Global Forest Journal Vol.04, No.01 (2026) 28–34

talenta PUBLISHER

Global Forest Journal

Journal homepage: https://talenta.usu.ac.id/gfj

Global Forest Journal

A systematic review and Meta-analysis of erosion occurrences on forest roads

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ARTICLE INFO

Article history:
Received 11 December 2025
Revised 15 January 2026
Accepted 20 January 2026
Available online 29 January 2026

E-ISSN: 3024-9309

How to cite:
M. N. Buniran, M. H. Ismail, P. H. Zaki, P. Bawon, Rahmawaty, S. Gandaseca, “A systematic review and Meta-analysis of erosion occurrences on forest roads,” *Global Forest Journal*, vol. 04, no. 01, January 2026.

http://doi.org/10.32734/gfj.v4i1.22428

ABSTRACT

Forest roads are essential in forested regions, supporting forestry operations, timber extraction, afforestation, log transportation to mills, recreation, and wildlife management. Nonetheless, forest roads are a major source of soil erosion and sedimentation in stream waters. They contribute to sedimentation through soil erosion on elements like the running surface, roadside slopes, and side ditches. On these routes, soil erosion primarily occurs due to rainfall-driven runoff and its duration. This study employs a systematic review, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), to compile data and examine findings on forest road erosion. The review aligns with the objectives of identifying factors that influence soil erosion on forest roads and skid trails, and developing techniques to control erosion, minimise its impact, and prevent its occurrence. Methods such as planting vegetation on roadside slopes have demonstrated effectiveness in mitigating erosion and reducing its severity and extent. It is advisable for future research to explore various soil erosion control techniques to deepen understanding and improve measures to reduce soil erosion on forest roads.

Keyword: Erosion, Forest Roads, Skid Trails, Systematic Review

1. Introduction

Forest roads are vital infrastructure for forest management, enabling the sustainable use and availability of renewable forest resources [1]. Properly constructed and well-maintained forest roads support responsible resource management. However, roads built without sufficient planning can cause considerable harm to habitats for flora and fauna, soils, rivers, and forest ecosystems. Typically, forest roads are categorised into several types, including primary forest roads, secondary forest roads, feeder roads, and skid trails [2].

Forest roads are widely recognised as a major source of soil erosion and stream sedimentation [3]. Both forest roads and skid trails can significantly increase overland flow and soil erosion, especially when bare soil is exposed to frequent traffic [4]. Skid trails used in ground-based harvesting systems are also identified as contributors to soil erosion and sediment delivery to nearby streams [5]. Soil erosion, a form of land degradation, involves the displacement of soil materials and the production of sediment. It can occur slowly, often unnoticed for long periods, or more rapidly, resulting in considerable loss of the topsoil and increased sediment production.

On forest roads, soil erosion is mainly caused by water, especially rainfall intensity and duration [3]. It is emphasised that rainfall and its duration are key factors affecting soil erosion on forest roads and skid trails. Soil erosion by water occurs in three stages: detachment of soil particles, transportation by raindrop impact (splash erosion) and overland flow, and eventual deposition of sediments in streams [6]. Additionally, gravity significantly influences soil erosion, as the gradient of forest roads impacts overland flow velocity and, consequently, erosion potential [7,8]. Research indicates that steep gradients speed up overland flow, carrying soil particles downslope. The amount of overland flow depends on precipitation intensity (rainfall and duration) and the ground's infiltration capacity. Compacted soil, often caused by heavy traffic, typically shows low water infiltration rates and reduced hydraulic conductivity, which worsens overland flow and soil erosion, particularly on forest road slopes and skid trail surfaces (Figure 1).

Figure 1. Soil erosion on the slope of a skid trail due to heavy rainfall. (JPSM, 2014).

Raindrops and surface runoff (overland flow) resulting from rainfall can cause four main types of soil erosion: splash, sheet, rill, and gully erosion. These processes are the primary mechanisms responsible for soil loss on forest roads and skid trails [9]. Overland flow significantly contributes to soil erosion in these areas, especially when it becomes channelled, forming rills and gullies (Figure 2). Furthermore, [7] found that sediment production from forest roads mainly originates from the running surface, driven by sheet, rill, and gully erosion. According to [10], soil erosion from forest roads and skid trails is a major contributor to sediment entering streams and rivers. In light of these issues, this study employs a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to identify factors affecting soil erosion on forest roads and skid trails. Additionally, the study aims to assess erosion control techniques to reduce soil erosion in these areas.

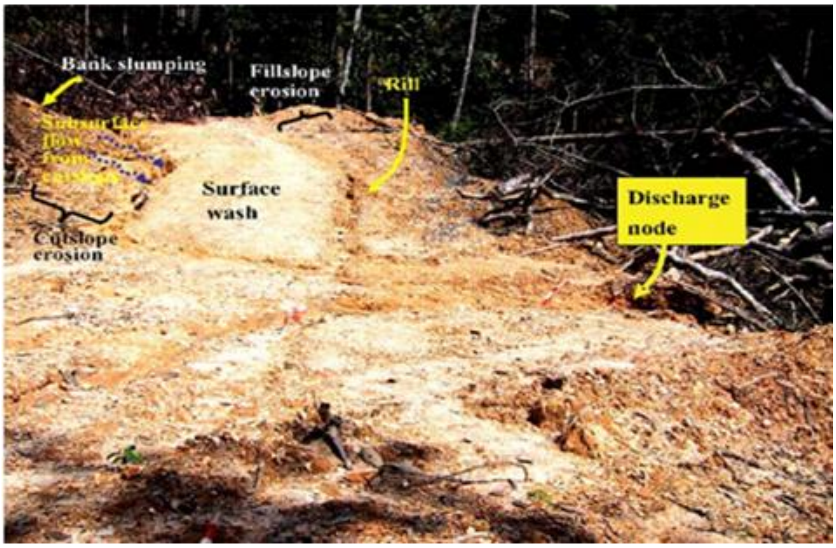

Figure 2. The rill and gully erosion on a forest road in Malaysia. (Sidle et al.,2006).

2. Methodology

2.1. Literature Search

The search for this systematic literature review was conducted manually, using the existing literature, between 3 September 2021 and 25 September 2023. Electronic databases, including Google Scholar and ScienceDirect, were used to retrieve relevant articles based on the following keywords: "[soil erosion, surface runoff, sediment delivery, soil loss, soil erosion control techniques, forest roads, and skid trails]". These databases were selected as the primary sources for literature retrieval because they provide complementary and comprehensive coverage of the interdisciplinary fields relevant to forest roads and skid trails. ScienceDirect offers access to high-quality, peer-reviewed journals in forestry, environmental science, and land management. At the same time, Google Scholar ensures broad cross-publisher coverage, including grey literature and open-access sources not indexed elsewhere.

The selected articles primarily focused on soil erosion on forest roads and skid trails, as well as on erosion control techniques to mitigate and prevent erosion in these areas worldwide. The main objective of this study is to identify the key factors influencing soil erosion on forest roads and skid trails, and to examine effective erosion control techniques to minimise its occurrence.

2.2. Selection Criteria

For the screening process, inclusion and exclusion criteria were applied (Table 1). These criteria encompassed literature type, language, timeline, and study location. Only journal research articles and review articles were considered, while book chapters were excluded. The selection was limited to English-language publications, excluding non-English articles.

The timeline for article selection was set to 2000-2023. The literature search was limited to studies published between 2000 and 2023 because the early 2000s marked a transition in forest operations research toward sustainability-oriented frameworks, including reduced-impact logging and environmental impact assessment. Additionally, studies unrelated to forest roads and skid trails were excluded, as the focus remained strictly on these areas. Based on these inclusion and exclusion criteria, 25 articles from various countries were reviewed.

Table 1. Inclusion and exclusion criteria for articles to be considered for critical appraisal, listed in hierarchical order

Criteria	Inclusion criteria	Exclusion criteria
Literature type	Journal (Research and Review articles)	Book chapters
Language	Articles are written in the English language.	Articles are written in languages other than English.
Timeline	Journal articles published between 2000 to 2023	Journal articles published before the year 2000

2.3. Data Handling, Analysis, and Extraction

After selecting the journal research articles, they were assessed, analysed, and extracted. The extraction process began with a review of each article's abstract, followed by a full-text examination to identify relevant topics and subtopics aligned with the study objectives. A summary of each article was then developed to facilitate extraction.

The literature selection followed the PRISMA framework. A total of 118 records were identified through database searching (Google Scholar, n = 65; Science Direct, n = 53). After duplicate removal, 118 records were screened by title, resulting in the exclusion of book chapters, non-English records, and records published before 2000. Subsequently, 100 full-text articles were assessed for eligibility; 75 were excluded because they did not focus on soil erosion related to forest roads and skid trails or on erosion control techniques. Ultimately, 25 studies were included in the final review.

From these summaries, the articles were further analysed to highlight key points relevant to the study. Emphasising these key points was essential to gaining a deeper understanding of the topic and ensuring a structured, coherent writing process. Figure 3 presents the PRISMA flowchart, outlining the selection process of the reviewed studies.

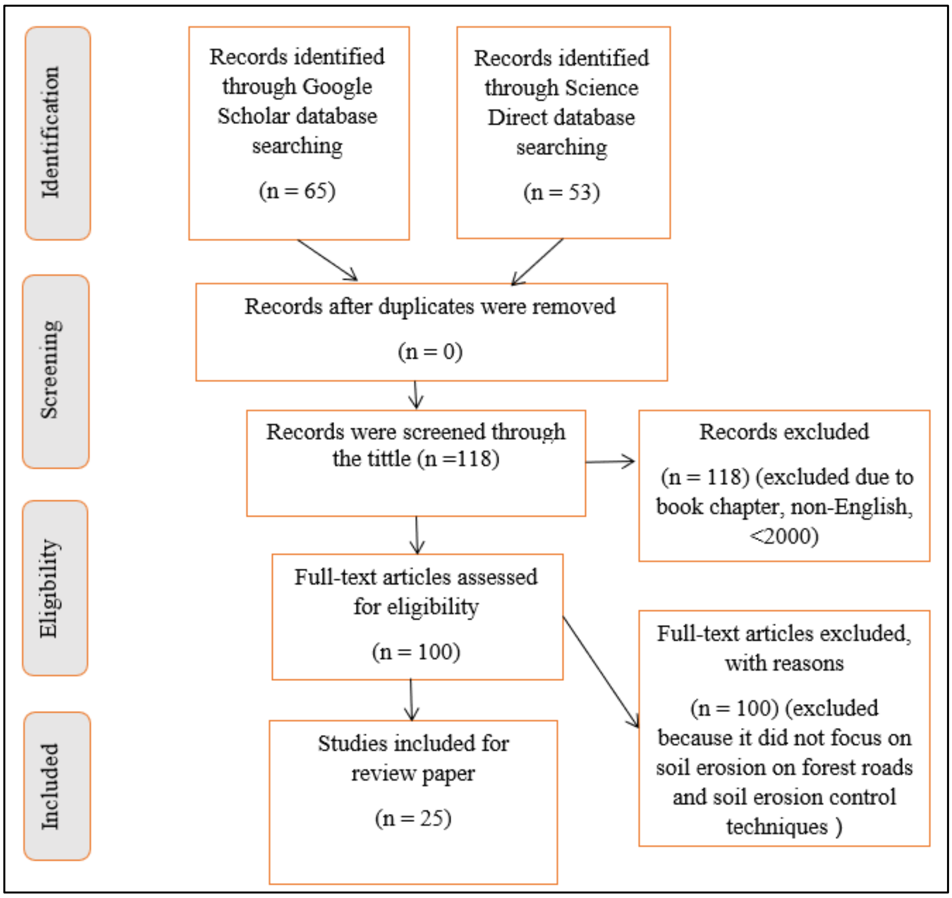

Figure 3. The processes of literature searches based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)

3. Results and Discussion

3.1. General Findings

The findings from the literature search and review are categorised into three main sections: (1) general findings, (2) soil erosion on forest roads and skid trails, (3) factors affecting soil erosion on forest roads and skid trails, and (4) soil erosion control techniques for reducing and preventing erosion on forest roads and skid trails. Although various studies on soil erosion related to forest roads and skid trails were identified, only a small proportion provided extensive literature and detailed information on both erosion processes and control techniques. For this study, 25 published articles from various countries were selected. No restrictions were imposed on the country or territorial criteria for article selection. The chosen studies primarily focused on soil erosion on forest roads and skid trails, as well as on techniques to mitigate and prevent erosion in these areas.

3.2. Soil Erosion on Forest Roads and Skid Trails

For this section, 18 relevant published articles from various countries were identified using the inclusion and exclusion criteria. [11] Identified forest roads and skid trails as major sources of soil erosion and sediment yield. Several factors influence soil erosion in these areas, with precipitation or rainfall among the most significant [3, 10-14]. According to [8], the success of forest road construction largely depends on the region's climate, particularly the rainy season.

Higher rainfall duration and volume significantly increase overland flow velocity, enabling the transport of soil particles from forest roads and skid trails [15]. Studies have reported that forest roads negatively impact soil properties by enhancing overland flow and erosion, leading to significant soil particle transport during prolonged rainy periods and intense rainfall events [16].

Beyond climate, other factors affecting soil erosion on forest roads and skid trails include pavement or surfacing material, traffic intensity, longitudinal slopes, and vegetation cover [10,17,18].

3.3. Factors Affecting Soil Erosion on Forest Roads and Skid Trails

This section critically analyses key factors influencing soil erosion on forest roads and skid trails based on existing literature. The main factors identified include precipitation, surfacing material for forest roads, traffic intensity, longitudinal slopes, and vegetation cover on roadside slopes.

Precipitation is a key factor in soil erosion on forest roads and skid trails, as it causes the detachment, movement, and deposition of soil particles [19, 11-13]. Raindrop impact, known as splash erosion, dislodges soil particles, especially on exposed surfaces such as roadside slopes and roads. Overland flow further accelerates soil transport, intensifying erosion. Ground vegetation is vital in reducing splash erosion by intercepting raindrop energy and increasing infiltration rates. However, on forest roads and skid trails, grading and traffic remove vegetation and compact the soil, decreasing infiltration capacity and boosting sediment transport.

The type of surfacing material also greatly affects erosion rates [20]. According to [11], surfacing material is the total forest floor that is scraped or removed using heavy machinery, without undergoing soil compaction. Primary and secondary forestry roads are usually surfaced with gravel, which effectively minimises soil erosion. In contrast, feeder roads and skid trails often depend on natural forest material, which is more vulnerable to erosion [20]. Studies by [10] and [14] found that natural road surfaces have a higher erosion factor than gravel surfaces, indicating that gravel surfacing can significantly lower erosion risk.

During the forest harvesting phase, constructing forest roads and skid trails with machinery such as excavators and bulldozers often removes vegetation cover. This disturbance can lead to soil erosion along parts of the forest road, including the running surface and roadside slopes (both cut and fill). Traffic levels further contribute to soil erosion and sediment production, as heavy traffic accelerates the breakdown of surface materials [17]. Frequent vehicle movement causes the crushing of surfacing materials, mixing of subgrade soil with surface layers, and displacement of gravel to the roadsides. This process gradually wears down the protective road surface, making it more vulnerable to erosion. Additionally, high traffic volumes result in significant soil compaction, reducing infiltration rates and promoting Horton overland flow, even during moderate rainfall events [21]. However, research by [18] indicates that skid trails with low traffic experience minimal soil disturbance, preserving organic matter and reducing erosion.

Slope gradient is another essential factor affecting erosion, as steeper slopes on forest roads and skid trails increase overland flow velocity and sediment transport capacity. Studies by [4,21] show that steeper slopes lead to higher erosion rates, whereas gentler slopes have lower erosion rates due to lower water velocity and reduced soil detachment.

3.4. Soil Erosion Control Techniques for Reducing and Preventing Erosion on Forest Roads and Skid Trails.

A total of seven articles from various countries were selected for this section based on the inclusion and exclusion criteria. Soil erosion control techniques for forest roads and skid trails primarily focus on managing the key factors that contribute to soil erosion. These techniques aim to reduce the severity and extent of erosion, minimising nutrient loss from the site and preventing sediment from forest roads from reaching streams [4].

Vegetation cover on roadside slopes also plays a vital role in controlling erosion [10]. Low vegetation cover results in decreased soil organic matter, reduced surface roughness, poorer soil structure, and lower infiltration rates, all of which increase erosion risks [22-24]. Vegetation helps stabilise slopes, reduce raindrop impact, and improve soil stability [3,14]. Establishing vegetation on steep slopes is essential for preventing erosion, especially during heavy rainfall. However, the impact of forest roads on soil erosion can be mitigated by planting vegetation on roadside slopes. [4] Found that sediment production from forest roads decreased as vegetation cover increased, confirming that treatments with higher vegetation cover percentages effectively reduce and prevent sediment production. Additionally, applying slash and wood chips to cut-and-fill slopes is effective in controlling soil erosion [25]. Moreover, using high-quality surfacing materials, such as gravel, is an effective strategy for minimising soil erosion across the entire forest road surface. Gravel is particularly suitable for surfacing forest roads as it improves stability, reduces slipperiness, and prevents surface failure [11]. Another effective practice involves installing water diversions, such as water bars, on skid trails after skidding operations are complete. These structures have been shown to reduce and control overland flow volume and soil erosion significantly [19,4,26].

4. Conclusion

Research indicates that various factors contribute to soil erosion on forest roads and skid trails. Among these, raindrop impact and rainfall-induced overland flow are the most significant erosion mechanisms. Water-induced erosion dislodges and transports soil particles from critical parts of forest roads, such as the running surface and roadside slopes (cut-and-fill slopes). Besides precipitation, other factors, such as the type of road surfacing material, machinery traffic, longitudinal slope, and vegetation cover on roadside slopes, also affect the likelihood and severity of soil erosion.

Research conducted worldwide has identified forest roads as a major source of sediment in stream water. Soil erosion from the road surface, roadside slopes, and side ditches increases sediment loads, negatively affecting water quality and aquatic ecosystems. Newly constructed forest roads often feature exposed, unstable cut-and-fill slopes, making them highly vulnerable to erosion. Establishing vegetation on roadside slopes and retaining logging residues after road construction can help stabilise the soil, reducing the impact of raindrops and overland flow. Additionally, using gravel as a surfacing material can minimise the formation of rills and gullies, thereby decreasing sediment yield and delivery to streams. Implementing water-diversion structures, such as water bars (also known as water shelves), on skid trails after logging operations can further reduce sediment transport by encouraging sediment deposition before runoff reaches streams.

The use of effective soil erosion control techniques on forest roads and skid trails is crucial for managing key erosion factors. These measures primarily aim to minimise the severity and extent of erosion, preventing sediment from entering streams and rivers. Consequently, the findings of this study are valuable for forest management, offering insights into the sources of soil erosion and identifying strategies to reduce its impact. By addressing the contributing factors, forest managers can effectively lower erosion severity and prevent excessive sedimentation in nearby water bodies.

Acknowledgements

We are grateful to all the authors for their contributions towards preparing this manuscript. Thank you to the reviewers for helping to improve this writing.

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