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Effects of Site Conditions on Costs and Profitability in the Extraction and Use of Dead Trees in Mongolia

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Abstract

This study estimates the costs and profits of extracting dead trees from forests to be sold at provincial centers via sub-provincial centers as lumber, to be sold at sub-provincial centers as firewood and unused materials for the production of energy. The effect of site conditions on cost and profit was examined. Forest registration data including subgroup area, tree species, and forest stocks; polygonal data describing province/sub-province, protected/nonprotected, and subgroup boundaries (shape file); point data of provincial/sub-provincial center (shape file); and linear data about roads (shape file) were acquired from the Mongolian government. Subgroups comprising Siberian larch, Scotch pine, and Asian white birch trees were analyzed. A positive correlation was found between off-road/primary transportation distance and harvesting/total cost; the total cost and ratio of lumber yield in each subgroup, resulting from the additional cost of transporting lumber from the sub-provincial center to the provincial center. The strong positive correlation between profitability and the ratio of lumber yield to the total yield of each subgroup means that profits will increase as more lumber is harvested, although lumber costs more than firewood or other unused wood. Therefore, the extent to which lumber can be harvested from each subgroup has a significant influence on profitability.

Keywords: Biomass recovery, circular economy, lumber, firewood, unused materials for energy production

1. Introduction

Mongolian forests can be broadly classified into two types: Boreal and Saxaul forests (Figure 1). Boreal forests are mainly distributed in the subarctic zone in northern Mongolia, where annual rainfall is 300 to 400 mm. In contrast, Saxaul forests are sparse shrub forests, dominated by *Haloxylon ammodendron*; these forests are distributed in deserts and steppes in southern Mongolia, where annual rainfall is only about 100 mm, and it is difficult for trees to grow (Forestry Agency of Japan, 2013). In Mongolia, land that bears tree with a height of 2 m or more, cover an area of 1 ha or more, and have a trunk coverage of 10% or more is defined as a forest. Since Saxaul forests do not meet these criteria, only Boreal forests are treated as true forests. Therefore, in this study, Mongolian forests refer exclusively to Boreal forests.

The forested area of Mongolia (Table 1) varies according the two statistics, namely the "Global Forest Resource Assessment (FRA) 2020" by the Food and Agriculture Organization of United Nations (FAO, 2021) and "Mongolian Multipurpose National Forest Inventory (NFI) 2014-2017" by the Mongolian Ministry of Environment and Tourism (MET, 2019). Of the national land area of 155 356 000 ha, forest cover is 9,1% according to FRA and 7,3% according to NFI. Both values indicate that Mongolia has a low forest cover. Regarding tree species, Siberian larch (*Larix sibirica*) accounts for 68,9%, followed by Asian white birch (*Betula platyphylla*) at 11,1%, Siberian pine (*Pinus sibirica*) at 6,0%, and Scotch pine (*Pinus sylvestris*) at 5,2% (Figure 2).

Similar to the forested area, the forest stock rate varies according to FRA and NFI. However, forest stock rate per hectare is comparable, at approximately 96 m^3/ha (Table 1), according to the two statistics. In addition, the stock rate for each tree species differs depending on the statistics. However, according to both statistics, the stock rate increases in the order of Siberian larch, Siberian pine, Asian white birch, and Scotch pine in both, and these four tree species occupy most of the Mongolian forest stocks (Figure 3).

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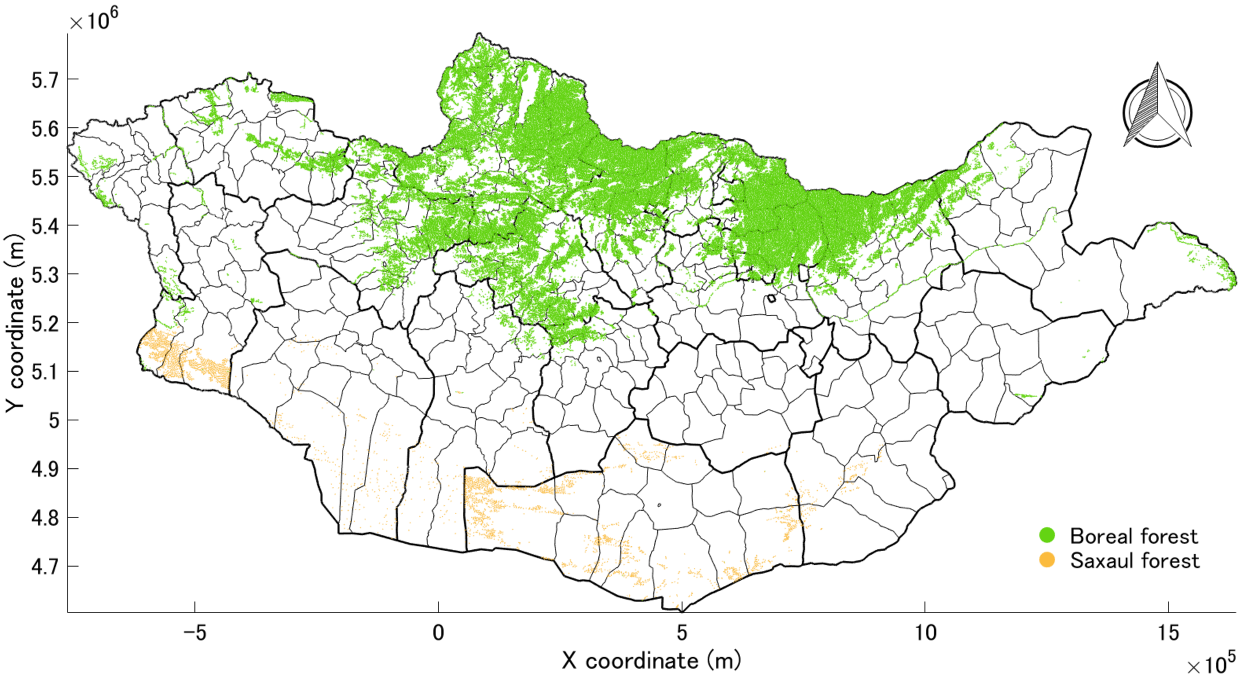

Figure 1. Forest distribution (EPSG:32648)

Table 1. Forests in Mongolia

	FRA	NFI
Area, ha	14 172 780	11 300 000
Rate, %	9,1	7,3
Stock, m^3	1 364 840 000	1 084 800 000
Stock per area, m^3/ha	96,3	96,0
Managed by		
Private company, ha	522 230	400 000
Forest user group, ha	3 517 000	1 600 000
Subtotal, ha	4 039 230	2 000 000
Protected area, ha	2 976 230	2 976 230

FRA: Forest Resource Assessment, NFI: National Forest Inventory

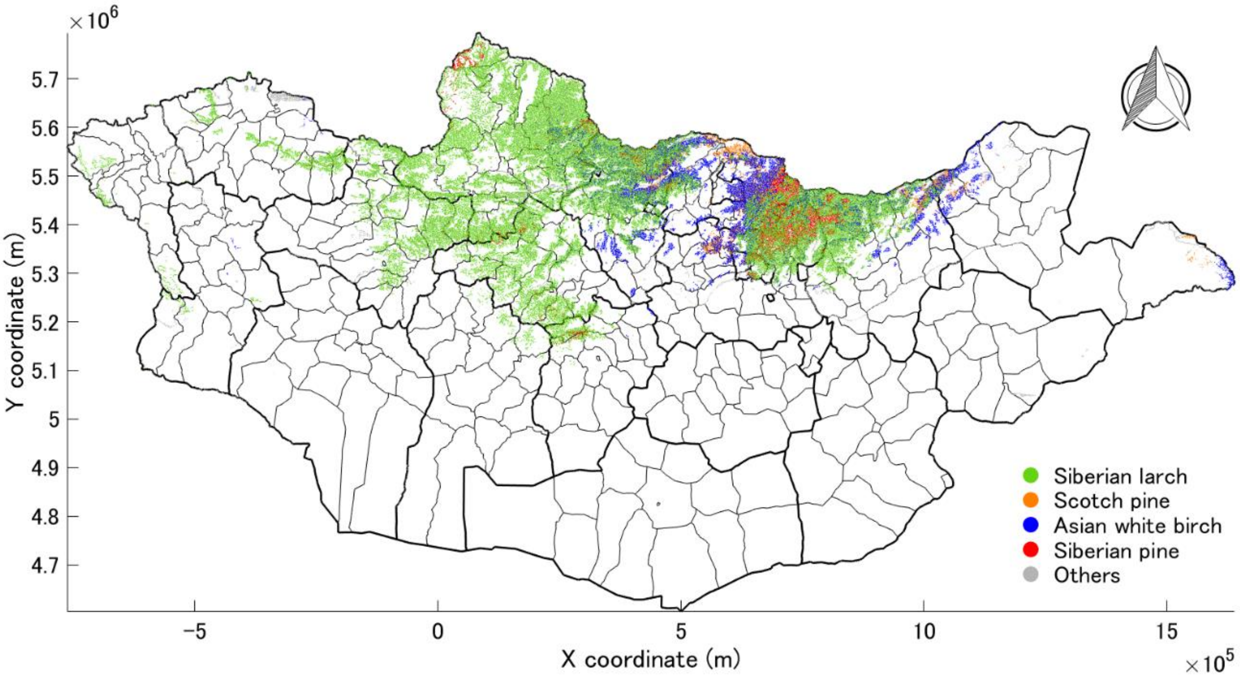

Figure 2. Species distribution (EPSG:32648)

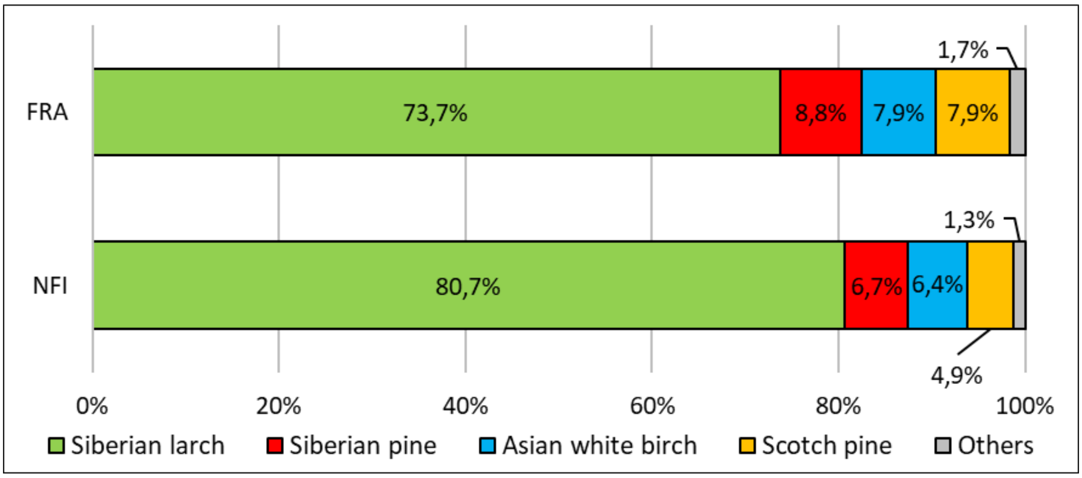

Figure 3. Forest stock rate for each tree species

The growth rate in Mongolia is classified into five levels from 1 to 5, with lower numbers indicating high forest productivity. Forests with a growth rate of 4 were found to account for 73,6% in the inventory, which were closely followed by forests with a growth rate of 5. In addition, only approximately 0,5% of the total forest showed a growth rate of 1 to 3, indicating significantly low productivity in terms of the forestland in Mongolia. Forest stock is therefore relatively common at approximately 96 m^3/ha although the Mongolian forests are aging in general (MET, 2019). Forests that are older than 100 years account for 67% of the total forest; this does not comprise the 0-year-old subgroup that includes burned areas, the non-vegetative sides of mountains, areas affected by pests and disease, and timber harvested areas. Assuming that forest management is carried out appropriately and the current composition of tree species is maintained, it is estimated that the forest stock will more than double (Altrell, 2019). The forests of Mongolia have undergone deterioration owing to issues with management, and their potential has not been fully utilized. Mongolian forests therefore have potential for significant growth. In the future, it will be necessary to actively manage forests to increase the amount of forest stock and maintain the health of forests, while also producing and utilizing wood as lumber and for the production of energy (Altrell, 2019).

All forests in Mongolia are a property of the Mongolian government (i.e., national forests). This was a remnant of the socialist era until democratization in the early 1990s. However, since 2009, the states can temporarily transfer forest management rights to private companies and citizen groups called forest user groups (Forestry Agency of Japan, 2013), and the privatization of forest management has partly progressed. Forest areas managed by private companies and forest user groups vary according to the two statistics, but there are still more forests managed by the government (Table 1). Forests managed by private companies and forest user groups are classified as production forests for lumber and firewood. The Mongolian government has declared protected forests to restrict use. In such protected forests, only thinning and salvage logging can be performed. The area of protected forests is approximately 2.9 million ha according to both FRA and NFI (Table 1). The distribution of protected and non-protected forests is shown in Figure 4. Non-protected forests, excluding those managed by private companies and forest user groups, are currently designated as neither production nor protected forests. However, undesignated forests are recognized as part of production forests, as the transfer of forest management rights to private companies and forest user groups is anticipated to expand in the future (Altrell, 2019). Therefore, the proportion of Mongolian forests that can be used without restrictions is estimated to be approximately 8,4 million ha according to NFI.

Aging forests result from the low average annual logging of approximately 0,23 m^3/ha, which is far below the estimated annual growth of approximately 1 m^3/ha and is a result of prohibiting clear cutting in Mongolia (Altrell, 2019). Forests are weakened by aging as trees that die and are left to litter the forest floor are subject to an increased risk of forest fire and pest damage, and it is therefore recommended that such trees should be removed (Altrell, 2019) although the lack of veteran trees and deadwood in Europe's forests is a major cause of biodiversity loss (WWF, 2004). Dead trees account for 86,3% of the timber yield in Mongolia (Government of Mongolia, 2018), and are actively harvested, unlike living trees, because the practice is not considered to lead to the deterioration of forests (FAO, 2021). Only private companies that have received special permission from the government can harvest living trees, while no special permission is required to harvest dead trees, meaning that they can be harvested by local citizen groups (Gradel and Petrow, 2014). Dead trees are therefore a valuable resource in Mongolia, and removing them from the forests, while promoting the use of dead trees, can protect forests from fire and pest damage.

Based on the above research background, the purpose of this work is to evaluate how we can study an optimized supply chain process aimed at reducing costs

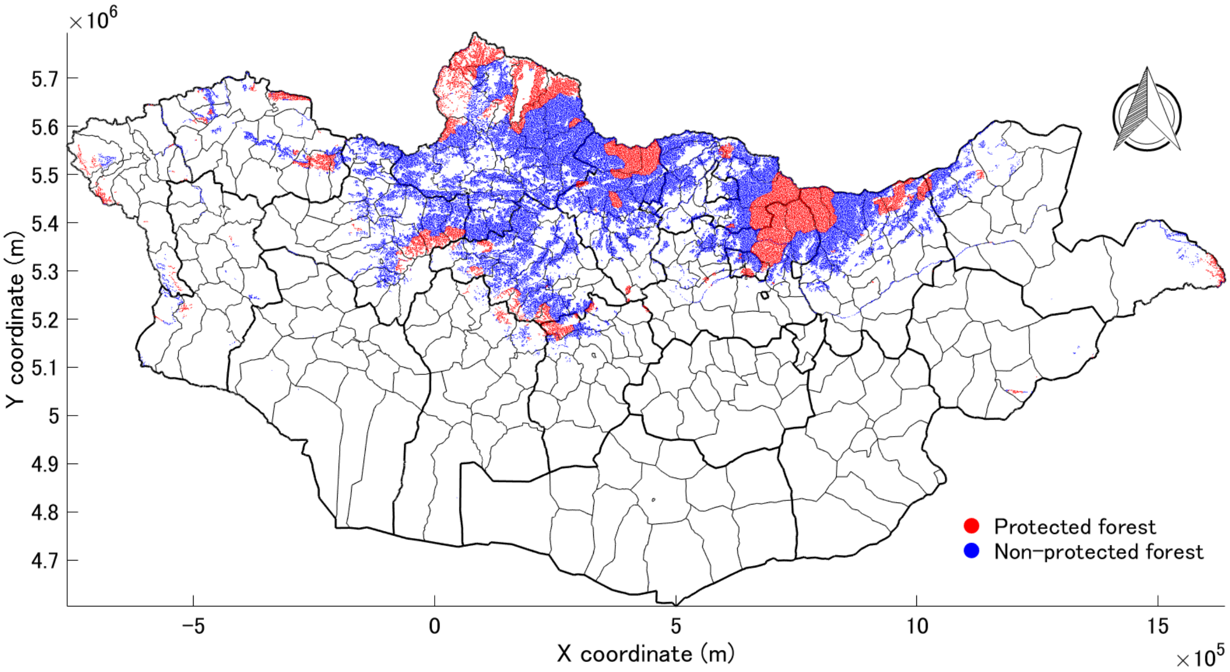

Figure 4. Protected and non-protected forest areas (EPSG:32648)

and making the collection of dead trees and unused wood that is left in the forest, more efficient. Harvesting dead trees and removing unused material also mean that the land covered by forests will be prepared for planting new trees. The promotion of reforestation is inherent in the sustainable management of forests. The study also aims to increase the profits gained by selling this unused material by creating demand and aid in the transition to the sustainable forest management of living trees by effectively utilizing dead trees. To accomplish these aims, the costs and profits of extracting dead trees that have been left in the forests for use as lumber, as firewood, and in the production of energy is estimated. Some amounts of research have been conducted regarding the effects that site conditions have on costs and profits (Aruga and Uemura, 2015; Accastello et al., 2017; Nakahata et al., 2019). However, this has not yet been investigated in terms of Mongolia, and therefore, is examined in this study.

2. Material and Methods

2.1. Study Area and Data

Forest registration data such as subgroup area, tree species, and forest stocks, polygonal data about province/sub-province, protected/nonprotected forest, and subgroup boundary (shape file); point data detailing the province/sub-province center (shape file); and linear data describing roads (shape file) were acquired from the Mongolian government. Two datasets describe the roads in Mongolia: "Roadnet" and "MinorRoad" (Figure 5). "Roadnet" is new; however, some local road data are missing because the survey is not yet complete. "MinorRoad" includes all such local roads; however, data describing newly constructed roads are missing, or the roads are misaligned because of outdated information. Because of the evident advantages and disadvantages of using both datasets, the transportation distance in this study was calculated using both. ASTER Global Digital Elevation Model (GDEM) version 3 with a 30-m mesh (GeoTIFF file), which was obtained from the Land Processes Distributed Active Archive Center (LP DAAC) at NASA, was used. MATLAB was utilized for all the analyses.

Other freely available 30 m grid elevation data include Shuttle Rader Topography Mission-1 Arc-Second Global (SRTM-1) and ALOS World 3D-30m (AW3D30). SRTM-1 boasts high reliability as the first published elevation data of the three but does not cover some areas of Mongolia. In addition, AW3D30 was not suitable for this study, because it is a digital surface model (DSM) not a DEM. The current ASTER GDEM is inferior to SRTM-1 in terms of data accuracy, but because ASTER is still collecting elevation data, we can expect future improvements in data accuracy. Therefore, in this study, ASTER GDEM, which is a DEM covering Mongolia, was adopted as the elevation data.

The coordinate reference system of ASTER GDEM, WGS84 (EPSG: 4326), is a geographic coordinate system and cannot be used in its raw state for the analysis in this study. MATLAB was therefore used to convert the ASTER GDEM coordinate system to the projected coordinate system, WGS84/UTM zone 48N (EPSG: 32648), because the other GIS data describing Mongolia were unified with this coordinate reference system. Because the territory of Mongolia covers a significant distance from east to west with multiple UTM zones, significant distortion therefore results from expressing Mongolia in its entirety in one UTM coordinate system. In addition, the specifications of MATLAB mean that an error will occur when the GeoTIFF file of ASTER GDEM is downloaded from the LP DAAC site. Therefore, ASTER GDEM was downloaded with QGIS, and saved as a GeoTIFF file for analysis with MATLAB.

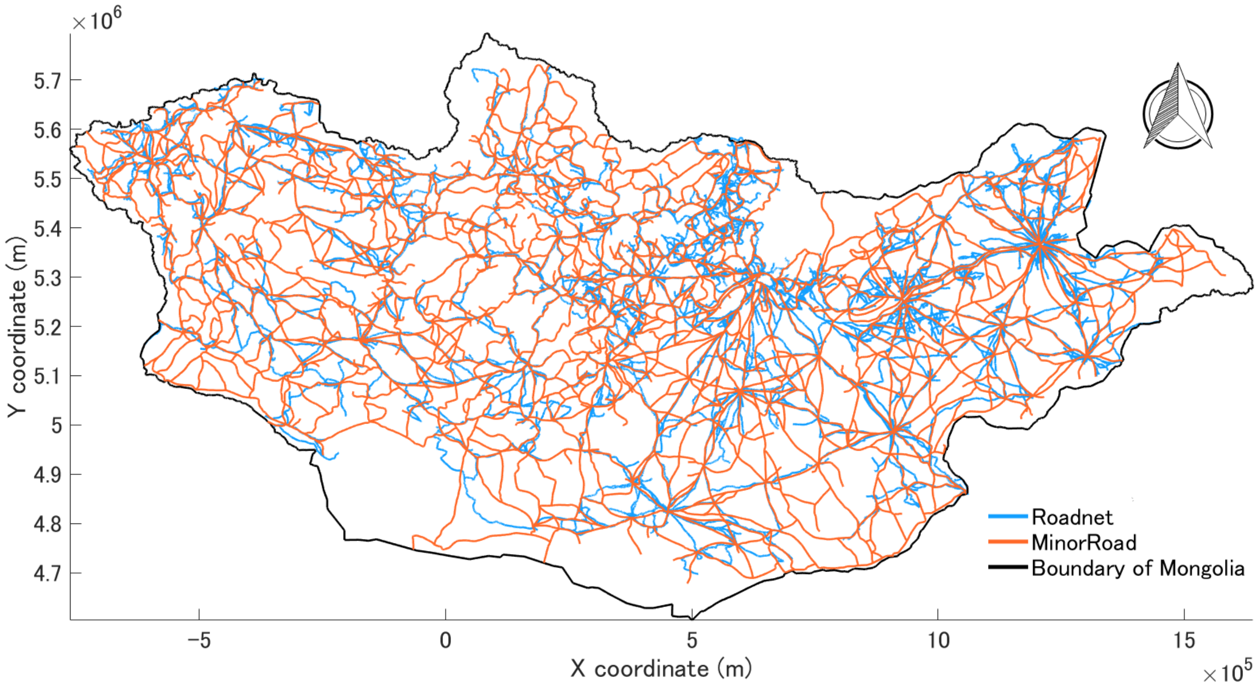

Figure 5. Road data (EPSG:32648)

Mongolian forests are mainly composed of four tree species: Siberian larch, Scotch pine, Asian white birch, and Siberian pine. The logging of Siberian pine is prohibited in Mongolia; therefore, the subgroups with dead trees of Siberian larch, Scotch pine, and Asian white birch were analyzed in this study (Figure 2). The species of a dead tree are not described, and are replaced by the first living tree species in the same subgroup. Using the three numbers that are used to define each subgroup (describing the province/sub-province, forest group, and subgroup), the forest registration data and the polygon data describing the subgroup boundary were combined. Then, the data were prepared in a form that was easy to analyze with MATLAB. The forest registration data could not be combined with the polygonal data describing some of the subgroup boundaries owing to inadequate data (Table 2, Figure 6). These subgroups were therefore excluded from this study, although dead trees were present. Because the subgroups that were excluded from this study account for only approximately 0,5% of the total in terms of the number of subgroups and the area covered, the number of exclusions can be considered insignificant. A total of 96 379 subgroups and 2 979 026 ha were analyzed in this study.

Table 2. Number and area of subgroups

Province	Combined		Not combined	
	Number	Area (ha)	Number	Area (ha)
Arkhangai	6 766	208 328	33	1 570
Bayan-Ulgii	61	3 937	0	0
Bulgan	11 643	383 464	50	1 293
Darkhan	26	1 184	18	524
Dornod	1 384	51 787	68	3 088
Khentii	11 864	406 217	129	4 717
Khuvsgul	31 215	945 946	100	3 193
Orkhon	5	191	0	0
Selenge	7 091	342 879	34	1 415
Tuv	21 301	453 059	24	316
Ulaanbaatar	722	17 261	19	473
Uvs	1 207	25 680	31	578
Uvurkhangai	735	24 299	0	0
Zavkhan	2 359	114 794	3	81
Total	96 379	2 979 026	509	17 248

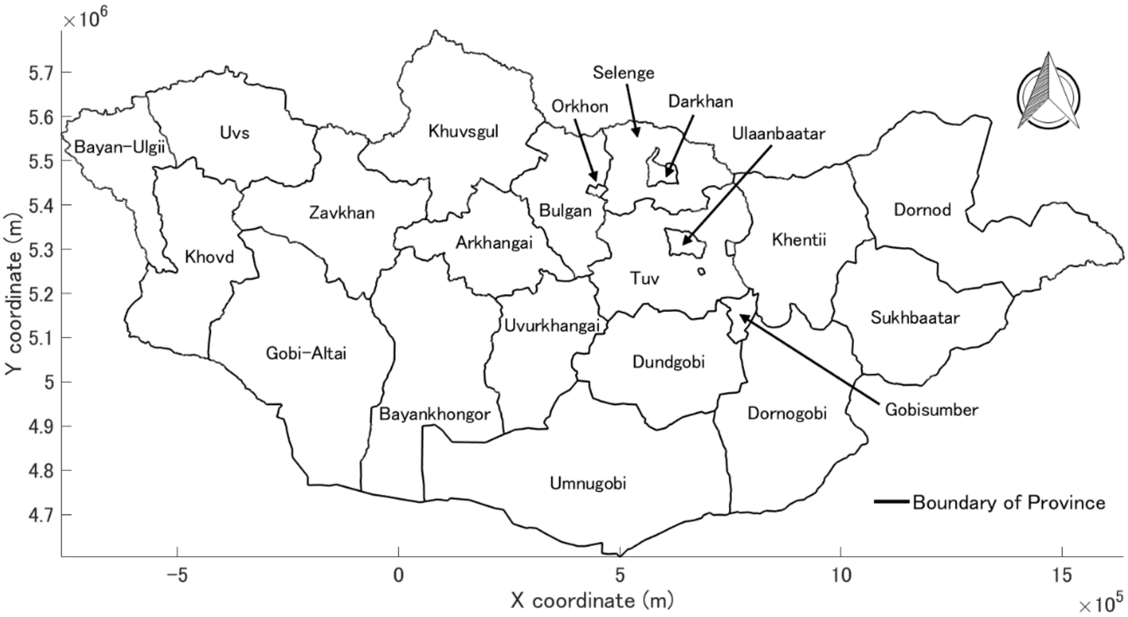

Figure 6. Provinces of Mongolia (EPSG:32648)

The costs and profits associated with extracting dead trees that have accumulated in the forests for use as lumber, as firewood, and in the production of energy were estimated. The order of evaluation is as follows: 1) Estimation of yield and revenue; 2) Calculation of average slope and average skidding distance for each subgroup to select the optimum skidding method and calculate the cost of skidding; 3) Calculation of the off-road transportation distance, while considering the detour rate, to estimate the primary and secondary transportation distances to the final destination of lumber, firewood, and unused materials for use in the production of energy; 4) Calculation of other costs and stumpage price as well as an estimation of the profits together with revenue and cost.

2.2. Estimation of Yield and Revenue

Three types of dead trees are identified in the Mongolian forest registration data: commercial fallen dead trees, normal fallen dead trees, and standing dead trees. Based on an interview survey of forest officials in Mongolia, the utilization rate was set at 70%, and the unused material rate was set at 20% of the total volume. Of the 70% that is utilized, it is assumed that 100% of commercial fallen dead trees will be used for lumber and 100% of normal fallen dead trees will be used for firewood, while 39,2% of the standing dead trees will be used for lumber and 60,8% will be used for firewood. Based on an interview survey of forest officials in Mongolia, the market prices of lumber and firewood are 260 000 MNT/m^3 and 50 000 MNT/m^3, respectively, and the volume ratio of lumber products to lumber logs before processing in Mongolia was 80%. The price of lumber logs was therefore estimated at 208 000 MNT/m^3. The volume ratio of firewood to unprocessed firewood logs was assumed to be 100%. The price of unused materials that are used to produce energy (i.e., 45 000 MNT/m^3) is competitive with that of coal (NIRAS, 2018).

2.3. Calculation of Average Slope and Average Skidding Distance for Each Subgroup

To efficiently transport dead trees that are scattered in each subgroup out of the forest, it is necessary to temporarily collect dead trees in one place before final transportation. In this study, assuming that dead trees are evenly distributed in the subgroups, the center of gravity in each subgroup was set as the location at which wood was temporarily placed, namely the lumber yard. This study assumed three types of skidding methods: human-powered skidding for slope angles below 15% and a maximum skidding distance of 300 m, horse-powered skidding for slope angles below 40% and a maximum skidding distance of 1 500 m, and skidding with an agricultural tractor that can be performed without limitations and is based on the results of an observational survey (Baasan and Mohns, 2019). The average slope and skidding distance in each subgroup were calculated to select the optimum skidding method. The cheapest skidding method within the limiting conditions was then selected as the optimum skidding method for each subgroup. The equations employed to estimate the cost of skidding, Cs (MNT/m^3), using each method over a skidding distance of Ds (m) was derived by our study (Battuvshin et al., 2022) based on Baasan and Mohns, (2019), to convert the unit cost from USD to the Mongolian currency, MNT. The average exchange rate of 1 USD = 2 663.5 MNT, as of 2019, was used (Japanese Ministry of Foreign Affairs, 2021).

Human-powered:

$$Cs = 2\,663.5(0.0266Ds + 1.0625) \quad (1)$$

Horse-powered:

$$Cs = 2\,663.5(0.0106Ds + 1.9125) \quad (2)$$

Agricultural tractor:

$$Cs = 2\,663.5(0.0047Ds + 3.7381) \quad (3)$$

2.4. Calculation of off-road Transportation Distance Considering Detour Rate

The off-road transportation distance of *Dot* (m) in this study refers to the distance from the lumber yard to the nearest road data point. A truck cannot always travel the shortest distance (straight line) between a road data point to the yard, meaning that it is often necessary to detour to an extent depending on the slope. No method for calculating the detour rate has yet been produced for Mongolia; hence, a detour rate that was established for Japan was used in this study (Battuvshin et al., 2020). The detour rate used in this study might not be suitable for Mongolia and warrants further study. The information gained from the interviews was used to calculate the distance to the primary destinations for the lumber, firewood, and unused materials at the sub-provincial center. There are 22 provincial centers and 314 sub-provincial centers throughout Mongolia.

Lumber logs that are transported to the sub-provincial centers are processed into lumber products, and then, undergo secondary transportation from the sub-provincial center to the provincial center for sale in the market. In this study, the price of lumber products is the same at each destination, so the destination with the shortest transportation distance is considered the most profitable. Therefore, the secondary destination for lumber products was set to the provincial center that was closest to the sub-provincial center, which was used as the primary destination for lumber.

The firewood destination was assumed to be the closest sub-provincial center to the road data point that was closest to the subgroup. The firewood logs that were transported to the sub-provincial center were cut to a suitable length for use as firewood, but were not divided vertically or further processed as firewood. In Mongolia, consumers that purchase firewood either chop the wood themselves or use personal wood-chopping services and bear the cost. As the market price of firewood does not include these costs, firewood processing costs were not counted in this study. However, a possible pre-treatment (divided vertically or further processed as firewood) could improve storage and transport of the material, positively affecting costs. Future study will examine this pre-treatment.

Firewood is generally sold at the sub-provincial center, and does not undergo secondary transportation to a provincial center. However, exceptions occur when the destined sub-provincial center is in contact with the sub-province in which the provincial center is located. In this case, firewood is transported to the provincial center as a secondary destination, and sold there alongside the lumber products. This is because provincial centers are of larger scale and there is more demand for wood products in these locations than there is at sub-provincial centers. Firewood that is transported to sub-provincial centers that are sufficiently near provincial centers is better sold at the higher prices demanded at the provincial center, although secondary transportation is required. However, this study did not consider the higher prices and increased demand for these products at provincial centers and the price of firewood was considered the same at each destination, so the primary destination with the shortest transportation distance is considered most profitable. In exceptional cases, the secondary destination for firewood was set to the provincial center that is closest to the primary sub-provincial center. The effects of the larger scales and increased product demand at provincial centers on the price of wood should be considered in future studies.

Assuming that the other unused material will be used locally for heating within a sub-province, the destination of this material is the sub-provincial center that is closest to the subgroup. As with lumber and firewood, the price of unused materials is considered uniform regardless of the destination, and the destination with the shortest transportation distance is assumed the most profitable.

In this study, primary transportation refers to transportation from the lumber yard to the nearest sub-provincial center via the nearest road data point with a Zil 131 truck (2021). The hourly fixed and variable costs for the Zil 131 truck and labor costs were set with reference to the interview survey, and productivity was estimated at 30 km/h with a 15-m^3 payload (Baasan and Mohns, 2019; Nakahata et al., 2014). The unit cost of primary transportation, *Cpt* (MNT/m^3), was also derived by our study (Battuvshin et al., 2022) using the primary transportation distance, *Dpt* (km).

Zil 131 truck: $Cpt = 21\ 534Dpt/225\ 000$ (4)

In this study, secondary transportation refers to transportation from the sub-provincial center in the primary destination to the nearest provincial center. Based on the interviews, the cost of secondary transportation by trucks with 30-ton and 20-ton payloads of lumber is 44 000 MNT/m^3 or 55 000 MNT/m^3 when transporting from sub-provincial centers in Khuvsgul to the provincial centers in Khuvsgul or Ulaanbaatar, respectively. The average secondary transportation distances from the sub-provincial centers in Khuvsgul to the provincial center in Khuvsgul or Ulaanbaatar are 127 and 671 km, respectively. Therefore, the extended unit cost of secondary transportation distances that are greater than the average secondary transportation distance of 127 km within Khuvsul was estimated at 20.22 MNT/km/m^3. The secondary transportation costs, *Cst* (MNT/m^3) were estimated by adding 44 000 MNT/m^3 to the values that were calculated by multiplying the extended unit cost of 20.22 MNT/km/m^3 with the extended secondary transportation distances that are above 127 km, *Dst* (km). The costs of the secondary transportation of firewood obtained from the interview survey were 199 MNT/km/m^3 for trucks with a 4.5-ton payload.

Secondary transportation for lumber:

$$Cst = 44\,000 + 20.22\,Dst \tag{5}$$

2.5. Calculation of Other Costs and Stumpage Price with an Estimation of Profit

Other costs included the costs of marking and felling standing dead trees, loading/unloading costs, as well as lumber and firewood processing costs. The marking unit cost of 25 000 MNT/ha was set using "state expense rate for reforestation and forestry activities" that was obtained from the Mongolian government. The cost of felling (11 393 MNT/m^3) by chainsaw was set with reference to the observation and cost estimation survey of forestry activities in Mongolia (Battuvshin and Stritzke, 2015). Based on the interview survey, loading and unloading costs (1 650 MNT/m^3) accrued by a grapple loader were set based on use of the Doosan Solar 55V (2021). The processing costs (MNT/m^3) for lumber and firewood were also set with reference to the interviews. The cost of processing lumber (4 639 MNT/m^3) was set based on use of the Taiga 3 saw (2021). The processing of firewood in this research refers to the work associated with cutting firewood to an appropriate length with a chainsaw (4 172 MNT/m^3). In this study, it is assumed that unused materials are processed into firewood and burned in firewood boilers, rather than wood chip boilers. The processing cost of unused materials was set at 8 339 MNT/m^3, which is a combination of the cost of processing firewood materials (4 172 MNT/m^3) and the cost of splitting firewood (4 167 MNT/m^3) (NIRAS, 2018). The stumpage prices were calculated according to four conditions: region, tree species, operation methods, and transportation distance from the subgroup to the sub-province center based on data obtained from the Mongolian government. Then, profits were estimated from the revenue and costs in each subgroup.

3. Results and discussions

3.1. Site conditions

Figure 7 shows the distribution of the average forest age for the subgroups analyzed in this study. Figure 8 shows a histogram and scatter plot of the site conditions. In Mongolia, forests of different ages may be mixed in one subgroup. However, as there is no proportional data for each tree species in an area, the weighted average value using the volume ratio of each tree species was used as the average forest age of the subgroups. In addition, as there was no information on the age of the dead trees, instead the age of the living trees was used. Of the 96 379 subgroups, 35 352 (36,7% of the total) and 1 257 928 ha (42,2% of the total) were in the 0-year-old subgroup, which was the largest in terms of both number and area covered. The amount of living trees accumulated in the 0-year-old subgroups was 0 m^3. A total of 29 104 0-year-old subgroups were in burned areas (82,2% of the 0-year-old subgroups), 5 250 subgroups were affected by pest and disease damage (14,9%), and 40 subgroups included areas where trees had fallen because of wind or snow damage (0,1%). Of the other forests, 48 462 subgroups (79,4% of the total excluding 0-year-old forests) showed an average age of more than 100 years, which covered 1 414 683 ha (82,2%). Subgroups that included several dead trees tended to be older, excluding the 0-year-old forest. A histogram of the dead tree accumulation per hectare in each subgroup area is shown in Figure 8. The largest number of subgroups had dead tree accumulations covering 20–30 m^3/ha, and the average value of dead tree accumulation was approximately 29 m^3/ha. Approximately two-thirds of the total subgroups had dead tree accumulations of 30 m^3/ha or less; however, some subgroups in which dead trees were abundant with dead tree accumulations exceeding 100 m^3/ha were also confirmed.

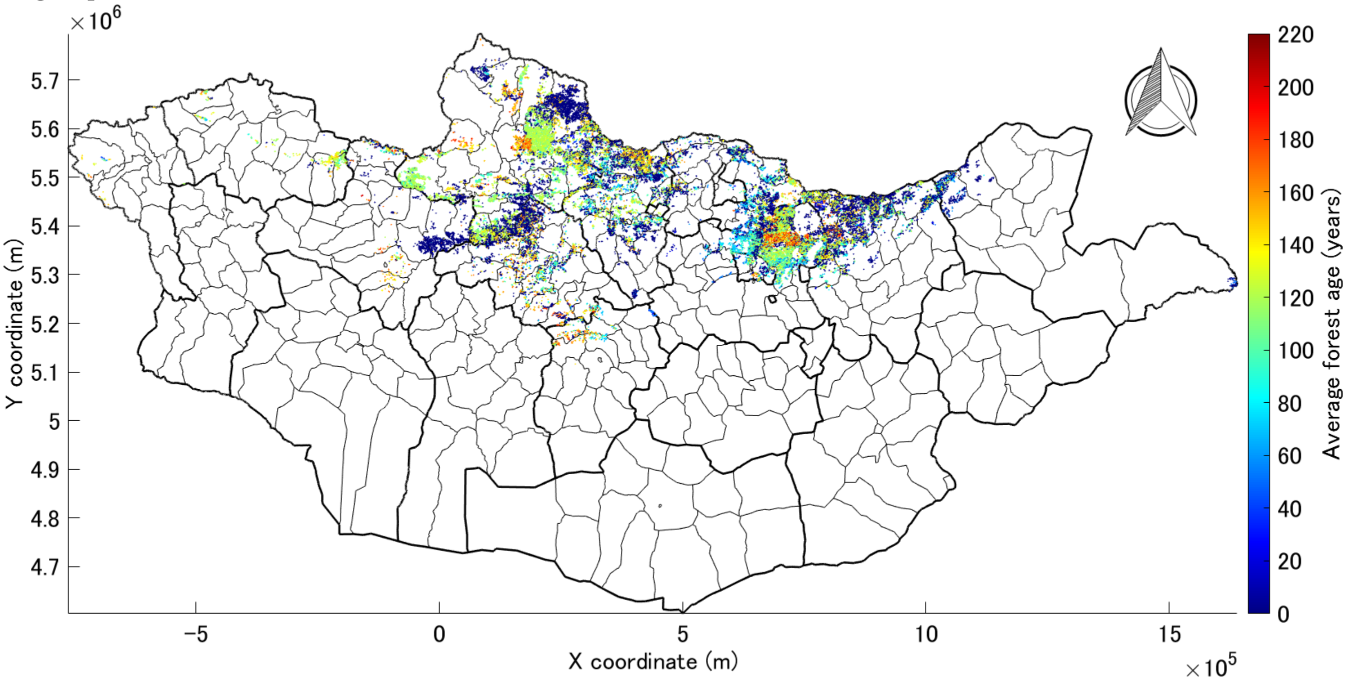

Figure 7. Average forest age in subgroups (EPSG:32648)

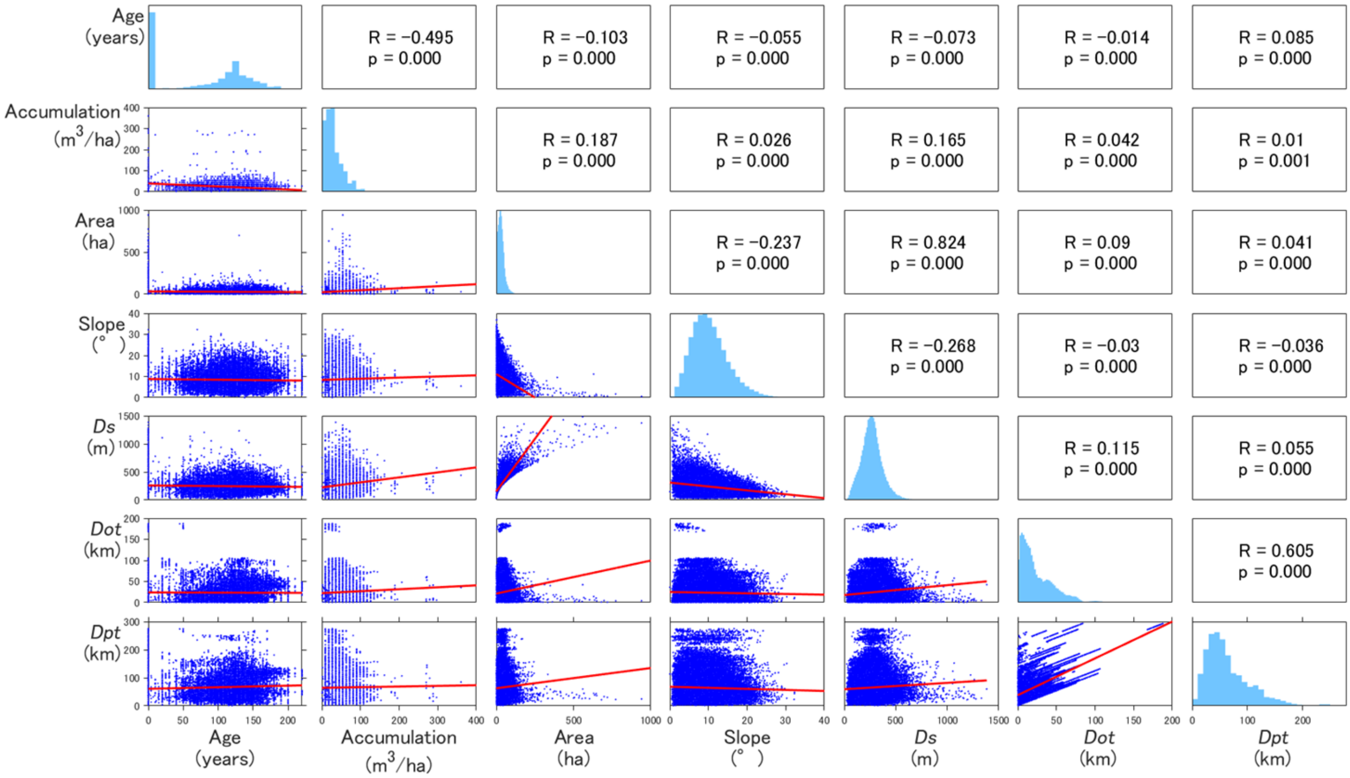

Figure 8. Histogram and scatter plot of site conditions created using Roadnet

The largest number of subgroups had dead tree accumulations covering 25–30 ha, with the average area covered by these subgroups at 31 ha. Several large subgroups cover areas of more than 100 ha. Most subgroups have a slope of 7–8°, with an overall average of 8.6°, and even the steepest subgroups generally do not exceed 30°. According to the Mongolian Forest Law (Glauner and Dugarjav, 2021), harvesting on slopes of above 30° is restricted. In addition, there were 52 961 subgroups (55,0%) with a gentle slope of less than 8,53° (15%), which is the maximum required value for human-powered skidding. The largest number of subgroups had a skidding distance of 240–250 m, and the overall average value was 251 m. According to Glauner and Dugarjav (2021), the skidding distance in Mongolia is generally in the range of 70–250 m; however, in 45 820 subgroups (47,5%), the skidding distance was larger than 250 m in this study. This study assumed the presence of one lumber yard for each subgroup, but subgroups that cover large areas are likely to have multiple lumber yards. Therefore, future studies should consider the possibility of multiple lumber yards within a subgroup to decrease the skidding distance accordingly.

Figure 9 shows a histogram of the off-road transportation distance that considers the detour rate of the subgroups. The average off-road transportation distance was 23,7 km when using Roadnet data and 14,6 km when using MinorRoad data. Roadnet data do not cover rural areas with abundant forest, meaning that the range of off-road transportation distances is wide enough that some subgroups are 100 km away from the nearest road, and there is a tendency for the overall off-road transportation distance to be longer. MinorRoad data, which cover even roads in rural areas with abundant forests, show less variation in off-road transportation distance than Roadnet; the off-road transportation distance tends to be shorter overall. Mongolia does not have many roads, leading to conspicuous subgroups, for which access is poor, that may be tens of kilometers away from the nearest road.

Figure 10 shows a histogram of the primary transportation distances. The average primary transportation distance was 64,9 km when using Roadnet data and 65,2 km when using MinorRoad data. Most subgroups showed a transportation distance of 40–50 km, regardless of which dataset was used. There was a clear difference in the off-road transportation distance in accordance with the road data used; however, there was no significant difference in the primary transportation distance, although it includes the off-road transportation distance. According to Glauner and Dugarjav (2021), the transportation distances in Mongolia are generally in the range of 50–250 km, with 70–120 km being the most common. However, the primary transportation distances of many subgroups in this study were shorter. The primary transportation distances of 42 883 subgroups (44,5%) were less than 50 km using Roadnet data, whereas those of 42 063 subgroups (43,6%) were less than 50 km when MinorRoad data were used. Figure 11 shows a histogram of the secondary transportation distances. The average secondary transportation distance was 151,9 km with Roadnet data and 134,8 km with MinorRoad. Significant variation can be observed in the secondary transportation distance under Roadnet with some subgroups exceeding 300 km, while the variation is small with MinorRoad data, and most of the subgroups do not exceed 250 km. Thus, secondary transportation distances differ depending on the road data used.

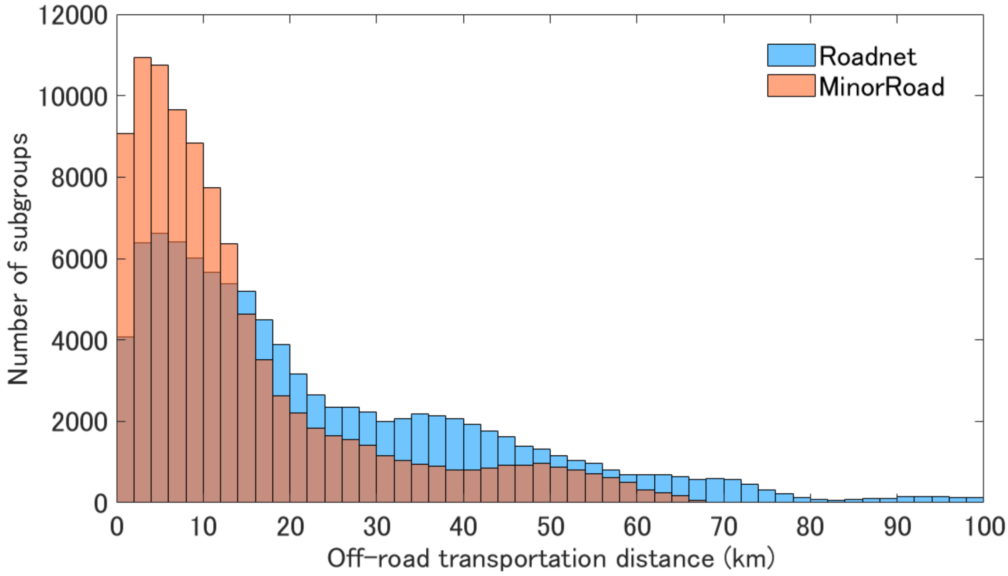

Figure 9. Histogram of off-road transportation distance

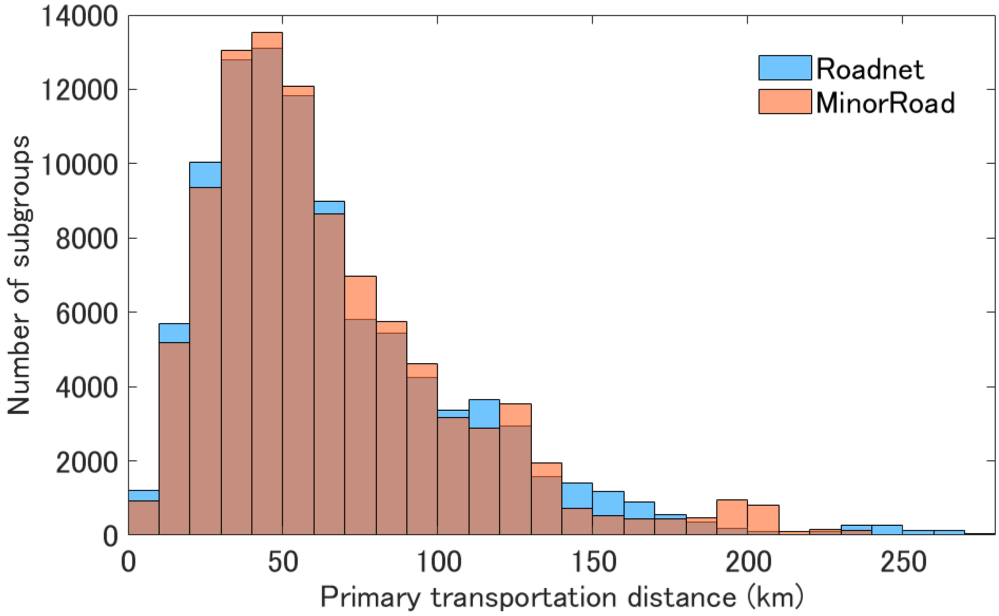

Figure 10. Histogram of primary transportation distance

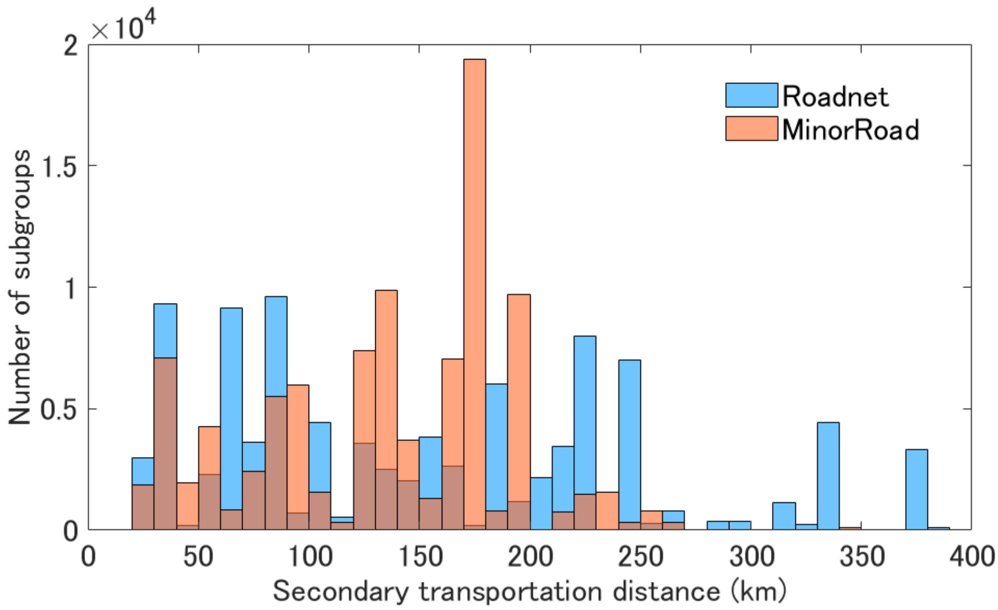

Figure 11. Histogram of secondary transportation distance

Correlation was confirmed for three combinations in this study: forest age and dead tree accumulation; subgroup area and skidding distance; and off-road transportation distance and primary transport distance (Figure 8). Altrell (2019) reported that aging forests produce more dead trees; nonetheless, no positive correlation between forest age and the accumulation of dead trees was observed, instead a weak negative correlation was confirmed. Because the data in the forest registration data are based on plot surveys rather than tree-by-tree surveys, it is possible that the theory that the number of dead trees increases as a forest ages may not be met. Moreover, the number of dead trees accumulated has decreased because many of the dead trees have already been harvested to some extent. In addition, as mentioned above, the subgroups analyzed in this study were often 0 years old, leading to negative correlations. Second, a strong positive correlation was found between the subgroup area and skidding distance. This is because, in this study, one lumberyard was set for each subgroup regardless of the size of the subgroup area. Multiple lumberyards are set for subgroups that cover large areas, while subgroups that cover small areas are combined with several surrounding small subgroups. This method is considered more realistic in terms of lumber yard settings. Aruga et al. (2013a) and Aruga (2016) previously examined the relationships between areas or skidding trail length and skidding distances in subgroups with multiple lumber yards. Aruga et al. (2013b) and Matsuoka et al. (2021) examined aggregated forests, while merging small subgroups in the same watershed. Third, a positive correlation was found between the off-road transportation distance and primary transportation distance. In this study, the primary transportation distance includes the off-road transportation distance, so subgroups that are at some distance from roads are generally also far from the sub-province center.

3.2 Cost, profitability, and stand conditions

Of the 96 379 subgroups in this study, the optimal skidding method was 208 (0,2%) human-powered, 73 604 (76,4%) horse-powered, and 22 567 (23,4%) agricultural tractor. Survey results suggest that horse-powered skidding is more productive in Mongolia than it is globally (Baasan and Mohns, 2019); similarly, horse-powered skidding was selected as the optimum skidding method in three-quarters of the subgroups in this study. The skidding method that uses the TDT 55 tractor (2021) is currently the mainstream method in Mongolia; however, skidding using such heavy machinery is costly (Figure 12). Skidding cost between 11 500 and 12 000 MNT/m^3 in most of the subgroups, with an average skidding cost of 11 926 MNT/m^3. The average cost of skidding with human-powered, horse-powered, and agricultural tractors was 5 892, 11 083, and 14 730 MNT/m^3, respectively. As horse-powered skidding is most suitable for the terrain of Mongolia, it may be necessary to actively promote this method in the future, especially in the case of dead wood, which is lighter because it is dry and has a low water content compared to raw wood.

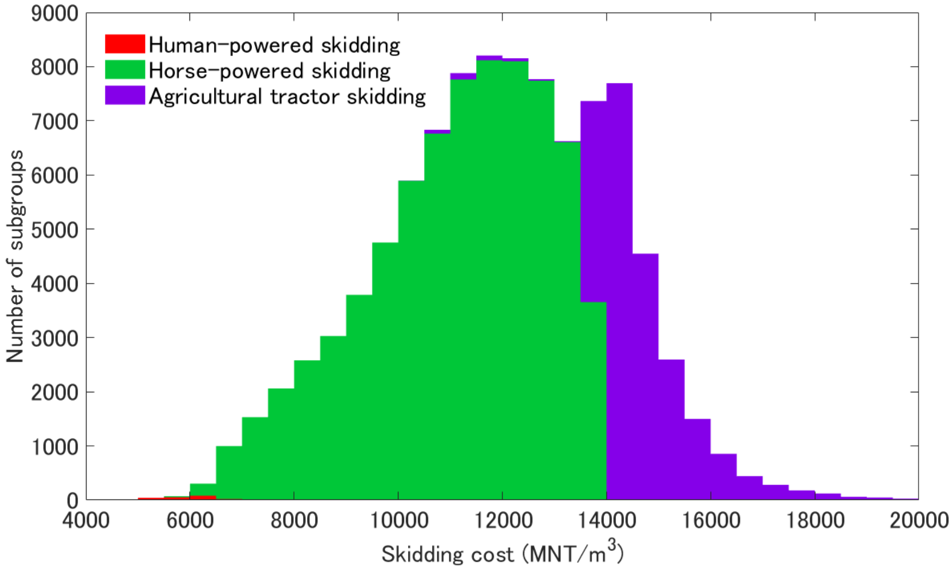

Figure 12. Histogram of skidding costs

Several studies have focused on the costs of transportation from landing to industry, in which it was assumed that in-forest costs are more or less constant (Nord-Larsen and Talbot, 2004; Panichelli and Gnansounou, 2008; Kamimura et al., 2012). This study has focused more on the costs associated with harvesting, which is similar to several previous studies (Battuvshin et al., 2020; Matsuoka et al., 2021; Yamamoto et al., 2019). Specifically, Yoshioka et al. (2011) considered skidding/yarding operations; Accastello et al. (2017) considered 10 ground-based logging systems, but not cable logging; and Nakahata et al. (2019) applied the optimal bucking method to estimate timber and forest biomass resources. Yoshioka et al. (2011) selected skidding/yarding machinery based on topographical conditions such as skidding/yarding distance and slope angle. Conversely, Battuvshin et al. (2020) as well as Matsuoka et al. (2021) selected forest operation systems and machine sizes based on topographical conditions, such as slope angles and height differences within 500 m (Goto, 2016). Forest operation systems include Cut-To-Length (CTL)—which includes harvester and forwarder, chainsaw felling, grapple loader bunching/winching/yarding, tower/conventional sledge yarding, and processing. Furthermore, Aruga et al. (2011) selected skidding/yarding machinery with the lowest skidding/yarding costs for different topographic conditions, whereas Aruga et al. (2014) selected operation systems with the lowest total harvesting costs. Nakahata et al. (2019), and Aruga and Uemura (2015) determined forest operation systems and the sizes of machines used based on the interview with the forest owners' cooperative official for the region analyzed. In contrast, Yamaguchi et al. (2014) and Yamamoto et al. (2019) determined forest operation systems and the sizes of machines based on interviews using information given by multiple forest owners' cooperative officials in the prefecture.

As mentioned above, using the TDT 55 tractor (2021) for skidding is common in Mongolia; however, as no survey has been conducted on the relationship between skidding distance and productivity, other skidding methods (Baasan and Mohns, 2019) were analyzed instead. In the future, further research on skidding operations should be conducted in Mongolia, and it should be possible to flexibly select the skidding method according to the situation of each subgroup. Moreover, the on-line interview survey conducted in 2020 mainly involved forest unit staff and engineers of private companies in the Khuvsgul province, which has the most abundant forest resources in Mongolia and has a thriving forestry industry. Information from Khuvsgul province may not describe the local circumstances in some other areas in Mongolia. Interview surveys should involve forest unit staff and engineers of private companies in all of the provinces in Mongolia to apply the regional situation to analysis. In terms of harvesting operations, CTL is the most productive and low-cost harvesting system worldwide (Strandstrom, 2018; Cavalli and Amishev, 2019; Visser and Stampfer, 2015). CTL has been developed and widely used in Nordic European countries such as Finland and Sweden (Strandstrom, 2018), as well as other regions with relatively gentle terrain. In Mongolia, more than half of the subgroups have a gentle slope of less than 8,6° (15%). Therefore, CTL is a future option that may provide the most productive and low-cost harvesting system in Mongolia after the transition to the sustainable forest management of living trees has been implemented.

The average primary transportation cost was 6 216 MNT/m^3 using Roadnet data and 6 239 MNT/m^3 when MinorRoad was used, with no significant difference overall. The average harvesting cost from forest to sub-provincial center including stumpage price, marking, felling, skidding, loading/unloading, and primary transportation costs was 35 663 MNT/m^3 when using Roadnet data and 35 680 MNT/m^3 when using MinorRoad, with no significant difference between the two types of data observed. The average total cost including the harvesting cost as well as lumber/firewood processing, loading/unloading, and secondary transportation costs was 54 405 MNT/m^3 with Roadnet data and 54 608 MNT/m^3 with Minor Road data. Figure 13 shows a histogram of the profits. The average profit was 47 539 MNT/m^3 with Roadnet and 47 335 MNT/m^3 with Minor Road. Therefore, no significant difference between the results was derived from using the two different types of road data as a whole because there was no difference in the costs involved. Throughout Mongolia, 96 303 of the 96 379 subgroups (99,9%) covering 2 975 336 ha of an area of 2 979 027 ha (99,9%) were profitable using Roadnet data whereas 96 273 subgroups (99,9%) covering 2 974 593 ha (99,9%) were profitable using MinorRoad data. Therefore, dead trees can be used as a resource until transition to the sustainable forest management of living trees.

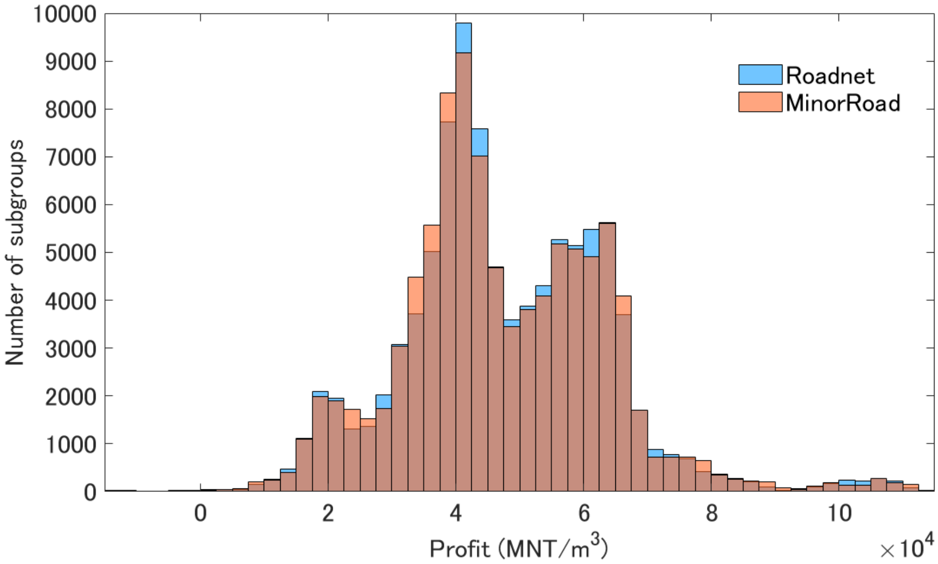

Figure 13. Histogram of profits

Figure 14 shows a scatter plot of the harvesting cost, total cost, profitability, and site conditions. As was the case between site conditions, a few combinations exhibited a correlation. A weak positive correlation was found between the off-road/primary transportation distance and the harvesting/total cost. This is because, when the off-road/primary transport distance is further, the off-road/primary transport cost is higher. There was also a positive correlation between total cost and the ratio of lumber to the yield of each subgroup. This is assumed to be because of the additional cost of transporting lumber from the sub-provincial center to the provincial center. Conversely, as there is a strong positive correlation between the profitability and ratio of lumber yield to the total yield of each subgroup, the profits will be greater if more lumber is harvested, even if the cost of lumber is higher than that of firewood and unused wood according to the assumptions made in this study. There is a negative correlation between the harvesting/total cost and the ratio of normal fallen dead trees. This is because there is no cutting cost for fallen dead trees. These trees were mainly used for firewood, and did not basically require secondary transport to the provincial center, meaning that the transportation cost is lower than that of lumber. In contrast, a cost for the cutting of standing dead trees is incurred, and a positive correlation was found between the harvesting/total cost and the ratio of standing dead trees.

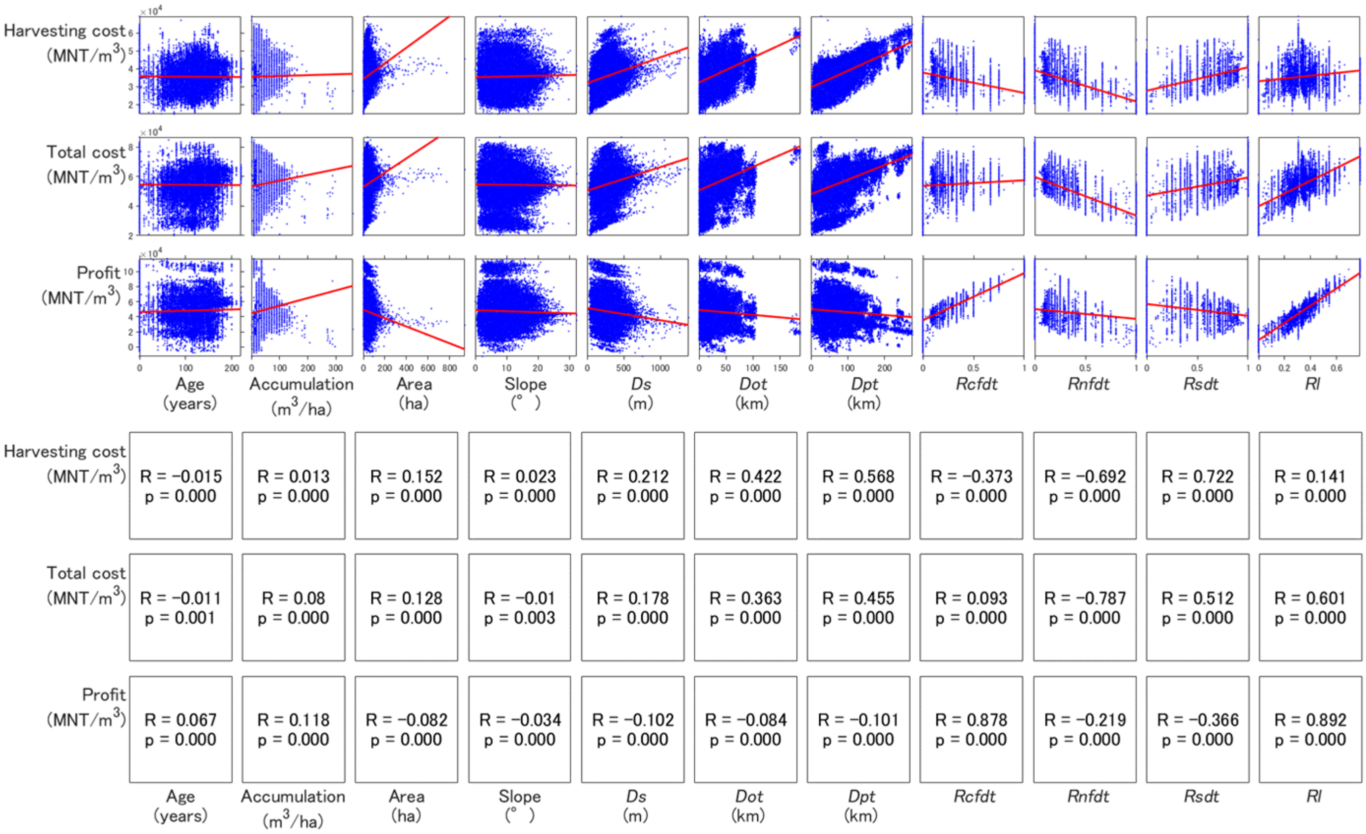

Figure 11. Scatter plot between cost, profitability, and site conditions using Roadnet (*Rcfdt*: Ratio of commercial fallen dead tree, *Rnfdt*: Ratio of normal fallen dead tree, *Rsdt*: Ratio of standing dead tree, *Rl*: Ratio of lumber)

4. Conclusions

This study estimated the costs and profits of extracting dead trees that have accumulated in the forests for use as lumber, as firewood, and in the production of energy. The effects of site conditions on costs and profits were examined. A strong positive correlation was found between subgroup area and skidding distance. This is because in this study, one lumberyard was set for each subgroup regardless of the size of the subgroup area, with multiple lumberyards set for subgroups that cover large areas while subgroups that cover small areas were combined with several surrounding small subgroups as associated with one yard. This is more a realistic condition in which to set the lumber yard. As previously mentioned, skidding using the TDT 55 tractor (2021) is common in Mongolia; however, as no survey has been conducted on the relationship between skidding distance and productivity, other skidding methods (Baasan and Mohns, 2019) were analyzed instead. In the future, further research on skidding operations should be conducted in Mongolia, making it possible to flexibly select the skidding method according to the situation of each subgroup.

There are two types of road data that describe the road network in Mongolia, i.e., "Roadnet" and "MinorRoad." The average off-road transportation distance was 23,7 km when using Roadnet data and 14,6 km when using MinorRoad data. Compared to MinorRoad, Roadnet does not cover rural areas with abundant forests, meaning that the range of off-road transportation distances is wide enough that some subgroups are 100 km away from the nearest road and there is a tendency for the overall off-road transportation distance to be longer. There are not many roads in Mongolia, and several conspicuous subgroups suffer from poor access at distances of tens of kilometers away from the nearest road. There was a clear difference in the off-road and secondary transportation distances in line with the dataset used, but there was no significant difference in the primary transportation distance, although this parameter included the off-road transportation distance. Also, there was no significant difference in profit between the results obtained using both road types data as a whole, since there were no differences in the costs.

There was also a positive correlation between the total cost and the ratio of lumber to the yield of each subgroup. This is because of the additional cost of transporting lumber from the sub-provincial center to the provincial center. Conversely, as there is a strong positive correlation between the profitability and the ratio of lumber yield to the total yield of each subgroup, the profits will be greater if more lumber is harvested, even if the cost of lumber is higher than that of firewood and unused wood, according to the assumptions made in this study. Therefore, the amount of lumber that can be harvested from a subgroup has a significant influence on profitability. This study assumed that 100% of commercial fallen dead trees will be used for lumber, based on the interview survey. However, the Forest Policy and Coordination Department of the Ministry of Environment and Tourism in Mongolia reported that the amount of lumber produced from fallen dead trees was 50 593 m^3, while 449 619 m^3 of firewood was sourced from fallen dead trees in 2019. Based on these values, 10,1% of the total fallen dead trees were used for lumber and 89,9% for firewood. Furthermore, the numerical value, indicating the specific degree of decay of dead trees to the available volume, has not been clarified in Mongolia. Therefore, the available volume was assumed to be the same as the volume provided by the forest registration data in this study. Future studies should clarify a numerical value indicating the specific degree of decay in dead trees to the available volume to accurately estimate the volumes of lumber and firewood available.

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