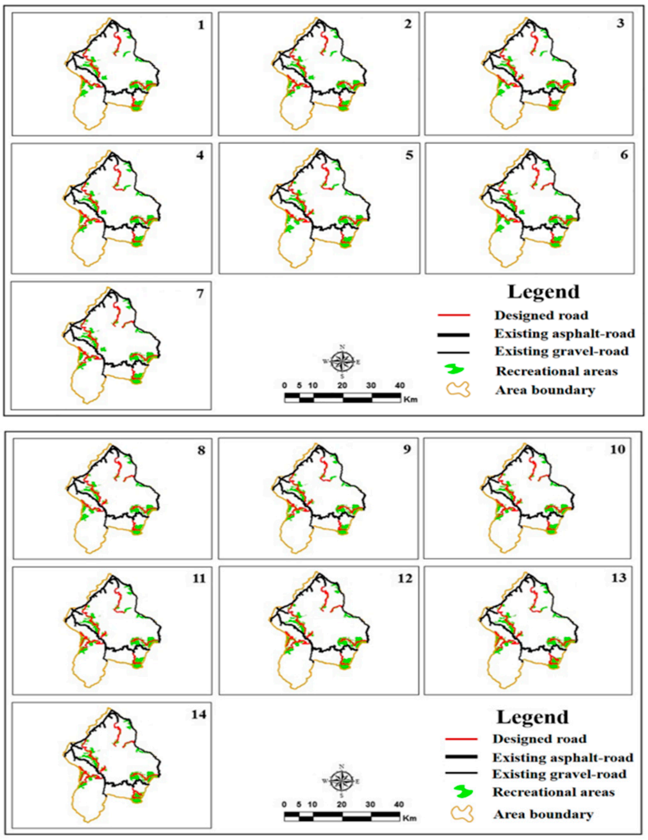


Figure 11. Road network scenarios designed for planning and management.

AHP is one of the most widely used methods in MCDM. It is designed to offer a consistent and quantifiable method. By calculating incompatible coefficients using ideas from various experts and combining quantitative and qualitative criteria, AHP can assist decision-makers in prioritizing goals and developing a set of criteria [61–63]. The technique was first incorporated into GIS applications by Rao et al. in 1991. Application of AHP has become easier in GIS environments and better to help calculate and analyze data, providing the possibility of combining different types of information [58]. For instance, Abdi et al. [64] presented a method for quantitatively selecting forest road networks, utilizing AHP to analyze the weights of the elements associated with the cost of building forest roads and create a final suitability map. Tampekis et al. [65] used GIS to create thematic maps and charts to evaluate the effects of road network construction on the environment. Hayati et al. [66] presented an integrated approach that combines SMCE (an MCDM method using spatial data) with Delphi and AHP in a GIS environment. The three-stage methodology allows experts to make judgments about road network planning and ultimately choose the most appropriate option. With the deepening of research, AHP is sometimes subjective in its application. So, some researchers, such as Bugday et al. and Nefeslioglu et al., have adopted the M-AHP method, which does not require expert opinion or other typical methods of MCDM, such as fuzzy inference system (FIS) and logistic regression (LR) for its calculation [67,68]. Some research has also incorporated SWOT analysis to obtain a more rational result after comparing the advantages, disadvantages, opportunities, and threats of building a forest road by weighing the SWOT items [69].

In summary, GIS is an effective tool for managing, analyzing, and gathering data while planning forest roads. To fully utilize its benefits, it is necessary to integrate it with other technologies or decision processes. This technique is now the foundation of forest planning. However, the model's outcomes depend on the data's correctness. Future researchers could include environmental aspects into the model, allowing managers to combine construction costs and environmental factors in route assessment and selection.

4.2.3. Using Heuristic Algorithms for Forest Road Engineering

Harvesting is one of the most important forest operations, including locating harvesting machinery, selecting roads for harvesting operations, and dividing up harvesting techniques logically according to different stands. This module accounts for about 55% of the total cost of production [70]. Thus, one of the main challenges for forest managers is to find a solution that guarantees operational efficiency while minimizing costs. To do this, a network design as a mixed-integer programming (MIP) problem should be described. MIP problems are appealing due to their optimal results, but they have the drawback of having a limited problem-solving space. In 1980, when using the branch and bound to solve MIP problems, researchers found it applied only to small-scale issues. Later, as research developed, Jone et al. (1986) and Kirby et al. (1986) proposed the integrated resource planning model (IRPM), which was tested and shown to be limited to solving medium-sized planning problems as well [71]. Despite further advancements, its ability to solve practical problems remains disappointing. As a result, heuristic techniques have been used, such as genetic algorithms, Tabu search, simulating annealing arithmetic, and others, to address these issues.

Numerous techniques for creating forest road networks utilizing heuristic algorithms and GIS have been presented. Bont et al. [72] developed an MIPL model to identify the best road network while lowering the costs of road construction and road transportation. They introduced a digital elevation model on GIS, which enabled road construction engineers to locate spatially optimal roads. Najaf et al. [71] proposed an optimized MIP model to design a forest road network with logging roads and skidding roads. The GIS was used to systematically discretize the landscape to design a finite number of construction decisions or potential road segments. This study addressed constraints earlier field research has encountered by employing improved formulations and general solvers. GIS-based methods can also identify forest roads with high traffic loads to upgrade roads and support road planning [73–75].

In summary, the effective utilization of GIS in conjunction with LiDAR, a decision-making system, and heuristic algorithms can generate precise data on forests, assess the best option for building a forest road, and maximize the benefits with limited funding. Figure 12 illustrates the proportion of the literature on GIS-based methods in forest road construction. With a total literature share of almost 85%, LiDAR, MCDM, and heuristic algorithms are more frequently utilized in this direction. These methods are more precise, practical, and comprehensive. It is also a potential development and more beneficial than conventional approaches.

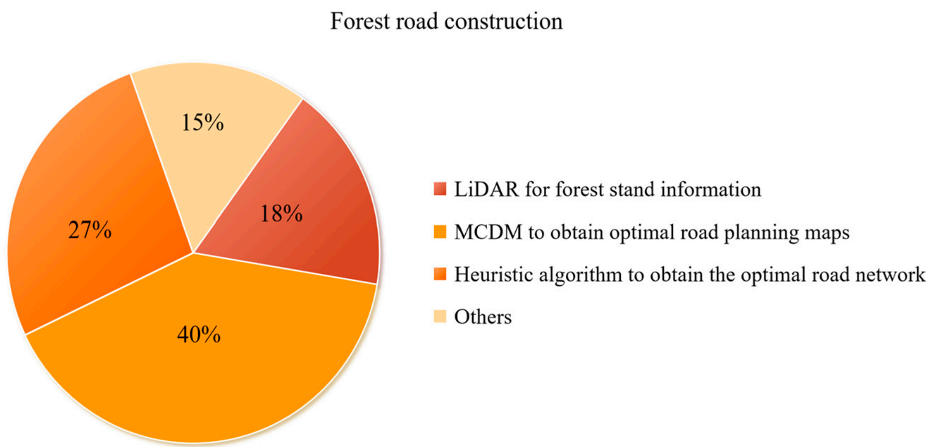


Figure 12. Methodology for forest road construction.

5. Application of Geoinformatics in Forest Management

5.1. Application in the Transport of Forest Materials

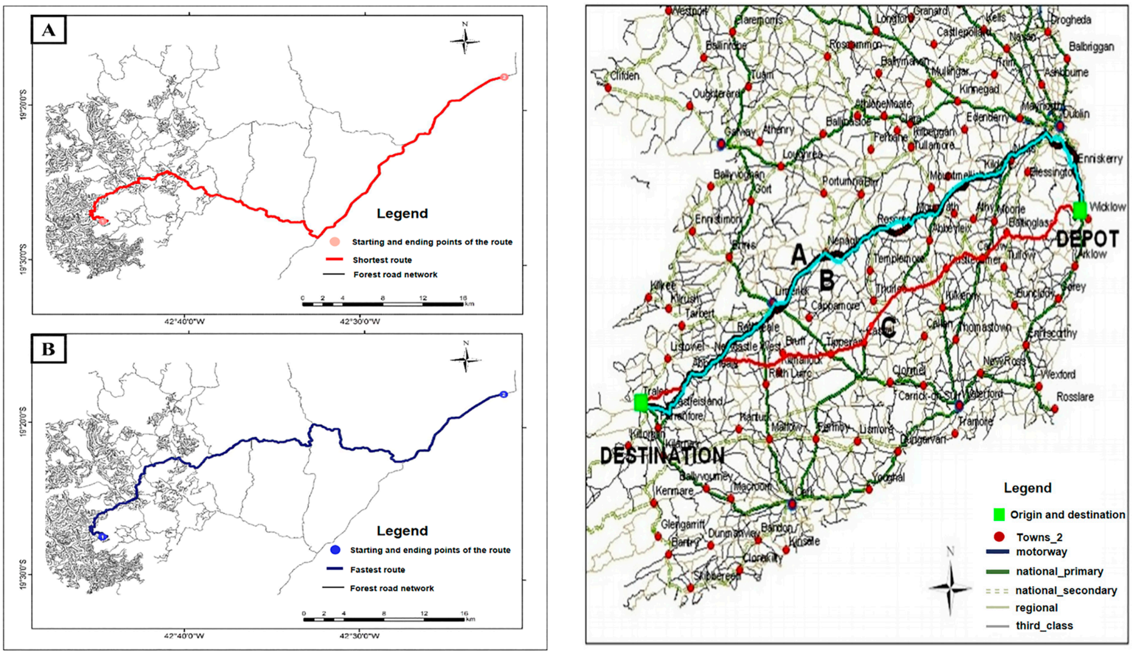
Forest transportation is an important part of the forest product production process, which connects the production in the logging stage and the operation in the storage stage [76]. In recent years, researchers have widely used modern computer technology and GIS in forest transportation, which is more efficient and high-precision in obtaining forest material information.

Researchers planned the transportation routes of trucks from the harvesting site to the wood processing plant with GIS spatial data. They combined the shortest path model and several constraints to achieve the selection and optimization of transportation roads. The final results are displayed on GIS maps, as shown in Figure 13 [77,78]. A straight-line road segment may not be the fastest due to traffic and vehicle speed constraints [79], so Dowdle et al. [80] created a model to effectively predict the changes in forest transportation patterns. This model can monitor and update road conditions in real time and monitor the various arrangements for forest product transportation. In this way, it can respond to emergencies in a timely manner. It can also reduce waste to ensure the best transportation of forest products.

Generally, several variables can affect the accuracy of transportation cost assessments, such as driving speed and transport distance. A GIS-based model involves geographic datasets and contains various attribute information of the forest. Datasets are the fundamental difference between GIS-based models and non-GIS-based models, such as biogeographical distribution, road networks, and environmental information, which can be layered and integrated. Multi-layered datasets allow for the spatial manipulation of this integrated information, such as extracting regional available information [81]. The benefit of the GIS is that it integrates site-specific datasets to produce a more accurate assessment. It is extensively applied for supply chain cost analysis or least cost site selection [82]. Sosa et al. and Keramati et al. [83,84] selected the lowest cost route by estimating biomass allocation and then serving timber mills. Contreras et al. [85] planned the forest roads from the stump to each candidate landing and selected the best landing location to minimize forest road costs with GIS data. Mohtashami et al. [86] used GIS with terrestrial laser scanning datasets to avoid soil damage and pave better roads. This method increased the profitability of timber transportation in Sweden.

Furthermore, with the development of timber transportation plans, a substantial amount of non-spatial and spatial data, data processing tools, and decision models have been utilized to address challenging issues in the forest [87]. Some researchers planned the transportation method of forest products according to ground slope, soil type, and equipment with the AHP method [88]. Some researchers integrated linear programming with GIS and used general algorithm languages such as C++ or Visual Basic to provide better program processing speed and flexibility. The results were able to realize various functions, including obtaining the vehicle's positional information, tracing the timber source, and finding the least cost path [87,89,90]. Figure 14 illustrates the thematic methodology for material transport.

In conclusion, using GIS for forest transportation planning is more effective. It can improve the efficiency of traditional transportation, save the time and cost of surveying the logging area, and reduce the danger of surveying. There is much more potential for the development of GIS-based decision models. For instance, researchers can create transportation time sub-models to compute the time required for each section of the road, thus using road classification data as an independent parameter.



(**a**) (**b**)

Figure 13. (**a**) Transport routes identified by the GIS network analysis function: shorter distance transport routes (**A**) and fastest routes (**B**); (**b**) GIS maps showing A (GPS), B (road class), and C (shortest route).

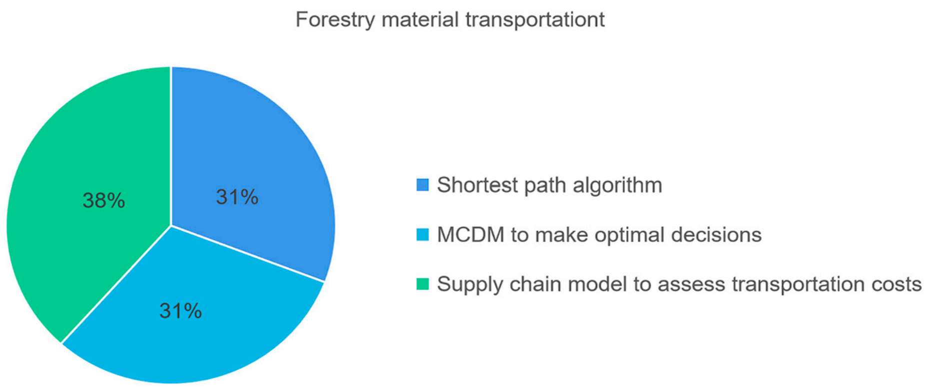


Figure 14. Thematic methodology for forest material transport.

5.2. Application in Harvesting Operations

Normally, traditional forest harvesting focuses on economic benefits, but ignores environmental protection. Therefore, integrating harvesting methods with ecological benefits has become an essential consideration in harvesting planning [91,92]. Since harvesting decisions are primarily spatial, GIS is an indispensable tool which can provide spatial and non-spatial data. Currently, GIS has solved problems like the harvesting order, harvesting size, and division of timber flow [93].

Qiu et al. [91] applied GIS MapInfo, DBMS, and mathematical planning methods to create a harvesting decision support system with MapBasic language, which improved the accuracy of decision-making. In the forest management inventory, the survey content is only up to the subcompartment, not including individual trees. So, to make the survey data more detailed, Dang et al. [92] developed an Internet client to build an enterprise-oriented GIS system combined with the SuperMap 6R platform and J2EE and RIA technology. The information and spatial structure of all individual trees in the subcompartment were reconstructed and visualized. Most researchers start from the secondary development of the decision-making system, combining GIS and digital analysis to create an auxiliary decision support system for forest harvesting information collection, storage, querying, updating, etc. [93,94].

Researchers from various countries have used different approaches for different situations. For instance, Kühmaier et al. [95] created an SDSS model for harvesting decisions in the steep terrain of southern Austria. These models use GIS to analyze forest data, fully combining ecological, economic, and social impacts. However, researchers should note that this solution may be the best compromise based on subjective judgments. To minimize errors, Phelps et al. [96] introduced a harvest operability index (HOI) for the Jocassee Gorges Natural Resource Area, in Northwestern South Carolina, USA. They developed a GIS model applicable to mechanized harvesting with wheeled equipment in hill-shaped terrain and obtained data layers for the HOI including GIS data from a Jocassee staff and publicly available US Census, hydrology, elevation, and soil data, as shown in Tables 9 and 10. This method can analyze the operability of timber harvesting and determine the harvesting operations effectively, and it can reduce costs to facilitate the rational allocation of time, equipment, and people, as shown in Figure 15. However, HOI did not consider the distance from the harvesting area to the mill. Future research objects should include cost analysis and precise trucks' maneuverability. Researchers can also use the model combined with other decision-making systems to improve the quality of timber harvesting, such as prioritizing the most feasible locations for ecological restoration or fuel dilution. Some researchers continue to use AHP and LiDAR to collect spatial data and observe timber harvesting [97,98].

Table 9. Data layers acquired for the HOI model in Jocassee.

Data Layer	Type	Source
Roads (Pickens Co., SC)	ShapeFile	US Census TIGER/Line®
Access roads	ShapeFile	Jocassee Gorges Staff
Forest stands	ShapeFile	Jocassee Gorges Staff
Stream/Lake waterbodies	ShapeFile	USGS NHD
Soil map units	ShapeFile	NRCS SSURGO
Digital elevation model (Pickens, Oconee Co., SC)	Raster	SCDNR

Table 10. HOI criteria and their 0–4 class values.

										SMZ Buffers			
Slope (Percentage)		**Skidding Distance (Meters)**		**Cost Distance to Major Highways (Meters)**		**Stand Age (Years)**		**Soil Suitability for Harvesting Equipment**		**Distance from Trout Stream/Lake Primary SMZ (Meters)**		**Distance from Non-Trout Stream/Lake Primary SMZ (Meters)**	
	CV		CV		CV		CV		CV		CV		CV
0%–10%	4	0–200	4	0–10,000	4	>61	4	Well suited	4	>24.384	4	>12.192	4
11%–20%	3	201–400	3	10,001–20,000	3	41–60	3						3
21%–30%	2	401–600	2	20,001–30,000	2	21–40	2	Moderately suited	2				2
31%–40%	1	601–800	1	30,001–40,000	1	10–20	1						1
>41%	0	>801	0	>40,001	0	Open area, 9	0	Poorly suited	0	0–24.384	0	0–12.192	0

CV: Class value.

Furthermore, Jaziri [99] examined the subject from a different perspective. He contended that most spatial planning problems discovered by computer techniques and heuristics only deal with simplified rather than real-world issues. Therefore, he proposed a multi-criteria optimization approach based on optimization techniques and GIS. This method uses the potential of GIS for spatial data processing to choose the less costly harvesting direction based on each tree's neighborhood and the current road network. He reduced the damage by optimizing the direction of harvesting. Figures 16 and 17 illustrate this strategy. However, the method also has some limitations. In the current study, researchers only considered four main potential directions of harvesting, which can be refined to be more precise (e.g., eight directions) in the future. Secondly, besides financial objectives, researchers should include ecological parameters in management to maintain biodiversity, forest profitability, etc.

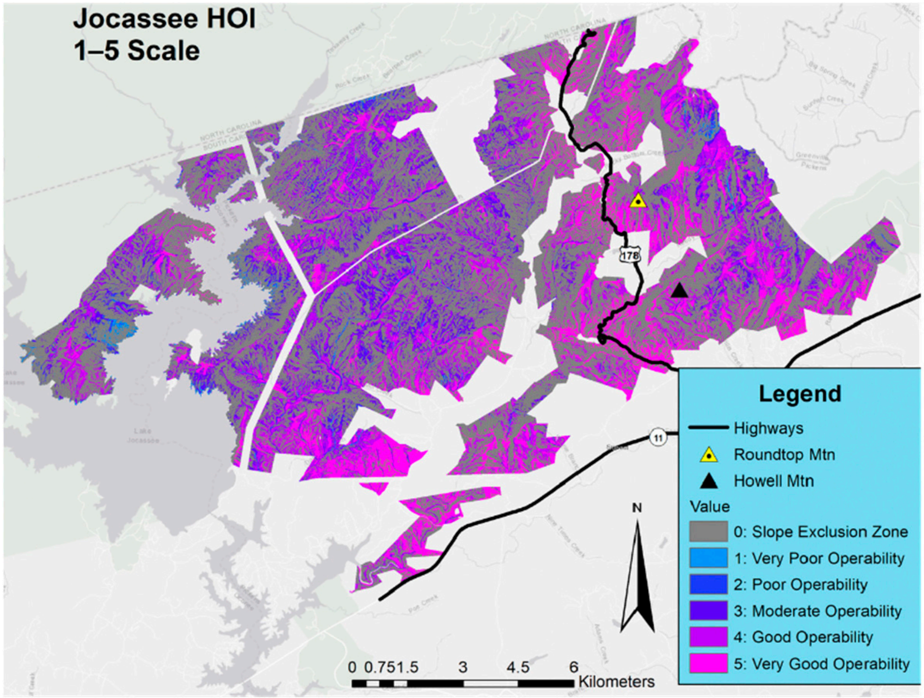


Figure 15. Operability of HOI model outputs as levels 1–5.

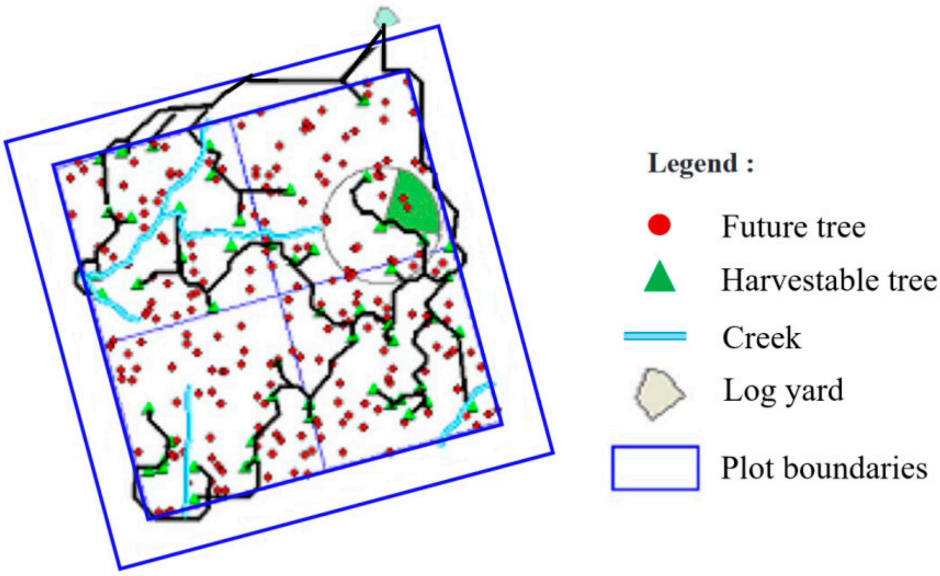


Figure 16. Selecting the optimal direction from four harvesting directions.

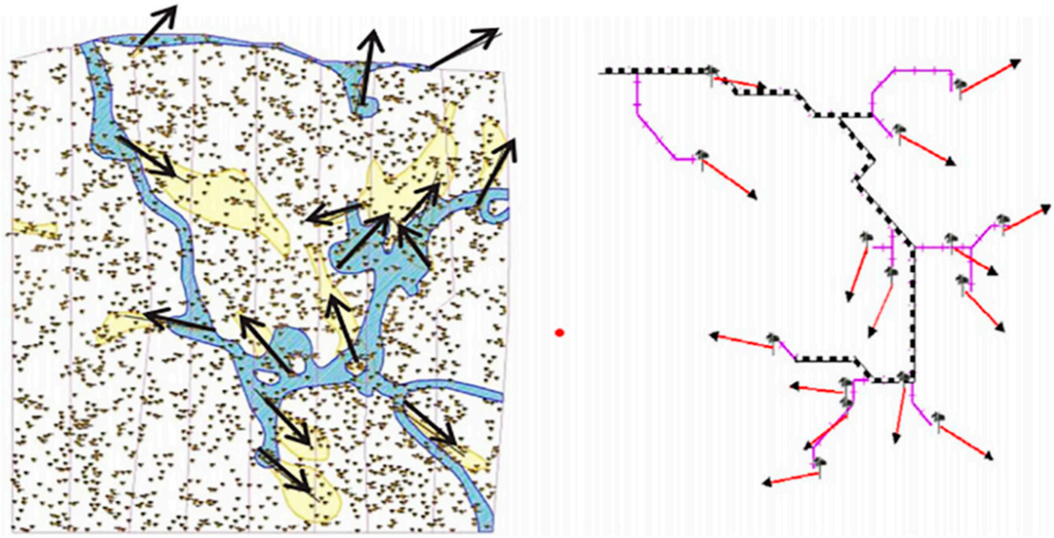


Figure 17. Manually selected harvesting direction (**left**) and harvesting direction proposed by the method (**right**). The direction of the arrows indicates the cutting direction.

5.3. Application in Forest Resource Management

The spatial distribution of forest resources can exhibit clustered, uniform, or random patterns depending on the species' traits and locality. Forest managers can plan forest activities and reduce environmental disturbance efficiently though understanding the spatial distribution of forest resources. Geoinformatics-based research on forest resources enables management both spatially and temporally. It also can allow forest resource planning and operational regulations to achieve sustainable utilization. For example, Berendt [100] used species suitability maps and soil sensitivity data to identify the forest development types and harvesting areas based on GIS. Miron [101] assessed the spatial distribution pattern of six species and analyzed the relationship between terrain and population density.

Species surveys play a crucial role in macro-monitoring forest ecosystems and biodiversity [102]. With the support of RS, researchers can not only obtain information on the quantity, spatial distribution, and dynamic changes in forest resources but also realize the quantitative retrieval of forest canopy closure and biological resources by combining various models. Therefore, RS as a practical monitoring tool has been widely used in forest resource inventory, forest planning, and management [103]. Especially in recent years, low-altitude UAV technology has been developing rapidly. It can obtain high-spatial resolution and high-spectral resolution images of vegetation by carrying different sensors and providing the possibility of forest-type identification. The parameters of the standard sensors held by UAVs are summarized in Table 11. Researchers can use multi-source RS data to recognize wood species individually or complement each other. For example, Shi et al. [104] combined multispectral and LiDAR for temperate tree species classification, and the accuracy of their result was significantly improved. Mao et al. [105] used QuickBird multispectral images and SAR data for forest-type classification and found that the advantages of multi-scale combination are obvious. Based on RGB images and hyperspectral images taken by UAVs at 83–94 m flight altitude, Nevalainen et al. [106] analyzed the performance which combining multi-source data in detecting single trees and classifying tree species in boreal forests. Both results reached more than 90% accuracy.

After gaining a thorough understanding of forest resource distribution, several researchers began to research their distribution of resources [107]. For instance, Voivontas et al. [108] created an environmental decision support system to estimate the power generation potential of agricultural residues by GIS. Freppaz et al. [109] proposed a decision support system for forest biomass energy development. In their study, GIS was combined with mathematical programming methods to assess the possibility of producing thermal and electric energy. Frombo et al. [110] innovatively considered the different energy conversion technologies (pyrolysis, gasification, or combustion) in optimization equations and made decisions by visualizing a forest through a GIS-based graphical interface. Establishing a decision support system can help managers obtain forest information and make management decisions.

Table 11. Summary of parameters of sensors onboard UAV.

	Model	Spectral Range/nm	Resolution/Pixel	Weight/g
Multi-spectral sensors	Sentera Quad	RGB Red: 655 Red edge: 725 NIR: 800	1248 × 950	170
	ADC Micro	Green: 520~600 Red: 630~690 NIR: 760~900	2048 × 1536	200
	MiniMCA6	Blue: 490 Green: 550 Red: 680 Red edge: 720 NIR1: 800 NIR2: 900	1280 × 1024	700
	Buzzard	Blue: 500 Green: 550 Red: 675 NIR1: 700 NIR2: 750(10) NIR3: 780(10)	1280 × 1024	500
Hyperspectral camera	**Model**	**Spectral Range/nm**	**Spectral Resolution/nm**	**Weight/g**
	Field Spec 4	350~2500	3	5.4
	Caia Sky-mini	400~1000	4	4
	Cubert S185	450~950	4	4.9
Laser radar	**Model**	**Maximum Distance/m**	**Scanning Frequency/(Line/s)**	**Weight/g**
	hummingbird	250	16/32	738
	Velodyne	100	16	830

In addition, to effectively determine the impact of forest operations on the environment, researchers have used forest data such as terrain and soil as predictive variables. They developed a prediction model for soil disturbance by implementing generalized regressive analysis and spatial prediction. Then, they depicted land types susceptible to disturbance during operation by GIS and thus predicted the effects of forest operations on soil properties [111,112]. Overall, although the amount of the research literature in this area is minor, environment-oriented forest resource allocation is becoming the focus of governments' concern in the context of sustainable development. With the current fusion of RS data sources in the process of data structure mismatch and other problems, the mining of information on specific bands is less. So, the research prospects in this direction are broader. The popular techniques for forest management are compiled in Figure 18.

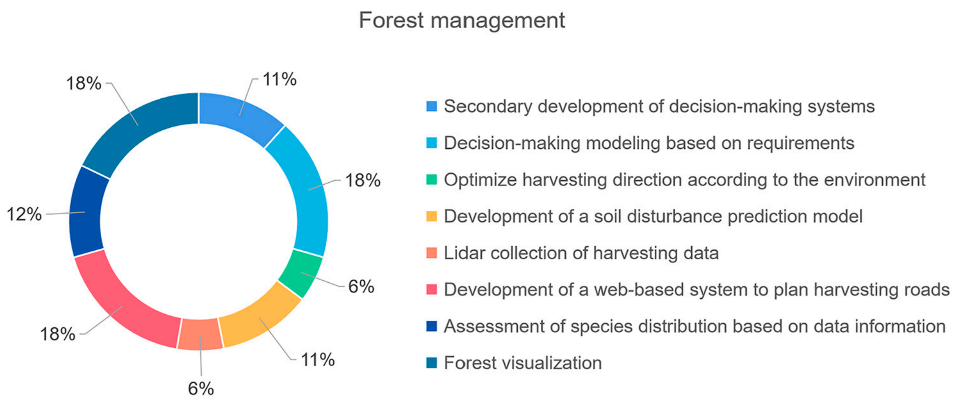


Figure 18. Forest management thematic research methodology.

6. Conclusions and Outlook

In the last 20 years, the software of GIS combined with decision support tools and the LiDAR system are the main geoinformatics technologies applied in forest planning and management. In addition to being widely and effectively applied in forest fire prevention and forest road construction, GIS has also been successfully applied in forest management activities such as material transportation and timber harvesting. The application of GIS in supporting the planning, design, and management of forests will have great potential in the future.

In the field of forest fire prevention, the vast data processing and storage capabilities of GIS have been used to show forest fire spread trends, identify risk areas, create different forest fire warning systems, pinpoint the location of watchtowers, and understand forest ecosystem recovery after disasters. GIS has also been combined with LiDAR technology, decision evaluation tools, and heuristic algorithms, which has been applied to the mapping selection and information detection of forest road construction and forest material transportation. Therefore, the ability of system models to solve general problems should be improved. Currently, GIS technology can be used in conjunction with laser scanners and other photogrammetric techniques to perform 2.5D or 3D spatial analysis. However, it still cannot break through the restrictions of natural, economic, social, and other factors around the world. Therefore, accelerating the research and application of 4D forest simulation and virtual reality (VR) systems in the future is the key to solving this problem.

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