Current Forestry Reports (2025) 11:26
https://doi.org/10.1007/s40725-025-00259-3

FOREST ENGINEERING (R PICCHIO, SECTION EDITOR)

Forest Accessibility and Road Network Density: A Global Overview with a Special Focus on Europe

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Received: 10 October 2025 / Accepted: 14 October 2025

Abstract

Purpose of the Review Forest accessibility and road network density are important concerns not only for forest managers, but also for everyone who benefits from forests, whether for professional or personal use. A well-planned forest road network, integrated with the forest ecosystem, is a fundamental element of rational and efficient forest management. This review aims to describe the current state of forest road density and overall forest accessibility in Europe, as well as relevant global examples.

Recent Findings When a forest road network is distributed adequately across an area, it can support many, if not all, tasks outlined in forest management plans, with high efficiency and minimal costs during construction and maintenance. Collecting data on forest accessibility and primary forest road density at the national level in many countries is a complex task. Diverse terrain conditions, economic factors, and forest management practices have led to variability in the data. A common thread, however, is the optimistic outlook on the use of modern technologies for road network planning and data acquisition.

Summary Efficient forest management, especially harvesting operations, relies on a road network with appropriate density, load-bearing capacity, and alignment. Primary forest transport infrastructure helps reduce timber extraction costs by minimising extraction distances and shortening the travel time from the forest stand to the market. As such, forest road density and accessibility are crucial elements in planning forest operations. Despite differences in terrain conditions, harvesting systems, and economic contexts across Europe and globally, research consistently highlights the need to improve the efficiency of road network planning. Future research on forest accessibility should focus on integrating valuable data collection with scientific research and ensuring effective knowledge transfer to forest practitioners.

Keywords Forest road network planning · Primary forest infrastructure · Secondary forest infrastructure · Road density · Forest accessibility · Timber transport

Introduction

Forest roads are essential for effective forest management, as they provide critical access for timber harvesting, monitoring, fire control, and other silvicultural operations, while also influencing the environmental and economic outcomes of forest activities [1].

The primary forest transport infrastructure plays a crucial role in reducing timber extraction costs by shortening the average extraction distance and increasing truck travel speed during timber transport [2]. This infrastructure comprises a network of forest and public roads as well as navigable waterways, along which roadside log landing sites are strategically located [3]. Efficient forest management, particularly timber harvesting, depends on a road network of adequate density, alignment, and load-bearing capacity [4]. Forest roads are often referred to as the lifeblood of forest operations [5], with primary and secondary networks functioning in an interconnected and complementary manner.

The secondary forest transport infrastructure includes tractor roads, trails, and forest skyline corridors, which are

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primarily designed to move timber from the stump to the landing site [6]. Tractor roads are semi-permanent structures, typically constructed only with a lower structural layer, and are suited to sloped terrain and challenging soil conditions. In contrast, tractor trails are temporary pathways formed by repeated passes of skidders or forwarders, commonly used in flat terrain with minimal ground obstacles [7].

Together, the primary and secondary forest road networks form a cohesive system that enables the full implementation of forest management tasks as outlined in forest management plans. Their functional integration is essential for operational efficiency, cost control, and minimising environmental impact [8].

Road construction and timber extraction from stump to roadside landing are among the most costly and environmentally disruptive operations in forest management, frequently resulting in soil erosion and degradation [9]. High forest road densities can further exacerbate these issues by increasing operational costs, reducing productive forest area, and intensifying environmental impacts [10]. Consequently, the economic viability and profitability of forest management plans are strongly influenced by the cost of road construction and maintenance, as well as the spatial configuration of the road network [11]. Considering the research made by Eliasson [12] and Bergqvist et al. [13], where they found that the costs required for the construction of forest roads and their maintenance per harvested cubic metre are constantly increasing, it is important to find and determine the optimal forest road spacing that will enable effective forest management with minimising the total costs.

Road development can result in significant forest loss, leading to both ecological changes and financial losses [14]. Therefore, evaluating forest road networks is essential for assessing forest accessibility, transportation efficiency, and the effectiveness of forest operations [15]. The conceptual foundation for forest road layout planning traces back to Matthews [16], who introduced a geometric model for road spacing under assumptions of flat terrain and evenly distributed timber volumes.

Subsequent refinements to this model accounted for variations in terrain. Segebaden [17] emphasised that irregular topography and variable stand conditions necessitate asymmetrical road networks, leading to non-linear, non-vertical timber movement during extraction. Backmund [18] later introduced relative openness as a qualitative parameter for analysing forest accessibility. Incorporating not only total length of roads vs. forest area, but the ratio of the area accessible to roads (buffer area) to the total forest area reflected as a distinctive measure in defining forest accessibility. Originally, Backmund [18] proposed that the buffers' width is equal to the distance between forest roads. The same author graded forest accessibility based on values of relative openness and the forest road network factor.

This method was further refined by Sach [19], who modified the model's buffer width to reflect terrain slope. Specifically, the buffer zone extended 200 m on flat terrain and varied on slopes, with 100 m for uphill extraction and 200 m for downhill extraction. As Heinimann [20] stated, Segebaden's approach was used in many European studies regarding road density and network spacing throughout the 1970s to 1990s. The same author further concluded that in all the studies, the main relationships between timber extraction distance and road spacing were supported by a Matthews' 2D model. Hayati et al. [9] proposed a more dynamic approach, calculating buffer widths based on twice the optimal geometric timber extraction distance.

One of the central challenges in planning a forest road network for a given forest estate is indeed its integration with the concept of forest accessibility. In the context of forest operations engineering, forest accessibility refers to the ability to reach any point within a forest stand, considering terrain and logistical factors such as the existing road network, slope, and surface roughness [21]. As shown in Fig. 1, different forest roads in various countries and forest stands share the same goal – enabling forest accessibility during forest management, especially during harvesting operations and wildfire risk management. The concept of forest accessibility was initially based on the criterion of travel time; that is, an area was considered accessible if it could be reached on foot within a reasonable time [22]. With the advancement of forest mechanisation, this definition has evolved toward a distance-buffer criterion, whereby a point in the forest is considered accessible if a given machinery can reach it without the need to construct additional road segments [23].

Nowadays, with the current development of new technologies such as GIS (Geographic Information System), machine learning, GNSS (Global Navigation Satellite System), and Multi-Criteria Decision Analysis, our possibilities for carrying out the fundamental tasks of planning forest operations as a function of the road network and related accessibility have been significantly increasing. However, a comprehensive review on this topic that can summarise the findings and harmonise the outputs of research worldwide is lacking.

Considering the above, it is clear that forest road density and accessibility are fundamental concepts in the planning of forest operations. Accordingly, this review aims to collect and synthesise findings from the literature related to the assessment and optimisation of forest road network density and accessibility in support of forest operations planning. We focused on studies published over the last decade (2016–2025) that specifically address the evaluation of road

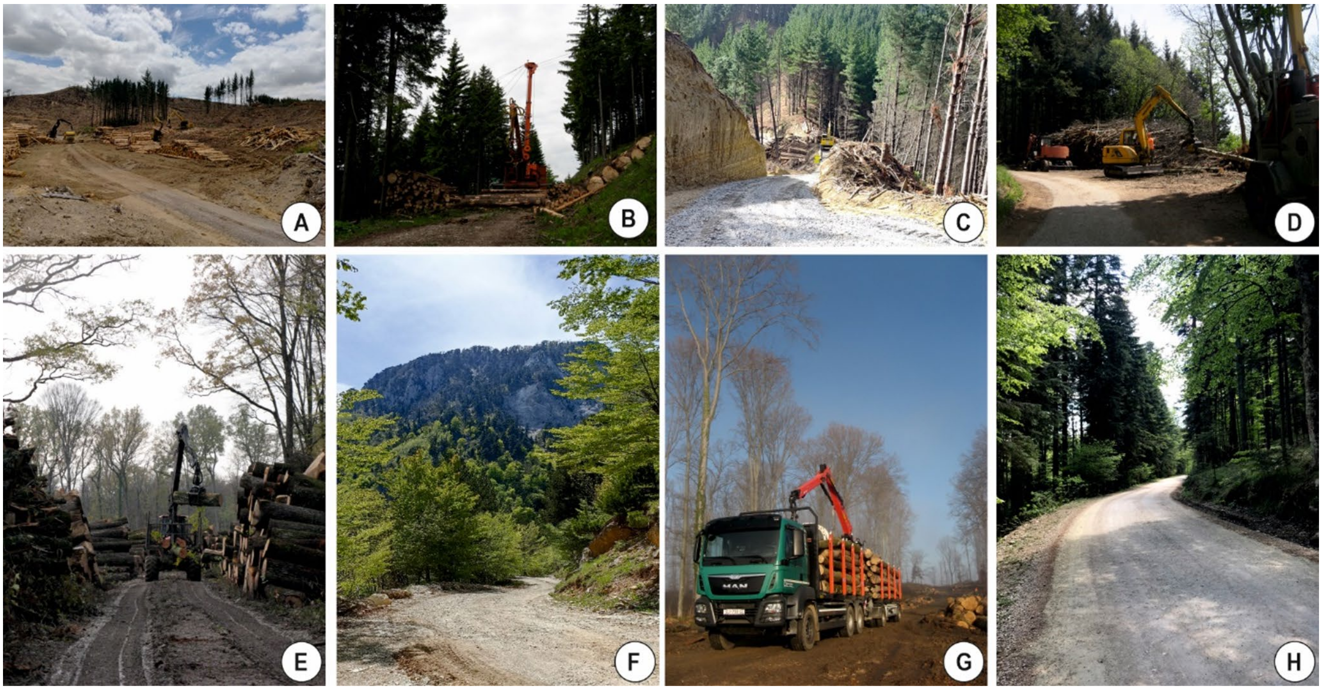

Fig. 1 Forest roads: (**A**) New Zealand (author: F.Latterini); (**B**) Austria (author: A.Đuka); (**C**) New Zealand (author: F.Latterini); (**D**) Italy (author: A.Đuka); (**E**) Croatia (author: A.Đuka); (**F**) Federation Bosnia and Herzegovina (author. Dž.Sokolović); (**G**) Croatia (author: A.Đuka); (**H**) Serbia (author: D.Stojnić)

density and forest accessibility within the context of sustainable forest management. Studies focused solely on road identification through remote sensing or those conducted purely in simulated computational environments were therefore excluded from the review.

Materials and methods

A literature review covering specific world regions (Europe, Western and Eastern Asia, South America) was conducted in the databases Web of Science and Scopus in April and May 2025, limiting the search only to texts in the English language. The following keywords were used to retrieve available studies: forest roads, road density, forest accessibility and forest viability. Initially, there was no specific time frame to establish a comprehensive basis for the crucial studies required for the introduction and discussion parts of the article. Titles, abstracts and/or keyword fields were read to decide whether each study was related to the topic. In total, 1,772 studies were identified using Web of Science, and 2,109 with Scopus. After defining which studies fall within the scope; the next step was to define studies published less than 10 years ago; studies that report indication of road density in the target study area and/or an evaluation of forest accessibility; studies that were developed in a real environment. In a subsequent step, national sources from the co-authors' countries were also searched, which included popular science journals dedicated to practitioners. Finally, research projects and dissertations were searched and considered. References were organised by region (Fig. 2). In total, we built a database of 63 references: 54 scientific papers, 3 papers from popular science journals, 2 books and 4 technical reports with the common goal to review and summarise the current state of forest accessibility.

Results and Discussion

Central-Eastern Europe (Poland, Slovakia, Russia)

In Central and Eastern Europe, the density and accessibility of forest road networks have been the subject of growing attention, reflecting the region's diverse forest conditions, infrastructure legacies, and operational challenges. Studies from Poland, Russia, and Slovakia highlight different starting points, from underdeveloped networks in vast concessions to highly dense but ageing infrastructures yet converge on a shared goal: improving forest accessibility through strategic planning, modelling, and data integration.

In Poland, recent analyses have focused on both the spatial distribution and the technical condition of the forest road network. The average road density managed by the State Forests National Forest Holding (SF-NFH) is

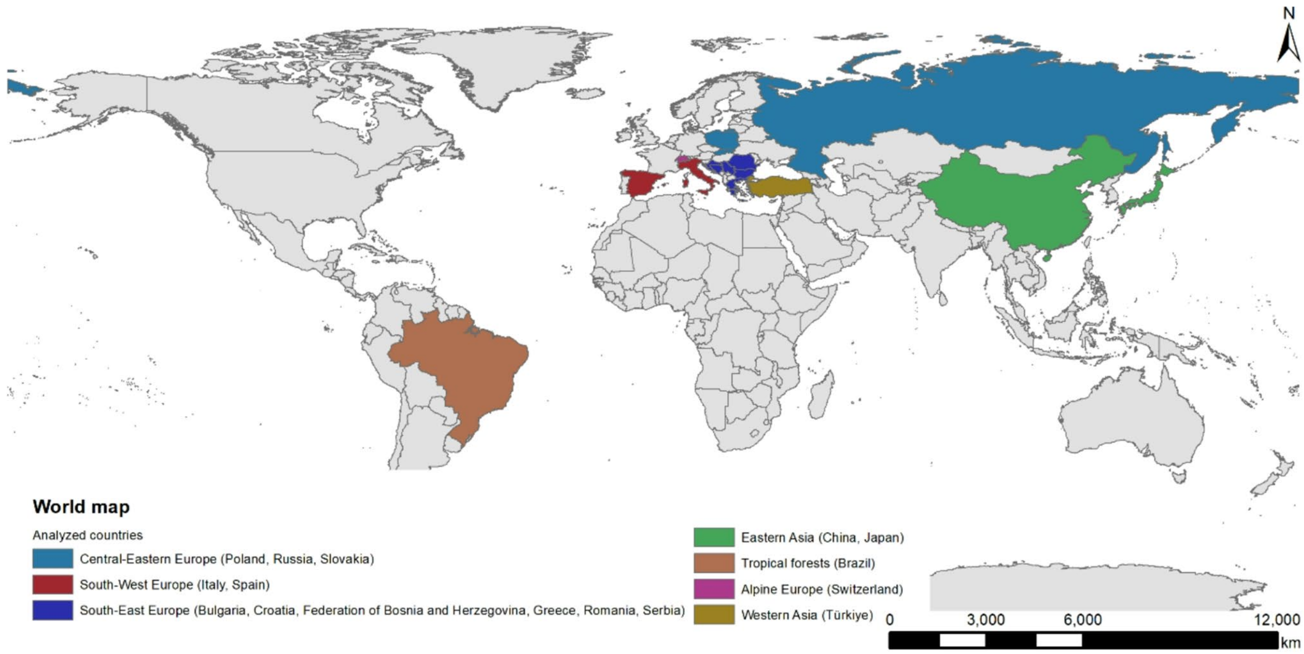

Fig. 2 Various world regions and countries studied in this review

approximately 15.28 m/ha, with substantial regional variation ranging from 8.87 to 23.17 m/ha, and even broader discrepancies at the forest district level, i.e. from as low as 0.75 m/ha up to 76.11 m/ha [24]. While these values generally fall within the range considered optimal for Polish conditions (typically 5.00 to 34.90 m/ha), many roads suffer from poor surface quality and insufficient bearing capacity. As a result, the actual forest road density, based on usable roads for modern harvesting machinery, is significantly lower than the nominal figures suggest [24]. Complementary research has also emphasised the role of spatial data quality in route planning: even when roads exist on the ground, their absence or poor representation in digital systems can hinder efficient operational planning. GIS-based terrain and routing analyses have further reinforced the need for accurate, continuous, and structurally sound road networks to ensure true forest accessibility [25, 26].

In Slovakia, the focus has been on integrating infrastructure data into operational models. A study [27] examining forest estates with network densities of approximately 148 m/ha (including both primary and secondary forest traffic infrastructure) used this input to estimate average skidding distances, which were found to be around 400 m. Despite the high density, this result suggests that spatial distribution, terrain, and machine specifications continue to play a defining role in determining actual extraction efficiency.

In contrast, the context in Russia reflects a need for expanded infrastructure in large-scale, low-density forest concessions due to the lack of reliable forest inventory data. A study [28] evaluating the optimisation of road networks in such a concession found the existing primary road density to be only 2.4 m/ha. Machine learning resulted in different harvesting scenarios, based on data on forest inventory (harvesting volumes and forest growth), existing road density, soil types, terrain elevation and hydrology, transportation costs and road construction costs. The authors identified a network configuration that included 3.2 m/ha of primary roads, supplemented by 12.9 m/ha of secondary roads accessible to all-wheel drive forest trucks. This hybrid configuration was found to support operational efficiency best while limiting environmental disturbance and infrastructure costs, showcasing the value of data-driven planning in remote and logistically constrained areas.

Together, these studies highlight the diverse challenges and strategies in forest road network planning across Central and Eastern Europe. From modernising ageing infrastructures in Poland to leveraging high-resolution geoprocessing in Slovakia, and expanding strategic access in Russian concessions, the regional literature reflects a multifaceted effort to improve forest accessibility through a combination of technical assessments, modelling, and spatial analysis. These approaches provide essential support for both sustainable forest operations and long-term infrastructure development.

South-West Europe (Italy and Spain)

In South–West Europe, particularly in Italy and Spain, the density and accessibility of forest road networks have been explored through a range of approaches. In these countries, forest roads play a strategic role in the socio-economic development of populations living in mountainous and hilly areas. Adequate forest road networks are considered essential for rational and economic management of forests, mountain pastures, and agricultural lands, as well as wildfire risk management.

Recent research has emphasised both traditional forest engineering assessments and evolving digital tools, contributing to a more comprehensive understanding of how road infrastructure supports sustainable forest management. In the Italian context, the concept of forest roads encompasses all roads, tracks, extraction routes, landings, and forestry infrastructures, whether permanent or temporary, on which ordinary motor vehicle traffic is generally prohibited [29]. Forest roads are also designed following a multi-purpose approach, with a long-term perspective, and are categorised into three main types, primarily based on size and construction techniques. A study by Picchio et al. [30] examined two forest estates in Central Italy, focusing on operational accessibility in relation to the working distances of typical forest machines. Specifically, the study defined accessible areas as those within 100 m for a tractor equipped with a winch and 300 m for a lightweight cable yarder. Areas beyond this threshold were deemed inaccessible. Road density, when limited to truck-accessible routes, ranged from 15.8 to 19.2 m/ha, but increased significantly to 43.4 and 52.6 m/ha when permanent skid trails were included. Despite these relatively dense networks, up to 14% of the forest area remained inaccessible. The authors calculated that fully accessible networks would require densities of 45.64 and 58.9 m/ha, demonstrating the critical link between machine-specific reach and required infrastructure investment.

Complementing this operational perspective, Cadež et al. [31] advanced a practical application of accessibility assessment by developing a web GIS tool that incorporates buffer-distance analysis from existing roads. This tool supports the preparation of forest management plans by spatially identifying areas of limited access and providing a planning interface for optimising road networks. While methodologically simpler than machine-specific working distances, the buffer approach allows scalable assessments across broad forest areas, integrating accessibility data into digital forest planning workflows.

Further extending the utility of accessibility metrics, Mostafa et al. [32] evaluated the adequacy of forest road networks for wildfire management. Analysing historical ignition data, the study found that the majority of forest fires occurred within 75 m of existing roads, suggesting that current road densities (around 50 m/ha) offer generally good coverage for emergency response. This reinforces the dual-purpose value of road networks, which not only facilitate timber extraction but also serve critical roles in mitigating landscape-level risks.

A different perspective was provided by Sferlazza et al. [22], who proposed a decision support system for optimising biomass extraction based on travel time to roadside landings. The authors evaluated forest accessibility considering the access time, which is explained as the time required of a forest worker to make a round trip on foot from the closest road to a specified point in the forest. The average walking speed is 1.11 m/s on terrain with slopes ≤ 10%. While this access-time criterion introduces a dynamic dimension to accessibility assessment, the approach is less directly tied to traditional forest engineering concerns such as road density, machine range, and terrain constraints. As such, it provides complementary insights rather than core operational metrics.

Expanding this regional analysis to the Iberian Peninsula, Pascual et al. [33] investigated a forest estate in Spain with a documented forest road network density of 17.6 m/ha. This parameter served as a key input in the optimisation of forest harvesting plans, intending to reduce extraction costs and improve the efficiency of forest management interventions.

Overall, literature from South-West Europe reflects a diverse but converging effort to integrate forest accessibility and road network planning into forest management. Whether through quantitative evaluations of road density, spatial buffer models, or decision-support tools, these studies underscore the importance of aligning infrastructure with both operational efficiency and broader land management objectives. Together, they illustrate how forest accessibility assessments are evolving from static measurements toward more integrated, multifunctional planning frameworks.

South-East Europe (Croatia, Federation of Bosnia and Herzegovina, Serbia, Romania, Bulgaria, Greece)

In South-East Europe, forest road network density data is often difficult to obtain. Studies from Croatia, the Federation of Bosnia and Herzegovina, Serbia, Romania, Bulgaria, and Greece reveal varying densities, depending on different terrain categories and similar ownership structures, where, in most cases, the state is the dominant owner of forest land. All of these countries share a common need– to increase forest accessibility and enhance efficiency in forest management.

In Croatia, primary forest transport infrastructure comprises all categories of forest roads and public roads that can be used for forestry work (excluding highways) [6], as well as secondary forest transport infrastructure, including skid roads and skid trails, which are primarily used by forwarders and skidders during timber transport.

According to Poršinsky et al. [34], Peternel [35] is considered the first author to report on forest road density in Croatia consistently. The author stated that out of a total of 5,427 km of existing forest infrastructure network, 3,560 km were forest roads and paths, and 1,867 km were forest railways, which gives a density of 3.9 m/ha of accessible forest area. The same authors [34] reported that Pentek et al. [36] and Hodić and Jurušić [37] presented similar values of the road density for forests managed by the state company Hrvatske šume Ltd. (the company manages more than 75% of the forests; authors' note) depending on different terrain categories: lowland (8.85 m/ha), hilly (11.26 m/ha), mountain (15.64 m/ha) and karst (7.63 m/ha). Targeted road network density, as prescribed by current state regulations, is specified. It depends on terrain categories: lowland (15 m/ha), hilly (25 m/ha), mountain and high karst (30 m/ha) and low karst (15 m/ha), which considers geometrical timber extraction distance for the same terrain categories: lowland (330 m), hilly (250 m), mountain (200 m) and karst (330 m).

The current length and density of the forest road network in the Federation of Bosnia and Herzegovina are calculated according to different forest categories, with no clearly defined short-term or long-term targets for the desired level of road density. The highest average road density is recorded in high forests (16.0 m/ha), primarily due to their economic value. The density in forest plantations is 9.6 m/ha, in coppice forests 11.2 m/ha, and productive barren land 10.2 m/ha. At the same time, the lowest value is observed in overgrown unproductive areas, at 6.6 m/ha [38]. Similar to Croatia, 82% of forests are state-owned, but with a significant challenge – the presence of landmines on approximately 124,975.1 ha (10%) of the forest area [39]. The data [40] on primary forest traffic infrastructure, collected in 2016 in the entity Republic of Srpska showed forest road density to be 9.28 m/ha. The highest density of forest road network was found in forest plantations (11.57 m/ha) and high forests with natural regeneration (11.13 m/ha).The Forest Infrastructure Master Plan [41] currently provides basic data describing existing road density, average skidding distances, and recommended timber extraction technologies according to geological-pedological complexes (GPCs) and slope classes. Focusing on the findings of recent research, Dražić et al. [42] (2023) highlight that terrain slope is the most important morphometric parameter in forest road construction, but also mention terrain suitability, which is not a linear parameter. It is important to highlight that there is no unified guideline or regulation to standardise the methodology for calculating road density, which complicates intercantonal comparisons. Petković and Potočnik [43] state that overall forest accessibility in Bosnia and Herzegovina (BiH) is 2 to 6 times lower than that in other countries in the region.

Regarding the forest road network density in Serbia, it can be said that there is no relevant data at the republic level. One of the reasons for this is that no standardised forest road cadaster has been created, although its development was prescribed by the Forest Law as early as 2010. Additionally, the large proportion of private forests (state forests account for approximately 42% of all forests, while the remaining 58% are privately owned) has almost no information on forest accessibility. The Forestry Development Programme in the territory of the Autonomous Province of Vojvodina (2013–2022) states that about 1,785 km of forest roads have been recorded in the area of state forests in Autonomous Province (AP) Vojvodina, which makes the density of the forest road network approximately 12.75 m/ha. The Autonomous Province of Vojvodina is one of the least forested areas in Europe, with forests and forest land accounting for only 6.51% of the total area. According to the internal records of the largest public forest management company, Public Enterprise Srbijašume, the total length of forest roads in the forests they manage is 11,941 km, of which 5,866 km are forest roads with a pavement structure and 6,075 km without a pavement structure [44]. The density of the forest road network in the forests managed by this company is 13.37 m/ha. The forests they manage belong to all types of terrain categories, but mainly to the hilly and low-mountainous terrain categories. There is a large proportion of forest roads without a pavement structure; the density of the forest road network with a constructed pavement structure is only 6.57 m/ha. The importance of forest roads in fire protection is highly recognised, especially after the fire in the summer of 2007, which destroyed 45.2 ha of forest in the national park Tara [45].

In Romania, forest roads are classified according to three main criteria: the terrain configuration, the location of the forest road relative to local topography, and their importance and functionality [4]. According to the terrain configuration, there are three categories: forest roads located in the plain area (below 150 m a.s.l.), hilly area (150 to 300 m a.s.l.), and mountainous area (above 300 m a.s.l.). By the location of the forest road, there are four categories: valley, slope, ridge, and forest roads that cross from one watershed to another. Finally, in terms of importance and functionality, the Romanian system classifies forest roads into three categories: (1) forest roads that serve forest areas of more than 10,000 ha and transport over 50,000 t/year; (2) forest roads that serve forest areas of more than 1,000 ha and transport between 5,000 and 50,000 t/year; (3) forest roads that serve forest areas of less than 1,000 ha and transport less than 5,000 t/year [46]. While there are no aggregated figures for the country, primarily due to the fragmentation of forest ownership, Hapa et al. [47] reported that the average current forest road density is approximately 6.5 m/ha. Still, a high variability in this parameter is present, depending on the county forest directorate in question. This typically leads to an average extraction distance that may exceed 1 km, which contributes significantly to the increment in harvesting costs. It is believed that a forest road density of 14 to 18 m/ha would be optimal when considering both timber extraction and transport costs.

Studies from Bulgaria and Greece highlight the importance of aligning road network development with harvesting efficiency and accessibility targets, particularly in terms of skidding distances and transport costs. In Bulgaria, recent studies have focused on quantifying existing road networks and identifying optimal density thresholds to support efficient harvesting and transportation. One study reported a current road density of 20.31 m/ha in a representative forest estate, with modelling indicating that an increase to 30.9 m/ha would be necessary to optimise timber extraction operations and maintain skidding distances within 300 m [48].

A more recent analysis [49] employed a road density value of 23 m/ha as a key input for estimating the costs of long-distance timber transport. The integration of road network parameters into transportation cost modelling reflects a growing emphasis on linking infrastructure characteristics with downstream economic impacts. By evaluating how road density influences extraction distances and cost structures, the study provides insights into the broader implications of road planning for the forest value chain.

In neighbouring Greece, an assessment of forest accessibility based on proximity to existing roads reported that areas within 250 m of the road network were considered accessible [50], with a current road density of 14.05 m/ha; less than half of the study area met this accessibility criterion. Modelling showed that increasing the density to 16.18 m/ha, through the construction of five additional forest roads, would render more than half of the area accessible. This relatively modest infrastructure investment highlights the sensitivity of accessibility outcomes to even minor adjustments in road density and distribution.

Alpine Europe (Switzerland)

In Switzerland, the evaluation of forest road network density and accessibility has been addressed at both regional and national scales, reflecting the country's diverse topography and the critical need to align forest infrastructure with the suitability of harvesting systems. Research has particularly focused on integrating road network characteristics with terrain and operational constraints to support efficient and sustainable forest management.

A regional-level study [4] in the Canton of Grisons evaluated the road network and allocation of harvesting systems across various forest conditions. The overall forest road density was found to be 17 m/ha, with a functional subdivision: 8 m/ha suitable for trucks weighing between 18 and 27 tonnes, and 9 m/ha for heavier trucks ranging from 28 to 40 tonnes. To support operational planning, a decision support system was developed to identify the most suitable harvesting system for each forest stand, considering the feasibility of both ground-based and cable-based methods. Notably, the model also integrated the optimisation of landing site locations, intending to minimise overall transport costs, thus highlighting the value of combining infrastructure analysis with spatial logistics planning.

At the national scale [4], a comprehensive assessment of forest accessibility and road infrastructure reported an average forest road density of 22 m/ha. However, this value varied significantly across districts, from nearly 0 to as high as 84 m/ha. Using these data, a classification of harvesting system suitability was conducted for the entire country. Ground-based harvesting systems were feasible on approximately 21% of the forest area, while cable-based systems, particularly tower yarders, could be applied across more than 40% of the terrain. Long-distance yarding applied to less than 10% of the area. Notably, about 25% of the country's forested terrain was deemed inaccessible under current infrastructure and operational criteria. These findings underscore the challenges posed by mountainous landscapes and the importance of tailoring harvesting strategies to local accessibility conditions [51].

Western Asia (Türkiye)

In Türkiye, research on forest road network planning and accessibility has focused heavily on integrating decision-support methodologies to optimise infrastructure concerning terrain, forest structure, and operational requirements. The studies reviewed emphasise a strong focus on enhancing the efficiency of forest operations while adapting to the country's varied and often challenging topography reflected in steep terrain (varying slope, elevation and aspect conditions), soil types and hydrology networks.

One line of research investigated the application of a decision support system (DSS) to determine the most suitable harvesting system, considering topographic, silvicultural, and logistical variables [52]. With a forest road density of only 11.74 m/ha, a level considered relatively low for ground-based extraction systems, the DSS consistently recommended cable-based harvesting methods as the most appropriate alternative. This approach underscores the importance of tailoring harvesting technologies not only to forest structure and terrain but also to the limitations of the existing road network. Rather than expanding the road infrastructure, the system prioritised aligning the harvesting system to the current level of accessibility, thereby minimising environmental disturbance and infrastructure costs. In parallel, another study [53] applied a multi-criteria decision analysis (MCDA) framework to optimise forest road networks at the estate scale. The method incorporated environmental, economic, and operational factors to guide infrastructure rationalisation. As a result, the total road length was reduced by approximately 1000 km, lowering the overall road network density from 75 m/ha to about 70 m/ha. This outcome demonstrates how structured, criteria-based planning can support the reduction of redundant or environmentally harmful roads while still maintaining adequate accessibility for forest operations.

Together, these studies from Türkiye highlight a strategic shift toward informed, systems-based approaches to forest infrastructure planning. Rather than focusing solely on expanding access, the emphasis is placed on aligning road network density with operational needs and terrain limitations. This reflects a broader trend toward efficiency and sustainability, ensuring that road development is both functionally justified and environmentally responsible. The Turkish experience illustrates how decision-support tools can be effectively deployed to balance competing priorities in forest road network planning and support more adaptive, context-sensitive forest management strategies [54, 55].

Eastern Asia (China and Japan)

In East Asia, forest road network planning has increasingly emphasised multifunctionality, with road accessibility supporting not only timber harvesting but also fire prevention and emergency response.

In China, research on accessibility has been significantly influenced by concerns over forest fire prevention. One study [56] analysed a forest estate with an existing road network density of 12.94 m/ha, using proximity to roads as a proxy for accessibility by firefighting machinery. In this context, areas located within 100 m of the road network were deemed fully accessible, while those within 200 m were classified as barely accessible. Based on this functional criterion, the authors concluded that to achieve adequate accessibility for effective firefighting, the viability density should be increased to approximately 17.5 m/ha. This analysis highlights how operational definitions of accessibility can vary according to management objectives, and that road planning must consider not only logistics but also risk mitigation infrastructure.

In Japan, a more infrastructure-intensive approach was applied to ensure full accessibility across an entire forest estate. Using the Minimum Spanning Tree (MST) method, researchers [57] optimised the layout of both primary and secondary forest roads, resulting in a total road density of approximately 85 m/ha. This high-density network reflects the country's steep terrain, fragmented ownership patterns, and strong emphasis on multifunctional forest use. The MST method, which is based on an algoritham of graph theory, used for network analyses creates a graph comprising nodes and edges and assigns weights to the edges, thus defining the shortest possible total road length of forest roads. In that way, the MST method facilitated the development of a cost-effective yet comprehensive access system, highlighting its value for planning in complex forest landscapes where road construction costs are high and space is limited.

Whether driven by fire safety or terrain constraints, the region's approaches demonstrate the growing use of quantitative models and spatial optimisation techniques to guide infrastructure development. These cases reinforce the broader finding of this review that effective forest operations, whether for extraction or protection, depend on aligning road network design with functional definitions of accessibility and management objectives.

Tropical Forests (Brazil)

In Brazil, where forest operations often take place in vast and ecologically sensitive landscapes, optimising forest road network density and accessibility is essential for ensuring both economic viability and environmental stewardship [58]. Recent studies have focused on the development and comparison of different planning methodologies to improve the efficiency of road layouts while minimising forest disturbance and operational costs.

A key contribution to this topic comes from a comparative analysis of conventional and optimised secondary road planning methods using a GIS-based approach [59]. The optimised layout reduced average skidding distances by approximately 20%, enhancing extraction efficiency. However, this improvement came at the cost of a 13.66% increase in the length of secondary roads, underscoring the trade-off between operational performance and infrastructure footprint. The study highlights the importance of spatial optimisation in balancing productivity with environmental impact.

Another study [60] focused on eucalyptus plantations and explored the relationship between forest road density and the combined cost of road construction and wood extraction under a whole-tree system. The analysis determined an optimal road density of 30.49 m/ha, corresponding to an average extraction distance of 81.99 m. This value was found to yield the lowest cost per unit of timber extracted, confirming that properly calibrated road spacing can significantly

Table 1 Forest road densities in different regions according to the literature review

Central-East Europe (Poland, Russia)*	South-West Europe (Italy, Spain)	South-East Europe (Croatia, F BiH, Serbia, Romania, Bulgaria, Greece)	Alpine Europe (Switzerland)	Western Asia (Türkiye)	Eastern Asia (China, Japan)	Tropical forests (Brazil)
Minimal reported primary forest road densities, m/ha						
2.4	15.8	6.5	8	-	12.94	-
Maximal reported primary forest road densities, m/ha						
76.11	52.6	20.31	84	-	85	-
Average primary forest road densities, m/ha						
11.96	17.5	12.81	22	11.74	48.97	17.48

* Slovakia was omitted since the value of 148 m/ha [27] refers to both primary and secondary forest roads.

improve the cost-effectiveness of forest operations in plantation forestry contexts.

A broader comparison of road planning methods was undertaken in a study [61] conducted within a selectively logged area of the Amazon. Four approaches were evaluated: a planned road network (based on terrain and inventory data), the network as implemented in the field, and two modelling methods, the Tomlin model and the Minimum Spanning Tree (MST) model. The Tomlin model, which mimics hydrological flow patterns to prioritise routes with higher simulated traffic, proved to be the most effective for main road allocation, balancing cost and forest disturbance. In contrast, the MST model excelled in planning secondary roads and skid trails, offering the most efficient spatial coverage despite slightly higher costs. Road network densities across these methods ranged from 17.48 m/ha (implemented network) to 22.51 m/ha (MST model), illustrating how different approaches impact both accessibility and forest integrity. This work emphasises the potential of hybrid modelling frameworks to enhance ecological and economic sustainability in tropical forest management.

In a similar operational context, another recent study demonstrated how optimisation techniques can reduce excessive road development. By redesigning the road network, researchers [10] were able to lower road densities from previously high values of 126–180 m/ha to a more efficient range of 92–123 m/ha. This result illustrates the potential to substantially reduce infrastructure intensity while maintaining or improving functional access, particularly in intensively managed forests.

Collectively, the Brazilian literature reveals a strong trend toward integrating spatial analysis, optimisation algorithms, and operational metrics to refine forest road network design. The studies emphasise that while increased accessibility improves harvesting efficiency, it must be carefully balanced against environmental considerations and construction costs. The varied ecological and logistical contexts in Brazil, ranging from industrial plantations to remote Amazonian concessions, underscore the need for adaptable, site-specific approaches that integrate road density with machine reach, terrain constraints, and long-term sustainability goals [62].

Overview

Road network density and generally forest accessibility vary in different regions and countries studied in this review. Variations are common even within countries due to ownership structure, terrain characteristics, the level of mechanisation in harvesting operations, and the type of forest management, among other factors. The highest values of forest road densities have been reported in Japan, while the lowest are in Russia, with all average values given in Table 1. Still, we must emphasise that many of these values, originate from specific studies of specific regions within each country. The national values are often unclear, and to obtain valid databases at the national level, further research is necessary.

Conclusions

A valid plan of forest roads is essential to reduce environmental impacts while ensuring adequate forest accessibility. Findings from the latest research on forest accessibility and road network density suggest that there are differences in data availability, which are highlighted by local challenges both globally and in Europe. In Central and Eastern Europe, forest accessibility and road network density are gaining more focus, combining diversity in stand and terrain conditions, as well as network quantity. Studies from Poland, Russia, and Slovakia share a common goal: to highlight forest accessibility through higher levels of planning, improved decision-making, and operational efficiency. Italy and Spain represented the region of South-West Europe. In these two countries, studies on road network density and forest accessibility have shown the use of both traditional and developing digital tools, all focusing on how road infrastructure networks can and should support sustainable forest management. In South-East Europe, studies from

Croatia, the Federation of BiH, Serbia, Romania, Bulgaria, and Greece show various data accessibility, which usually depends on the forest ownership structure. Different terrain categories reflect diversity in road network densities and timber extraction distances in this region. Alpine Europe has been represented by Switzerland, where various terrain conditions are highlighted in one country, to connect forest infrastructure to harvesting systems in an efficient and sustainable forest management. Türkiye, where research on forest road network planning and accessibility has focused on optimising the network in connection with terrain and stand conditions, as well as harvesting technologies, represents Western Asia. In East Asia, particularly in Japan and China, forest road accessibility has been studied and observed from three perspectives: forest management, fire prevention, and emergency response. Tropical forests were represented by Brazil, where minimising forest disturbance is mandatory. Recent studies have shown that the development and comparison of different planning methodologies are important for enhancing the efficiency of forest road networks and reducing costs.

Even though varying in terrain conditions, harvesting systems, starting points, and economic levels, in all the mentioned countries and studies, there is a common goal: to raise the efficiency of road network planning. This can be achieved by utilising modern technologies, where GIS, machine learning, and optimisation modelling have proven to be effective tools for planning forest road networks to improve forest accessibility conditions. Forest road networks are crucial not only for forest managers but also for the entire society, which benefits from the forests in one way or another. Better planning and consistent data gathering will bring benefits to practitioners, promoting more objective and scientifically oriented forest operations. Currently, the approaches for planning harvesting operations using GIS (for example, LiDAR) and modelling still belong to academia, and not much of this knowledge is transferred to forest practitioners. Knowledge transfer is therefore a challenge for future research.

Another key point is that in mountainous areas common in Europe, it is practically impossible to guarantee access to forest stands without relying on cable harvesting. Today, in several zones in the south and east of Europe, timber extraction is still performed with animals due to difficult terrain, tradition, management types, and economic issues. However, with ongoing modernisation and the abandonment of rural areas, animal logging is likely to disappear within the next few decades.Thus, we must invest in both general awareness and practical operator training to expand the application of cable yarders in these areas.

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  The paper focuses on forest accessibility and reviews traditional and computer-assisted road network layout approaches connecting them in an overall stream of development. The review identifies challenges for future research, among which the extension of the concurrent harvest/road-network layout systems for multi-objective functions is the most important.

Author Contributions "Conceptualization, A.Đ. and I.P.; methodology, A.R.P. and R.P.; validation, P.S.M. and S.A.B.; formal analysis, D.K.-T. and I.P.; investigation, D.K.-T.; resources, A.Đ., I.P., A.R.P., F.L., P.S.M., S.A.B., E.I., DŽ.S., A.K., D.S., M.D. and R.P.; writing—original draft preparation, A.Đ., I.P., A.R.P., F.L., P.S.M., S.A.B., E.I., DŽ.S., A.K., D.S., M.D. and R.P.; writing—review and editing, A.R.P., F.L., E.I., A.K., and D.S.; visualization, A.Đ. and I.P.; supervision, P.S.M., S.A.B., DŽ.S., M.D. and R.P.; funding acquisition, A.Đ." All authors have read and agreed to the published version of the manuscript.

Funding A part of his research was funded by the Croatian Science Foundation under the project "Quantity and structure of fir and spruce biomass in changed climatic conditions" (UIP-2019-04-7766).

Data Availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Competing interests The authors declare no competing interests.

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