

Satellite-Based Forest Cover Change in Northern Mongolia

Erdenetuya Boldbaatar^{1,#}, Piotr Wężyk², Wojciech Krawczyk³

¹ Department of Forest Resources Management, University of Agriculture in Krakow, Krakow, 31-120, Poland, erdenetuya.boldbaatar@student.urk.edu.pl

² Department of Forest Resources Management, University of Agriculture in Krakow, Krakow, 31-120, Poland, piotr.wezyk@urk.edu.pl

³ Department of Forest Resources Management, University of Agriculture in Krakow, Krakow, 31-120, Poland, wojciech.krawczyk@student.urk.edu.pl

Abstract

Monitoring forest area change is for understanding ecosystem dynamics and supporting sustainable management of Mongolia's boreal forests, which form the southern fringe of the Siberian taiga and face increasing pressures from wildfires and logging. This study assesses forest cover dynamics in northern Mongolia using multi-temporal Sentinel-2 satellite imagery collected from 2020 to 2024. Forest and non-forest areas were classified with a Random Forest algorithm, producing consistent annual maps to detect spatial and changes. Results show that forest area varied from 5.010 km² in 2020 to a maximum of 5.235 km² in 2023, representing 67,8–70,9% of the region's 7.386 km². Among forest types, Manchurian birch (*Betula platyphylla* Sukaczew.) accounted for the largest area (1.900–2.128 km²), followed by Siberian larch (*Larix sibirica* Ledeb.) (1.178–1.614 km²), Scotch pine (*Pinus sylvestris* L.) (602–770 km²), Siberian pine (*Pinus sibirica* Ledeb.) (590–685 km²), and Siberian spruce (*Picea obovata* Ledeb.) (243–281 km²). The approach achieved high overall classification accuracy (96,19%) and kappa coefficient (0,949), confirming its reliability for monitoring. The study underscores the importance of temporal spectral information in detecting forest change and supports the use of Sentinel-2 as a cost-effective, large-scale tool for forest management and restoration planning in northern Mongolia.

Keywords: Satellite imagery, forest cover change, boreal forests, Random Forest classification, northern Mongolia

Introduction

Comprehensive and spatially explicit information on forest cover is essential for detecting disturbance dynamics, supporting sustainable forest management, and evaluating restoration efforts in boreal ecosystems (Achard et al. 2014; Paquette and Messier 2011). In Mongolia, forest statistics vary widely across national and international sources due to differences in forest definitions, inventory methods, and reporting cycles (Food and Agriculture Organization of the United Nations (FAO) 2021; Curtis et al. 2018; Hansen et al. 2013). These inconsistencies are particularly pronounced in northern Mongolia, where remote terrain, limited accessibility, and frequent wildfires constrain the effectiveness and timely updating of conventional field-based inventories.

Recent advances in satellite remote sensing and machine learning provide new opportunities for large-scale forest monitoring. Multi-temporal Sentinel-2 (ESA) imagery has proven highly effective in capturing annual forest dynamics and seasonal spectral variations, which are crucial for accurate classification of forested and non-forested areas (Immitzer, Vuolo, and Atzberger 2016; Persson, Lindberg, and Reese 2018; Fassnacht et al. 2016). Temporal variation in spectral reflectance allows the detection of changes in forest extent and composition over multiple years, offering a cost-effective alternative to traditional ground surveys.

This study evaluates forest cover change in northern Mongolia between 2020 and 2024 using Sentinel-2 time-series imagery and a Random Forest classification approach. The research addresses three main questions:

1. How accurately forest extent can be mapped annually using Sentinel-2 imagery?
2. What are the spatial and temporal patterns of forest cover change across the five-year period?
3. How effective is Sentinel-2 data for routine forest monitoring in wildfire- and disturbance-prone boreal landscapes?

The study quantifies annual forest and non-forest areas, examines changes in dominant forest types, and assesses the applicability of multi-temporal Sentinel-2 data for large-scale forest management and restoration assessment in northern Mongolia.

Data and Method

Study area

The study area is located in northern Mongolia, covering parts of Selenge, Darkhan-Uul, and Tuv provinces, about 300 km north of Ulaanbaatar (48°51'N, 106°27'E) (Fig. 1). It spans approximately 7.386 km² within the forest–steppe ecotone at the southern boundary of the Siberian boreal taiga and is characterized by varied terrain and a continental climate (Dulamsuren et al. 2010).

Forests occupy 13,4% of the area and are dominated by Scots pine (*Pinus sylvestris* L.; 28,9%), Manchurian birch (*Betula platyphylla* Sukaczew.; 27%), Siberian larch (*Larix sibirica* Ledeb.; 25,9%), Siberian pine (*Pinus sibirica* Ledeb.; 15,2%), and Siberian spruce (*Picea obovata* Ledeb.; 0,7%; Environmental Information Center, 2025). Elevation ranges from 700 to 1.600 m, with mean annual temperatures between −4 °C and +2 °C and annual precipitation of 250–400 mm.

Wildfires caused 96% of tree cover loss from 2001 to 2024. At the same time, forest area expanded by 40.018 ha between 2000 and 2020, accounting for 51% of Mongolia's total forest restoration.

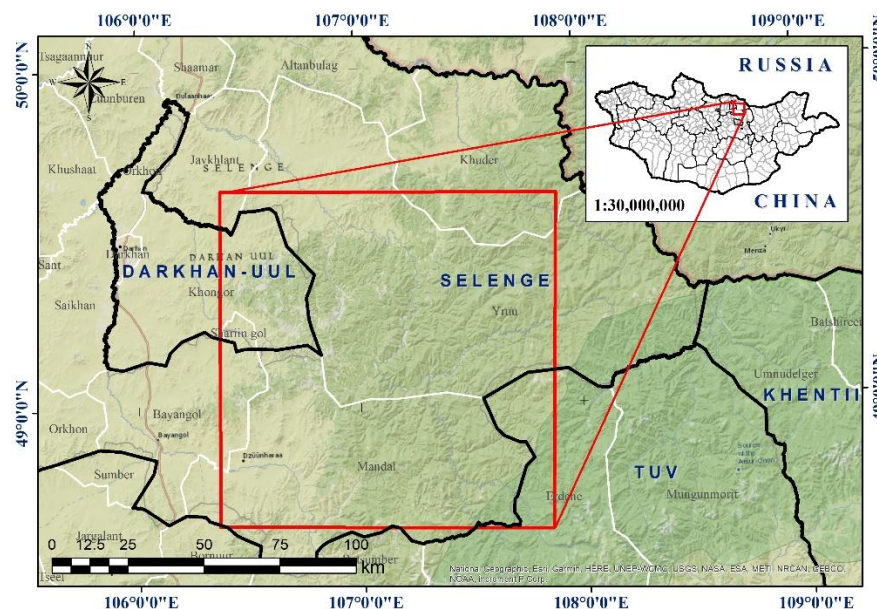


Fig 1. Study area: Selenge (Mandal, Bayangol, Javkhlant, Yruu, Khuder), Darkhan-Uul (Khongor, Shariin gol), and Tuv (Erdene) provinces (Mongolian environmental database).

Data

To evaluate yearly forest cover dynamics, five cloudless (<10% cloud cover) Sentinel-2 Level 2A (ESA) images from 2020 to 2024 were selected during the peak growing season (July–August), ensuring high-quality spectral data for accurate forest assessment. The Sentinel-2 constellation (S-2A, S-2B and S-2C) provides 13 spectral bands with spatial resolutions of 10–60 meters and a five-day revisit cycle, enabling multi-temporal analysis of vegetation dynamics. A total of five cloud-free scenes were compiled to cover the full 7.386 km² study area (European Space Agency 2024).

For classification, polygons representing Areas of Interest (AOIs) were generated from the Mongolian Forest Inventory (Government implementing agency Forestry Department 2019) and further refined using Sentinel-2 color-infrared composites at 10 m resolution to delineate homogeneous forest stands. The analysis prioritized quantifying forest extent and detecting interannual changes, rather than species-level mapping. In total, 202 AOIs encompassing 2.231 ha were used, with 32–51 samples per forest type and mean stand sizes ranging from 5,25 to 15,51 ha. AOIs were divided into training (70%) and validation (30%) datasets using spatially stratified sampling to maintain statistical representativeness and minimize spatial autocorrelation.

This methodology facilitated precise assessment of annual forest cover dynamics between 2020 and 2024, capturing both forest losses and gains. The approach provides a robust, reproducible framework for monitoring boreal forest changes and supports evidence-based management and restoration strategies in northern Mongolia.

Data Processing

1. Satellite Data Pre-processing

Sentinel-2 Level 2A images from 2020 to 2024 were pre-processed to ensure data quality and consistency for forest cover analysis. Spectral bands with 20 m and 60 m spatial resolution were resampled to 10 m to standardize pixel size across all images. Digital numbers (DN) were converted to top-of-canopy reflectance following ESA Level-2A guidelines (European Space Agency 2024). Cloud and shadow pixels were identified and masked using standard cloud masks. Additionally, forested areas were delineated using the PALSAR-2 FNF4 dataset through Google Earth Engine, producing a consistent and cloud-free forest layer suitable for subsequent classification and forest change detection analyses (Global Forest Watch, 2024; Hansen et al., 2013).

2. Generation of Training and Validation Samples

Vector polygons representing forested and non-forested areas were derived from the Mongolian Forest Inventory (Government implementing agency Forestry Department 2019) and rasterized to match the 10 m Sentinel-2 resolution. Single spectral bands, combined with environmental covariates such as elevation and climatic variables (mean annual temperature and precipitation), were used as predictors. A total of 222.870 sample points were generated, of which 70% were randomly assigned to the training set (156.012 samples) and 30% to the validation set (66.858 samples). Forest samples accounted for 94,9% of the total, while non-forest samples represented 5,1% (Congalton and Green 2019).

3. Random Forest Classification

Forest cover classification was performed using the Random Forest algorithm (Belgiu and Drăgu 2016; Breiman 2001). Model hyperparameters, including the number of trees ($T = 500$) and the number of variables considered at each split (m_{try}), were optimized via 10-fold cross-

validation. Out-of-bag (OOB) error estimates were used to assess model stability and performance.

4. Field Validation and Accuracy Assessment

Test AOIs were used to generate a confusion matrix, from which Overall Accuracy (OA) and Cohen's Kappa (κ) were derived (Congalton and Green 2019):

$$OA = \frac{\sum n_{ii}}{N}, \kappa = \frac{P_o - P_e}{1 - P_e} \quad (1,2)$$

These metrics provided both overall and class-specific assessments of Sentinel-2 Forest cover classification, ensuring robust evaluation of interannual forest change dynamics in northern Mongolia.

Results

Overall, the total forest area varied between 5.010 km² in 2020 and 5.111 km² in 2024, indicating measurable interannual fluctuations in forest extent. These changes reflect a balance between gains and losses across the region, likely driven by wildfire disturbance and regeneration processes. Sentinel-2 time-series data proved effective for detecting these spatial and temporal dynamics in northern Mongolia's boreal forests. Species-level differences were observed but mainly support the overall assessment of forest extent change.

Our analysis indicates that Manchurian birch (*Betula platyphylla* Sukaczew.) is the dominant tree species across the study area (Fig. 2). According to Sentinel-2 observations, its forested area decreased from 2.188 km² in 2020 to 2.008 km² in 2024, highlighting a gradual reduction of approximately 180 km² over the five-year period. Siberian larch (*Larix sibirica* Ledeb.) occupied the second-largest share, showing an increase from 1.178 km² in 2020 to 1.368 km² in 2024, reflecting a net gain of 190 km². Scotch pine (*Pinus sylvestris* L.) showed moderate fluctuations, ranging between 602 km² and 770 km², while Siberian pine (*Pinus sibirica* Ledeb.) increased from 590 km² to 685 km² over the same period. Siberian spruce (*Picea obovata* Ledeb.) remained relatively stable, ranging from 243 km² to 281 km².

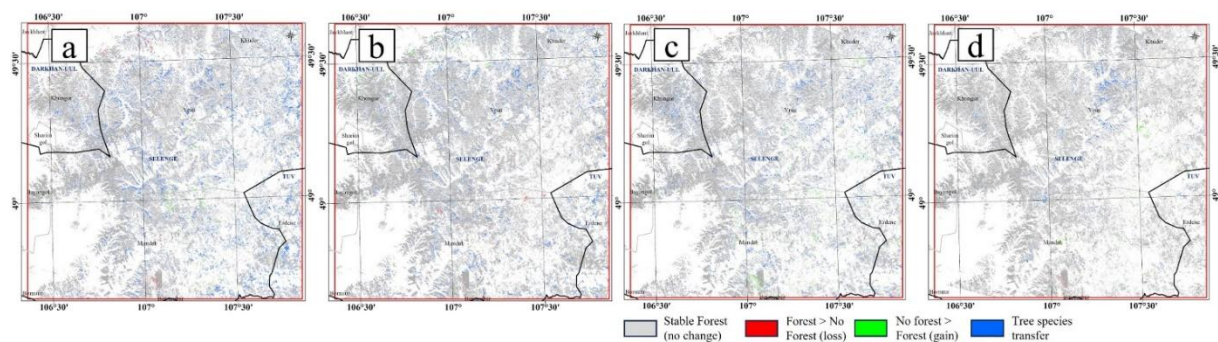


Fig 2. Forest extent classification change: a – from 2020 to 2021; b – from 2021 to 2022; c – from 2022 to 2023; d – from 2023 to 2024.

Sentinel-2 data reveal Manchurian birch (*Betula platyphylla* Sukaczew.) as the dominant species, with Siberian larch (*Larix sibirica* Ledeb.) and Siberian pine (*Pinus sibirica* Ledeb.) expanding over 2020–2024, while Scotch pine (*Pinus sylvestris* L.) and Siberian spruce (*Picea obovata* Ledeb.) remain stable (Table 1). Total forest area varied slightly between 5.010 km² (2020) and 5.235 km² (2023), highlighting Sentinel-2's capacity to capture annual forest dynamics and support sustainable forest management in northern Mongolia.

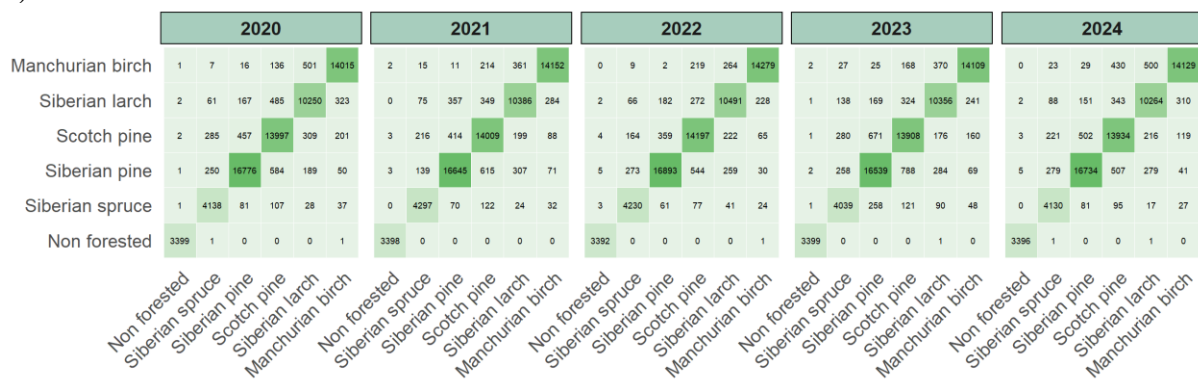
Table 1. Forest cover distribution in northern Mongolia (Sentinel-2, 2020–2024)

Year	Manchurian birch (<i>Betula platyphylla</i> Sukaczev.) (km ²)	Siberian larch (<i>Larix sibirica</i> Ledeb.) (km ²)	Scotch pine (<i>Pinus sylvestris</i> L.) (km ²)	Siberian pine (<i>Pinus sibirica</i> Ledeb.) (km ²)	Siberian spruce (<i>Picea obovata</i> Ledeb.) (km ²)	Total Forest (km ²)	% Forest	% Non-Forest & Other	Total Area (km ²)
21 Aug 2020	2.188,5	1.178,1	736,0	664,1	243,4	5.010,0	67,8	32,2	7.386,3
30 Aug 2021	1.900,7	1.614,3	692,5	626,5	280,8	5.114,7	69,2	30,8	7.386,3
30 Aug 2022	2.107,1	1.600,3	602,4	589,7	243,0	5.142,4	69,6	30,4	7.386,3
30 Aug 2023	2.127,3	1.555,1	699,0	612,5	241,7	5.235,5	70,9	29,1	7.386,3
24 Aug 2024	2.008,0	1.367,6	769,6	685,1	281,0	5.111,3	69,2	30,8	7.386,3

Classification validation

The forest tree species classification based on Sentinel-2 imagery showed high overall accuracy, ranging from 0,939 to 0,962, with Kappa values between 0,924 and 0,949. Classification performance was particularly strong for Manchurian birch (*Betula platyphylla* Sukaczev.), Scotch pine (*Pinus sylvestris* L.), and Siberian pine (*Pinus sibirica* Ledeb.), while Siberian spruce (*Picea obovata* Ledeb.) exhibited slightly lower sensitivity (0.867–0.917) due to spectral similarities with other conifer species. Misclassification occurred mainly among Siberian larch (*Larix sibirica* Ledeb.), Scotch pine, and Siberian pine.

The classified forest areas were further compared with the 2019 forest inventory to assess changes in forest composition and area coverage. Sentinel-2 results revealed that Manchurian birch (*Betula platyphylla* Sukaczev.) decreased from 2.188 km² in 2020 to 2.008 km² in 2024, while Siberian larch (*Larix sibirica* Ledeb.) and Siberian pine (*Pinus sibirica* Ledeb.) expanded over the same period. Scotch pine and Siberian spruce remained relatively stable (Fig. 3, Table 2).

**Fig 3.** Confusion Matrices for Forest Tree cover and non-forest (2020–2024).

Comparison with the 2019 forest inventory shows substantial shifts: Manchurian birch (*Betula platyphylla* Sukaczev.) declined from 2.774 km² (53,8%) to 2.008 km² (39,3%) in 2024, Siberian larch (*Larix sibirica* Ledeb.) increased by 455 km² (+49,9%), Siberian pine (*Pinus*

sibirica Ledeb.) grew by 168 km² (+32,4%), and Siberian spruce (*Picea obovata* Ledeb.) expanded most dramatically, from 51 km² (1,0%) to 281 km² (5,5%).

Table 2. Forest Cover Changes in northern Mongolia (2019–2024, km² and percent).

Year / Class	Manchurian birch (<i>Betula platyphylla</i> Sukaczew.)	Siberian larch (<i>Larix sibirica</i> Ledeb.)	Scotch pine (<i>Pinus sibirica</i> Ledeb.)	Siberian pine (<i>Picea obovata</i> Ledeb.)	Siberian spruce	Total Forest
2019 Inventory (km ²)	2.773,9	912,3	902,7	517,4	50,9	5.157,2
Sentinel-2 2020 (km ²)	2.188,5	1.178,1	735,9	664,1	243,4	5.010,0
Change 2020 vs 2019 (km ²)	-585,4	+265,8	-166,8	+146,7	+192,5	-147,2
Change 2020 vs 2019 (%)	-21,1	+29,1	-18,5	+28,4	+378,2	-2,9
Sentinel-2 2024 (km ²)	2.008,0	1.367,6	769,6	685,1	281,0	5.111,3
Change 2024 vs 2019 (km ²)	-765,9	+455,3	-133,1	+167,7	+230,1	-45,9
Change 2024 vs 2019 (%)	-27,6	+49,9	-14,7	+32,4	+452,1	-0,9

Conclusion

Comprehensive and spatially explicit information on forest cover is essential for detecting disturbance dynamics, supporting sustainable forest management, and guiding restoration efforts in boreal ecosystems (Achard et al. 2014; Paquette and Messier 2011). In northern Mongolia, Sentinel-2 time-series imagery combined with Random Forest classification provides a reliable and high-accuracy approach for monitoring forest area and composition (Immitzer, Vuolo, and Atzberger 2016; Persson, Lindberg, and Reese 2018; Fassnacht et al. 2016). Our analysis demonstrates that Sentinel-2 captures both annual and seasonal spectral variation, allowing accurate mapping of forest and non-forest areas with overall accuracy of 93,9–96,2% and Kappa values of 0,924–0,949 (Congalton and Green 2019; Belgiu and Drăgu 2016).

Results show that Manchurian birch (*Betula platyphylla* Sukaczew.) remains the dominant species, while Siberian larch (*Larix sibirica* Ledeb.) and Siberian pine (*Pinus sibirica* Ledeb.) exhibit expansion over 2020–2024. Scotch pine (*Pinus sylvestris* L.) and Siberian spruce (*Picea obovata* Ledeb.) remained relatively stable. Beyond species composition, the overall forest extent also experienced clear interannual changes during 2020–2024, reflecting gains and losses across the landscape (Hansen et al. 2013; Achard et al. 2014). These fluctuations highlight the need for continuous satellite monitoring to track disturbances and recovery (Dulamsuren et al. 2010; Food and Agriculture Organization of the United Nations (FAO) 2021), while species-level shifts illustrate compositional changes within broader forest dynamics (Belgiu and Drăgu 2016; Congalton and Green 2019).

Overall, the study confirms that multi-temporal Sentinel-2 imagery offers a cost-effective, scalable, and scientifically robust tool for operational forest monitoring, management decision-making, and restoration assessment in northern Mongolia (Food and Agriculture Organization of the United Nations (FAO) 2021; Government implementing agency Forestry Department 2019). Future improvements could include incorporating ecological and topographic variables, expanding field validation, and testing advanced classification techniques such as deep learning to further enhance accuracy and operational applicability (Belgiu and Drăgu 2016; Blickensdörfer et al. 2024).

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