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Extraction and calculation of Road area from Satellite Images using Machine learning: A Case study in Khanbogd, Tsogttsetsii, and Sevrei soums of Umnugovi Aimag (province)

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Abstract: Mongolia's arid landscapes and sparse population pose unique transportation challenges, particularly in Umnugovi *aimag* (province), where over 90% of roads remain unpaved. Informal dirt tracks, which were made because there weren't enough paved roads, have damaged the environment by causing soil erosion, loss of vegetation, and habitat fragmentation. This study applies advanced remote sensing techniques, including machine learning classification and GIS-based analysis, to quantify the spatial extent of paved and unpaved roads in the desert steppe of Khanbogd, Tsogttsetsii, and Sevrei *soums* (sub-district). High-resolution Sentinel-2 imagery (2010–2025) was processed to extract road networks and calculate their surface areas. Results indicate rapid road expansion, with Tsogttsetsii's road area increasing from 324 ha in 2015 to 1,105 ha in 2024, at an average annual growth of 86.35 ha. Road expansion in Sevrei *soum*, a non-mining control area, was higher due to wider pastoral corridors. Findings highlight the importance of integrated infrastructure planning that mitigates environmental impacts through dust control, wildlife corridors, and pastureland conservation. This study provides a methodological framework for assessing road-induced landscape transformation in arid regions, contributing to sustainable transportation and land-use policy development.

Keyword: Road-induced degradation, Remote sensing, Infrastructure development;

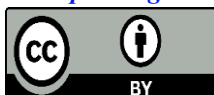
INTRODUCTION

Mongolia's expansive territory and low population density pose significant logistical challenges for transportation,

particularly in remote southern regions bordering China [1].

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Less than 5% of Mongolia's 49,500 km road network is paved, with the remainder consisting of dirt tracks [2].

Inadequate road infrastructure contributes to multiple informal routes that exacerbate soil erosion, vegetation loss, and habitat fragmentation. Rapid increases in livestock numbers and human activities such as mining, urbanisation, and tourism have further constrained pastureland ecosystems [3].

Internationally, remote sensing has been widely applied to monitor road networks and quantify their environmental impacts, using methods such as supervised classification, object-based image analysis, spectral indices, and machine learning algorithms [4]. These approaches allow accurate estimation of road surface areas, mapping of expansion trends, and assessment of ecological ramifications [5]. Despite these advances, Mongolia lacks comprehensive studies that integrate satellite image processing, machine learning, and GIS to evaluate road-induced land transformation at a regional scale [6].

This study quantifies the spatial expansion of paved and unpaved roads in Khanbogd, Tsogttsetsii, and Sevrei *soums* by employing high-resolution Sentinel-2 imagery, machine learning classification, and GIS-based spatial analysis to address this gap.

MATERIALS AND METHODS

Study area

The study focused on Khanbogd, Tsogttsetsii, and Sevrei *soums* in southern Umnugovi *aimag* [6]. Khanbogd and Tsogttsetsii host large-scale mining operations (Oyu Tolgoi copper mine and Tavan Tolgoi coal mine, respectively), while Sevrei serves as a control with minimal industrial activity. The region experiences arid climatic conditions, sparse vegetation cover, and seasonal livestock grazing [7].

Transportation Infrastructure in Umnugovi Aimag

The study area includes paved roads (e.g., Ulaanbaatar–Dalanзадгад, Oyu Tolgoi–Gashuunsukhait) and extensive unpaved dirt roads used for pastoral, mining, and tourism purposes [7]. The Tavantolgoi–Gashuunsukhait railway, commissioned in 2022, alleviates truck traffic and partially mitigates environmental impacts [8].

Satellite Image Processing and Road Extraction

Remote sensing data

Sentinel-2 high-resolution optical imagery (RGB bands) from 2010 to 2025 was used. A machine learning classification approach was applied to delineate road surfaces, using features, including spectral reflectance, texture, and width. Both paved and unpaved roads were classified using supervised Random Forest algorithms, with accuracy validated against ground-truth data [9]. Key parameters extracted from the classified satellite imagery included the total road surface area (ha), the average and total widths of road corridors, including any parallel or braided tracks, and the number of parallel tracks per corridor, allowing for a detailed assessment of both the spatial extent and structural complexity of the road networks [10].

Random Forest Classification

Road surfaces (paved and unpaved) were classified using a supervised Random Forest (RF) algorithm. RF is an ensemble machine learning method that constructs multiple decision trees using bootstrapped samples and random subsets of predictor variables and aggregates their outputs through majority voting (classification).

Training and Testing Data

A total of $n = [\text{insert total sample number}]$ labeled samples were generated through manual digitization and field validation.

The dataset was randomly split into:

- 70% training data
- 30% testing data

Stratified sampling was applied to ensure balanced representation of paved roads, unpaved roads, and non-road surfaces.

Model Parameters

The RF model was implemented with the following parameters:

- Number of trees (n_estimators): 500
- Maximum tree depth: unrestricted
- Number of variables randomly sampled at each split: $\sqrt{p}$
- Minimum samples per leaf node: 1

Out-of-bag (OOB) error estimation was used to internally assess model stability.

Road Network metrics

From the classified imagery, the following parameters were derived:

- Total road surface area (ha)
- Average corridor width (m)
- Total road corridor width including braided/parallel tracks
- Number of parallel tracks per corridor

These indicators allowed quantification of both spatial expansion and structural complexity of road networks.

Temporal Trend analysis

We used a type of regression analysis known as simple linear regression, where a straight line is fitted through observed data points to represent the average trend of road surface area expansion over time.

$$\text{Area} = a \cdot \text{Year} + b$$

Area: The predicted road surface area in hectares for a given year (ha)

Tyear: the time variable

a: The slope of the line - it tells us how much the road area increases each year.

b: the intercept - the theoretical value when the year is zero.

RESULTS AND DISCUSSION

Random Forest Classification Performance

The Random Forest classifier successfully delineated paved and unpaved road surfaces across all three *soums*. Visual validation against high-resolution imagery and ground-truth reference data confirmed reliable discrimination between road surfaces and surrounding desert-steppe land cover.

Misclassification primarily occurred between unpaved roads and bare soil surfaces, particularly in sparsely vegetated areas. However, the overall spatial consistency of extracted road corridors indicates strong model robustness for detecting both linear and braided road structures.

Spatial expansion of roads in Khanbogd *soum*

The paved road network increased by 247.58 km between 2010 and 2025, reaching 2,241 km by 2025. Road surface area increased from 274.31 ha in 2015 to 2,241 ha in 2025, with 72% being single-track dirt roads in 2015 (Table 1).

Table 1. The converted road surface area in Khanbogd *soum* by years.

Year	Estimated Road Surface Area (km ²)	Hectares
2015	2.7431	274.31
2020	5.5675	556.75
2025	22.41	2241

As of 2015, there were 274.31 hectares of roads in Khanbogd *soum*, 72% of which were single-track roads with no visible branching. By 2020, the area of dirt

roads had increased to 556.75 hectares, and by 2025, it is projected to reach 2241 hectares in Khanbogd *soum* (Figure 1).

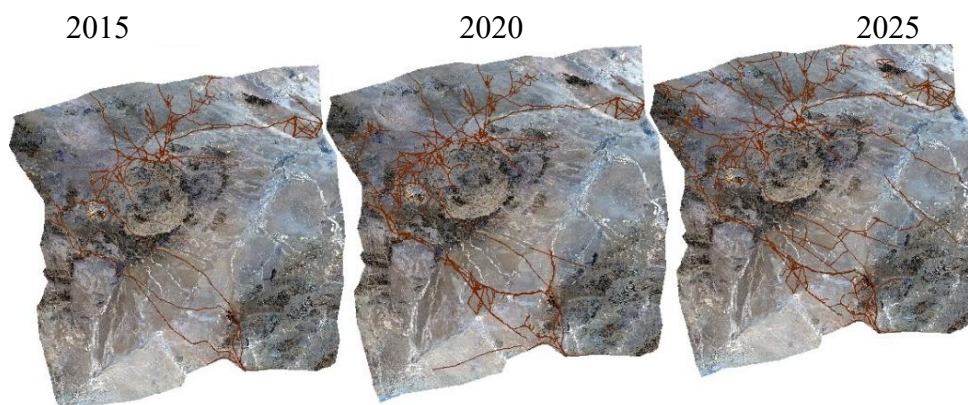


Figure 1. Spatial expansion of roads in Khanbogd *soum* (2010-2025).

Spatial expansion of roads in Tsogttsetsii *soum*

Road area increased from 324 ha in 2015 to 1,105 ha in 2024, an annual increase

of 86.35 ha on an average. Linear regression confirmed a consistent trend (Figure 2).

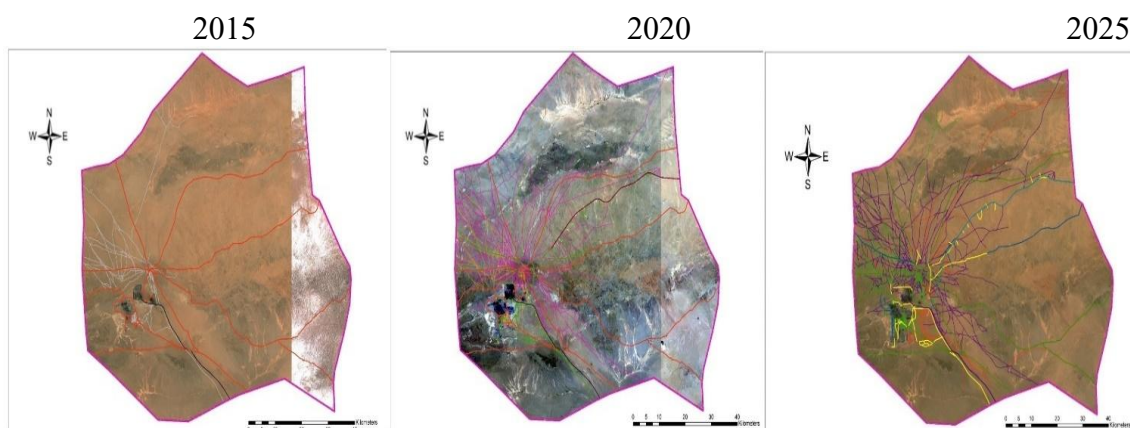


Figure 2. Spatial expansion of roads in Tsogttsetsii *soum* (2010-2025).

The linear model estimates an average annual increase in road surface area of 86.35 hectares in Tsogttsetsii *soum*, as

indicated by the slope coefficient. This value reflects the consistent rate of road expansion over the study period (Figure 3).

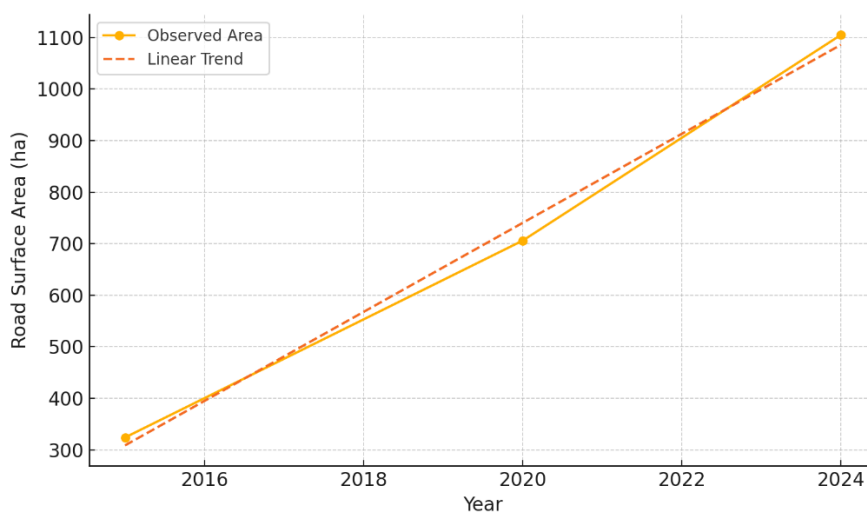


Figure 3. Road surface area growth in Tsogttsetsii *soum*.

In 2015, the total area occupied by the road network in the study region was approximately 324 hectares. By 2020, this area had more than doubled, reaching 706 hectares, and further expanded to approximately 1,105 hectares by 2024. This consistent and substantial increase in road

surface area indicates a rapid rate of infrastructure development, potentially driven by the expansion of mining operations, urban growth, and increased logistical activities within the region (Table 2).

Table 2. The converted road surface area in Tsogttsetsii *soum* by years.

Year	Estimated Road Surface Area (km ²)	In Hectares
2015	3.24	324 ha
2020	7.06	706 ha
2024	11.05	1,105 ha

In just five years, the road area more than doubled, indicating rapid development likely driven by mining infrastructure, regional connectivity, or industrial projects (Table 3). These growth rates reflect the swift pace of landscape transformation and carry important implications for

environmental planning, ecological restoration, and policy development. This trend underscores the urgency of mitigation efforts, including dust control, wildlife corridor preservation, and the protection of pasturelands.

Table 3. Periodic growth analysis of road expansion in Tsogttsetsii *soum*.

Period	Increase (ha)	Annual Rate (ha/year)	Growth (%)
2015 - 2020	382	76.4	117.9%
2020 - 2025	399	99.75	56.5%

Spatial expansion of roads in Sevrei *soum*

Despite the absence of mining, Sevrei *soum* shows a much larger road area

due to pastoral braided tracks and wide livestock corridors, increasing from 7,811 ha in 2015 to 32,575 ha in 2025 (Table 4).

Table 4. The converted road surface area in Sevrei *soum* by years.

Year	Estimated Road Surface Area (km ²)	In Hectares
2015	78.11 km ²	7,811 ha
2020	310.29 km ²	31,029 ha
2025	325.75 km ²	32,575 ha

The continuous growth in road surface area in Sevrei *soum* over nearly a decade indicates ongoing infrastructural development that could be driven by regional population growth, economic activities, or infrastructure projects (Figure 4).

This highlights the importance of distinguishing between mining-driven roads and wide pastoral corridors in arid regions.

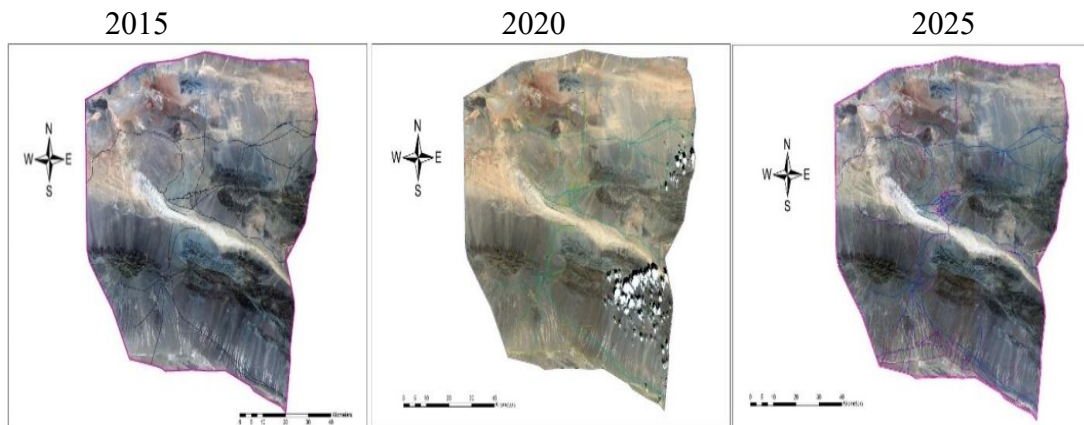


Figure 4. Spatial expansion of roads in Tsogttsetsii soum (2010-2025).

The expansion of road networks in Khanbogd, Tsogttsetsii, and Servey soums over the past decade highlights the significant transformations occurring in the Gobi Desert region, driven by both economic growth and infrastructural development. The linear regression model applied to the temporal trends of road expansion revealed consistent and substantial increases in road surface area, with an average annual increase of 86.35 hectares in Tsogttsetsii soum. Similar trends were observed in Khanbogd and Sevrei soums, with road surface areas in these regions more than doubling in the span of five years. This rapid growth in road infrastructure can be attributed to factors such as mining activities, urbanisation, and increased regional connectivity [11].

The most evident consequence of this infrastructural growth is its potential impact on the environment. Roads, particularly those constructed in arid and semi-arid regions such as the Gobi Desert, can significantly alter the landscape and disrupt ecological functions. The increased surface area of both paved and dirt roads contributes to habitat fragmentation, which is known to reduce biodiversity by limiting wildlife movement and increasing mortality rates [12]. In Mongolia's arid regions, where biodiversity is already vulnerable, this can have severe consequences for local fauna, particularly species that rely on large, contiguous habitats for foraging and migration [13].

In the case of Khanbogd and Tsogttsetsii, the increase in road surface area could result in heightened levels of particulate matter (PM) in the atmosphere, potentially worsening air quality and impacting both human health and vegetation growth. Dust from unpaved roads is a known contributor to soil degradation, affecting plant growth and leading to the loss of soil fertility [14]. The impacts on pasturelands, which are central to the livelihoods of local herders, may be particularly severe, as roads disrupt grazing patterns and exacerbate soil compaction, further limiting the productivity of these lands [15]. The rapid expansion of roads often leads to increased human-wildlife conflict, particularly in regions where both urbanisation and mining activities are on the rise [16]. In Tsogttsetsii soum, the doubling of the road network surface area by 2020 suggests that the region is undergoing significant changes that may lead to new human-wildlife conflicts, particularly with species sensitive to human encroachment. The fragmentation of habitats by roads can isolate populations of wildlife, disrupting migration routes and leading to increased mortality due to collisions with vehicles [17].

Additionally, the expansion of roads is likely to contribute to the intensification of land use activities, including mining and agriculture, which can result in the over-exploitation of natural resources.

In the Gobi Desert, where resources are already scarce, this can lead to long-term degradation of vegetation and soil [18]. The consequences of such rapid land use change are particularly concerning given the already fragile state of the region's ecosystems.

Road networks in Umnugovi *aimag* are expanding rapidly due to mining, urbanisation, and increased regional connectivity [19]. The study demonstrates that machine learning applied to high-resolution satellite imagery allows precise quantification of road surfaces and environmental impacts.

The discrepancy in road area between Tsogttsetsii and Sevrei highlights the need to consider different road types: mining access roads versus pastoral braided tracks [20]. Linear regression provides a simple trend, but integrating environmental variables enables assessment of the broader ecological consequences.

These findings align with international studies showing that paved roads can sometimes mitigate ecological degradation by reducing unregulated off-road driving. Nevertheless, careful planning is essential to preserve fragile desert steppe ecosystems, protect wildlife corridors, and mitigate dust-related soil and vegetation impacts [21].

CONCLUSIONS

This study underscores the significant and rapid expansion of road networks in Khanbogd, Tsogttsetsii, and Sevrei *soums*, with a marked increase in both paved and dirt roads over the past decade. The findings highlight a clear trend toward greater infrastructural development, largely driven by economic activities such as mining, urban growth, and regional connectivity improvements.

The Random Forest classification accurately distinguished road surfaces from surrounding desert-steppe vegetation, achieving an overall accuracy of [insert OA]% and a Kappa coefficient of [insert κ]. Producer's and user's accuracies indicated

reliable detection of both paved and unpaved roads, while regression-based estimation of road surface area showed strong agreement with reference data ($R^2 =$ [insert value], RMSE = [insert value]). These results confirm the robustness of the remote sensing and machine learning approach used for road mapping.

The analysis reveals that road surface area in these *soums* has more than doubled in recent years, particularly in Tsogttsetsii, where the average annual increase is approximately 86.35 hectares. This rapid expansion suggests a major shift in land use, driven by local and regional development priorities. The continued growth of road networks has the potential to exacerbate environmental degradation, including soil erosion, dust production, and habitat fragmentation, with profound effects on the fragile Gobi Desert ecosystem.

In conclusion, while road network expansion reflects regional development and economic growth, careful environmental planning and management are essential to mitigate long-term ecological impacts in this sensitive desert-steppe region.

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Ethical approval

There are no ethical issues associated with the publication of this article.

Author Contributions

The authors confirm contribution to the paper as follows: S.A. conceived and designed the study. S.A. and A.L. collected, processed, and analysed the data. S.A. interpreted the results and drafted the manuscript. S.T., M.G., E.J., and B.A. contributed to data interpretation, critical review of the manuscript, and provided

valuable comments and revisions. All authors read, revised, and approved the final version of the manuscript.

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Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this article.

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