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DYNAMICS OF KOREAN PINE-BROADLEAF FOREST RECOVERY AFTER SINGLE LOGGING IN THE 1960S IN THE SOUTHERN SIKHOTE-ALIN

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Relevance and aim. Korean pine-broadleaf forests of the southern Sikhote-Alin are unique forest ecosystems with high biological value and complex structure. Under ongoing forest exploitation and degradation of old-growth stands, the evaluation of long-term logging consequences is of special importance. This study aims to assess the state of forest stands 60–70 years after single selective logging conducted in the 1960s, and to compare them with preserved old-growth forests. **Materials and methods.** The data were collected within the Verkhneussuriysky biogeocenotic station, where 346 temporary sample plots were established. For analysis, 127 plots of the K4 forest type (multi-shrub Korean pine forest with yellow birch) were selected, including 69 old-growth and 58 post-logging sites. Tree diameter, height, basal area, and stem volume were measured. Calculations were performed in Python using nonparametric statistical methods. **Results.** The obtained results show that even after 60–70 years, post-logging forests still differ significantly from old-growth stands: they have lower timber stock, smaller average diameters, and lack large trees. Fast-growing pioneer deciduous species predominate, while the proportion of Korean pine is significantly reduced. **Conclusion.** The restoration of the original structure of Korean pine-broadleaf forests is extremely slow and remains incomplete even decades after logging. This highlights the need to reconsider forestry practices aimed at conserving and restoring these ecosystems.

Keywords: *Korean pine-broadleaf forests, single logging, stand recovery, southern Sikhote-Alin, species composition*

Forest ecosystems play a key role in the sustainability of landscapes, biodiversity conservation, and the provision of natural resources to humans. Therefore, in the setting of large-scale anthropogenic transformation caused by intensive logging and fires, the issues of rational forest management remain particularly relevant, including in the Far Eastern region of Russia (Danilin, 2004; Kovalev, 2004). Korean pine-broadleaf forests are one of the most vulnerable and at the same time valuable forest formations. Apart from high species diversity, these forests serve as a key element of ecosystem stability, creating a food base for game animals, including ungulates, whose abundance directly affects the population of the Amur tiger, the rarest endangered predator (Kurentsova, 1968).

Korean pine-broadleaf forests with *Pinus koraiensis* Siebold et Zucc. have a complex age structure and mosaic distribution of dominants (Kolesnikov, 1956). However, due to historically high demand for forest resources, especially during the period of massive logging in the mid-20th century, significant areas of primary cedar forests were transformed into secondary forests (Solov'ev, 1948; Rozenberg, 1975). Despite attempts to regulate economic activity, industrial logging in the 20th century led to habitat degradation, a decreased stand density, and a reduced proportion of *Pinus koraiensis* (Gukov, 1989).

Recovery after such logging is lengthy and ambiguous, as shown by classic (Solov'ev, 1948) and modern studies (Komarova et al., 2022). The initial stages of reforestation are usually characterised by the predominance of fast-growing deciduous species, first of all *Betula costata* Trautv. and *Populus tremula* L., while the participation of coniferous species, especially *Pinus koraiensis*, remains low. The natural recovery of *Pinus koraiensis* is complicated by a number of factors: low seed productivity, irregular fruiting, and eating of seeds by rodents (Usenko, 1984; Kudinov, 2007). Without special silvicultural measures, a return to the original structure of the Korean pine-broadleaf forest in the foreseeable future seems unlikely (Lebedev, 2003).

Against this background, the importance of assessing the state of stands after single industrial logging performed more than half a century ago is increasing. Such plots, in the absence of fires and other disturbances, provide a unique opportunity to trace long-term succession processes and assess the potential for natural restoration of primary forests. It is especially important to compare them with preserved old-growth stands that have not been subjected to human disturbance (Gromtsev, 1999). At the same time, it is extremely difficult to find such plots, since most of the area of the Primorsky Krai forest fund has been logged more than four to five times over the past 70–80 years (Kovalev, Kachanova 2023), which alters the reforestation processes significantly.

Despite this, the territory of the Verkhneussuriysky biogeocenotic station is a unique scientific test site in the southern part of Sikhote-Alin, where areas of primary Korean pine-broadleaf and spruce-broadleaf forests can be found, as well as areas that were subjected to single logging in the 1960s (Arkhiv DVO RAN, otchety VUS 1964–1965 gg.; Sibirina et al., 2022). This makes it possible to assess the structure of stands, the participation of dominant species, the presence of undergrowth and the features of the species composition at different stages of restoration in comparable conditions. *The aim of the study* is to assess the success of stand restoration in areas subjected to single logging in the late 1960s.

MATERIALS AND METHODS

Research area. The Verkhneussuriysky station of the Federal Scientific Center of the East Asia Terrestrial Biodiversity, Far Eastern Branch of the Russian Academy of Sciences, is located in the basin of the Pravaya Sokolovka River (Primorsky Krai, 44°02’N, 134°12’E, Fig. 1). The station includes mountainous areas at altitudes from 4 60 to 1,060 m above sea level and is characterised by high forest cover, mosaic relief and a variety of phytocenoses. The predominant types of forest vegetation are Korean pine-broadleaf, mixed broadleaf and spruce-fir fo-rests (Yakovleva, 2004). The climate is mode-rately monsoon, with annual precipitation of about 830 mm and a pronounced summer maximum. The average annual air temperature is 0.9 °C (Kozhevnikova, 2009). The duration of the vegetation period is 120–140 days.

Logging in the region and on the territory of the station. Intensive timber harvesting has been carried out in most of the Primorsky Krai since the middle of the 20th century, including the mass development of hard-to-reach mountain forests in the 1950–1970s. Large-scale logging in the Verkhneussuriysky station were carried out mainly in the 1960s. To analyse forest recovery after logging in forests with a predominance of *Pinus koraiensis*, the sites that in 1965–1969 underwent selective single-tree logging aimed at harvesting the best stems of *Pinus koraiensis*, as well as areas of continuous logging in dark coniferous forests with a predominance of *Picea ajanensis* Fisch. ex Carrière, were identified. At the same time, in the remote and hard-to-reach parts of the station, there are still areas of stands that have not been cut down or burned. They were used as reference plots.

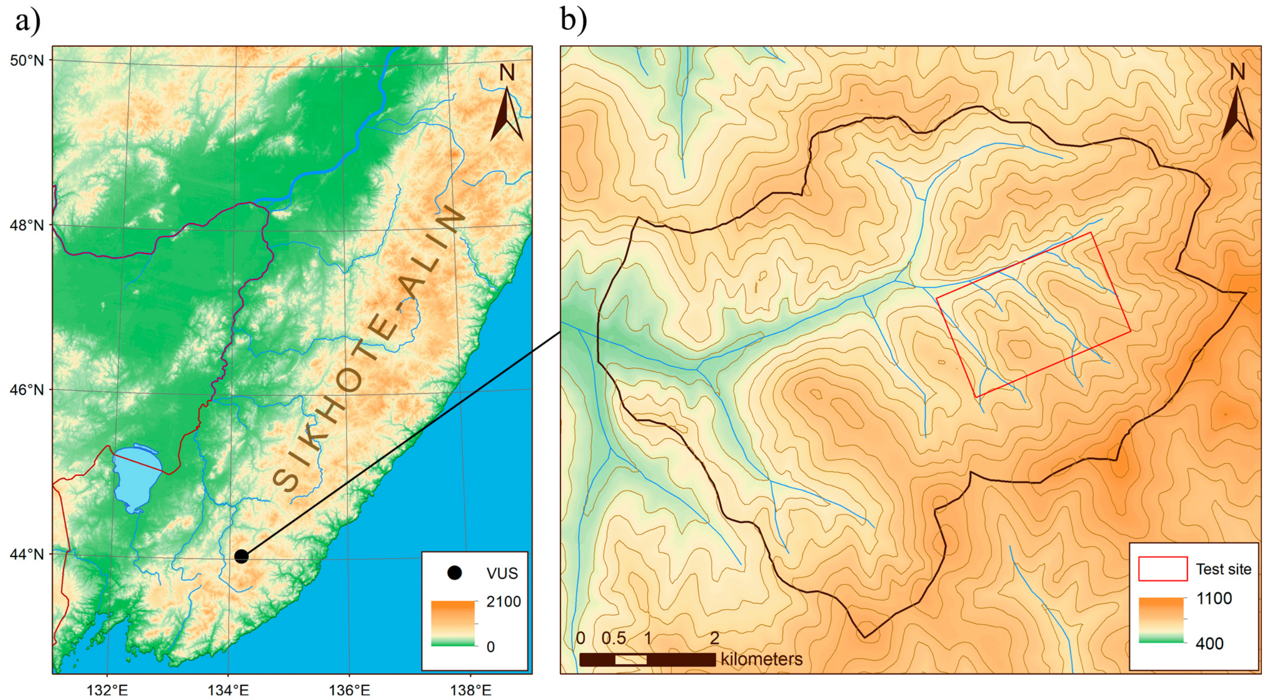

Figure 1. Research area: a—location of the Verkhneussuriysky station (VUS) of the Federal Scientific Center of the East Asia Terrestrial Biodiversity, Far Eastern Branch of the Russian Academy of Sciences, within Sikhote-Alin, b—layout of the station territory and the location of the test site

Data collection. A test site with an area of 400 ha (2.5 × 1.6 km in size) covering a mosaic of forests of various types was established on the territory of the station. Using algorithmic clustering of remote sensing data, the test site was divided into 346 elementary sections with an area of about 1 hectare each. A circular temporary sample plot with a radius of 11.3 m (an area of 0.04 ha) was established on each of them.

A comprehensive description of the stand was carried out within the temporary sample plot. The species, state (alive: normal or defective; dead: deadwood), and diameter at breast height (DBH) were determined for all trees. For some of the trees, the height was measured as well. Subsequently, the stem volume of each individual tree was calculated based on the combination of diameter and height values using standard tables of stem volumes.

During the work on the sample plots, a search was carried out for evidence of logging (stumps, traces of roads or skidding tracks, etc.). According to their presence or absence, all plots were divided into two categories: 1) old-growth plots, with no evidence of logging or fires, 2) post-logging plots, logged in the 1960s. According to the forest inventory data, which was carried out on the territory of the station according to the first class, the plots were classified as different types of forest. The K4 forest type (multi-shrub Korean pine forest with *Betula costata* Trautv.) was selected for statistical analysis, since, on the one hand, it turned out to be the most widespread (127 out of 346 plots), and, on the other hand, there were a comparable number of both old-growth and post-logging plots for this type (69 and 58, respectively).

Statistical analysis. The analysis was carried out on two levels: 1) general characteristics of the stand by plot category (old-growth and post-logging), 2) comparison of indicators for individual tree species. The present study focused on analysing the structure of the stand, since its characteristics are the most representative for assessing differences between plot categories; therefore, no analysis of undergrowth was carried out. Also, given the small size of the temporary sample plots (0.04 ha), which limits the completeness of the assessment of the structure and species composition in the setting of a high species diversity typical of Korean pine-broadleaf forests, all temporary sample plots within each category (old-growth / post-logging) were aggregated to analyse the characteristics of stands. The total area within the first category was 2.76 ha, and that within the second one was 2.32 ha.

At the first stage, a list of tree species found in old-growth and post-logging plots was compiled for subsequent comparison. Then, separately for each category of plots, the following indicators were calculated: number of trees, total basal area (BA), stock of the stand, average and median values of the diameter, height, and volume of the stem. All values were normalised to 1 ha. Distributions of characteristics were evaluated using histograms and cumulative distribution functions (CDFs). To statistically verify the differences between the groups, nonparametric methods were used: the Mann–Whitney test was used to compare median values, and the Kolmogorov–Smirnov test was used to analyse differences in the shape of distributions.

Additionally, analysis at the level of individual species was carried out. For all species represented by ≥10 live trees in each category, the diameter and volume of the stem were compared using the Mann–Whitney test. The structure of the timber stock by species was analysed based on the proportion of each species in the total stock per 1 ha; the χ^2 test was used to assess the differences between the categories of the plots.

The initial data were processed in Excel. The forest type map was compiled based on the digital forest management database, and spatial analysis was performed in QGIS. All further calculations and visualisation were performed in Python using the following libraries: pandas (McKinney, 2010), numpy (Harris et al., 2020), scipy (Virtanen et al., 2020), matplotlib (Hunter, 2007), and seaborn (Waskom, 2021).

RESULTS AND DISCUSSION

Species composition. 19 species of trees were identified in the old-growth plots. The most numerous species in terms of the number of stems were *Abies nephrolepis* (Trautv.) Maxim., *Picea ajanensis* Fisch. ex Carrière, *Tilia amurensis* Rupr., *Pinus koraiensis* Sieb. et Zucc., *Betula costata* Trautv., *Acer ukurunduense* Trautv. et C. A. Mey., and *Acer mono* Maxim. ex Rupr. *Quercus mongolica* Fisch. ex Ledeb., *Ulmus laciniata* (Trautv.) Mayr, *Populus maximowiczii* A. Henry, *Phellodendron amurense* Rupr., *Acer tegmentosum* Maxim. et Rupr., and *Cerasus maximowiczii* (Rupr.) Kom. were also present. There were sporadic finds of *Betula platyphylla* Sukaczev, *Picea koraiensis* Nakai, *Sorbus amurensis* Koehne, *Syringa amurensis* Rupr., *Padus maackii* (Rupr.) Kom., and *Fraxinus mandshurica* Rupr.

25 tree species were found in the post-logging plots. The species composition generally overlaps with that typical of old-growth plots, but there is also a number of pioneer or light-loving species. In addition to the dominant species common to both categories, a significant share of the post-logging stands is formed by *Betula platyphylla* Sukaczev, *Populus maximowiczii* A. Henry and *Populus tremula* L., *Salix cardiophylla* Trautv. et C.A. Mey, *Alnus hirsuta* (Spach) Turcz. ex Rupr., *Phellodendron amurense* Rupr., *Salix caprea* L., *Salix rorida* Laksch., and *Rhamnus davurica* Pall. Interestingly, *Taxus cuspidata* Sieb. et Zucc. was found only in the post-logging plots. This is, on the one hand, due to its rarity, and, on the other hand, due to a more successful restoration after logging. Some species that are common in old-growth stands, are almost entirely absent in post-logging forests, of particular note is *Pinus koraiensis*. This indicates a loss of the stable structure of the original community and its partial replacement by temporary successional elements.

General characteristics. A total of 2,534 trees were recorded in the old-growth plots, and 2,037 in the post-logging plots. The density of the stand (table), calculated per 1 ha, is slightly higher in the old-growth plots than in the post-logging ones. The total basal area of stems per hectare is also higher in the old-growth plots. The average height of the trees is practically the same, but the standard deviation is higher in the old-growth plots, which indicates a greater vertical heterogeneity. The average tree diameter is 20.6 cm (SD = 15.1 cm) for the old-growth plots and 19.3 cm (SD = 13.4 cm) for the post-logging ones. The average volume of a single stem is higher in the old-growth plots (0.54 m^3 versus 0.43 m^3), with a higher dispersion (SD = 0.99 m^3 versus 0.82 m^3). Of particular note are the differences in the timber stock, which amount to 116 $m^3 * ha^{-1}$ (or 106 $m^3 * ha^{-1}$, if only live trees are taken into account). Therefore, an old-growth stand is characterised by both higher productivity and a greater heterogeneity of the stand structure in most indicators.

Table. Characteristics of the stand of the old-growth and post-logging plots

Indicator, unit of measurement	Old-growth plots	Post-logging plots
Number of trees per 1 ha, pcs.	918	878
Average diameter (DBH), cm (SD)	20.6 (15.1)	19.3 (13.4)
Average height, m (SD)	16.1 (5.8)	16.2 (5.4)
Average stem volume, m^3 (SD)	0.54 (0.99)	0.43 (0.82)
Median diameter, cm (25%, 75% percentile)	15.2 (10.1, 26.5)	15.0 (9.8, 24.5)
Median height, m (25%, 75% percentile)	15.6 (10.5, 20.2)	15.5 (10.4, 19.8)
Median stem volume, m^3 (25%, 75% percentile)	0.16 (0.026, 0.55)	0.14 (0.024, 0.45)
BA per 1 ha, m^2	47.1	38.0
Stand stock per 1 ha, m^3, live; deadwood	496; 38	380; 28

Notes: BA, total basal area; SD, standard deviation.

The obtained medians of diameter at breast height (DBH), stem volume, and height turned out to be almost the same for the old-growth and post-logging plots. This similarity of the median values indicates that a ‘typical’ tree in a post-logging stand is almost the same in size as a tree in an old-growth one. However, the proportion of large trees in the old-growth stands is significantly higher, which is reflected in wider interquartile ranges. Thus, the medians do not reveal differences due to the presence of large specimens, but they reflect well the similarity of the dominant classes of stems in both plot categories.

Distribution of stem diameters and volumes. The results of the analysis of the stem diameter and volume distribution are shown as histograms (Fig. 2, 3). In the old-growth stand, the distribution of tree diameter is wider and more uniform: all thickness levels are represented, including large-sized trees with a diameter of more than 40 cm. The post-logging stand is dominated by trees with a diameter of up to 20 cm; larger trees are rare. A similar pattern is observed in the distribution by stem volume: in the old-growth stand, trees with a volume of up to 2–3 m^3 and more are found, whereas in the post-logging plots, specimens with a volume of less than 0.5 m^3 dominate. The contribution of trees with large stem volumes to the post-logging stand is minimal.

Differences in the shape of distributions highlight the key difference between the two categories of stands. The old-growth plots have a more complex structure with pronounced size and age differentiation, whereas post-logging plots remain relatively homogeneous in composition and structure.

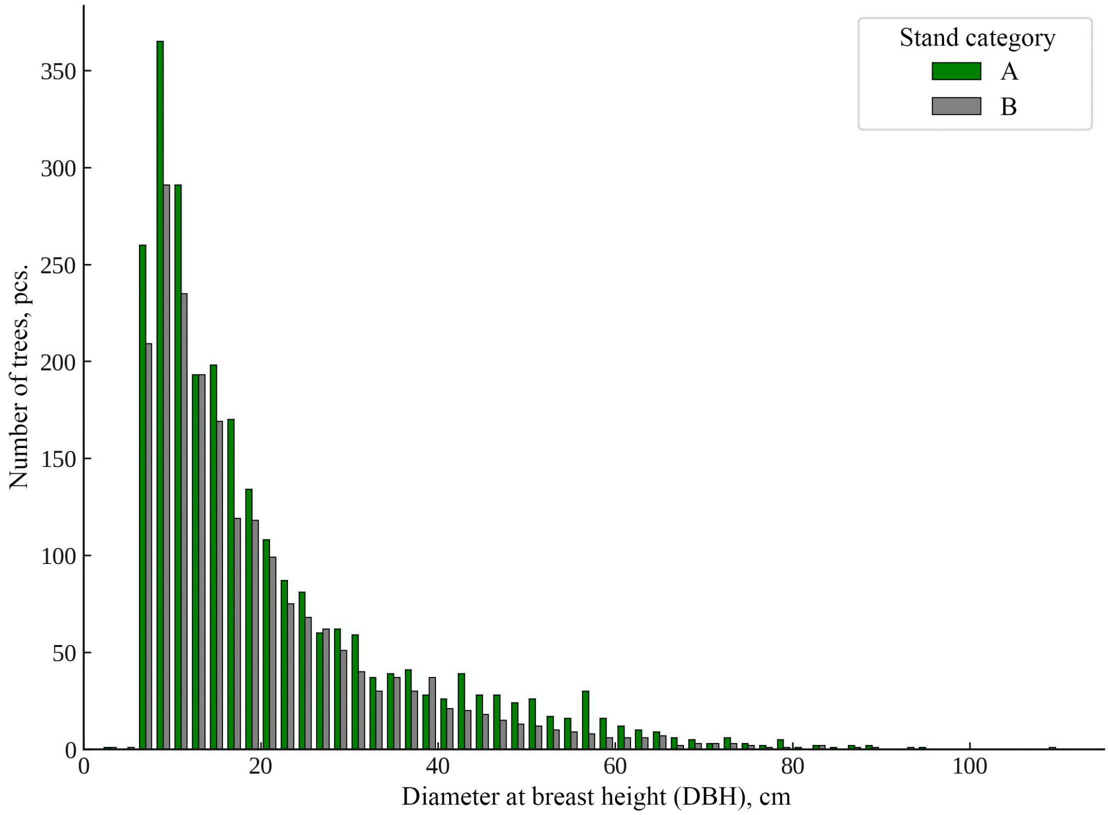

Figure 2. Distribution of trees by diameter (DBH). A, old-growth stand; B, post-logging stand

Comparison of the distributions of the main indicators of trees. The results of the nonparametric Kolmogorov–Smirnov test (Fig. 4) demonstrate statistically significant differences in the distributions of all the studied indicators between the old-growth and post-logging plots. The greatest difference was found for tree height (KS = 0.057, p = 0.0012), which indicates the hete-rogeneity of the vertical structure. Significant differences were also found in the diameter (KS = 0.043, p = 0.0285), total basal area of the stems (KS = 0.043, p = 0.0285), and the stem volume (KS = 0.047, p = 0.0124). This confirms that even 60–70 years after disturbances, the post-logging stand still has a simplified structure and does not reach the spatial and dimensional complexity typical of an old-growth stand.

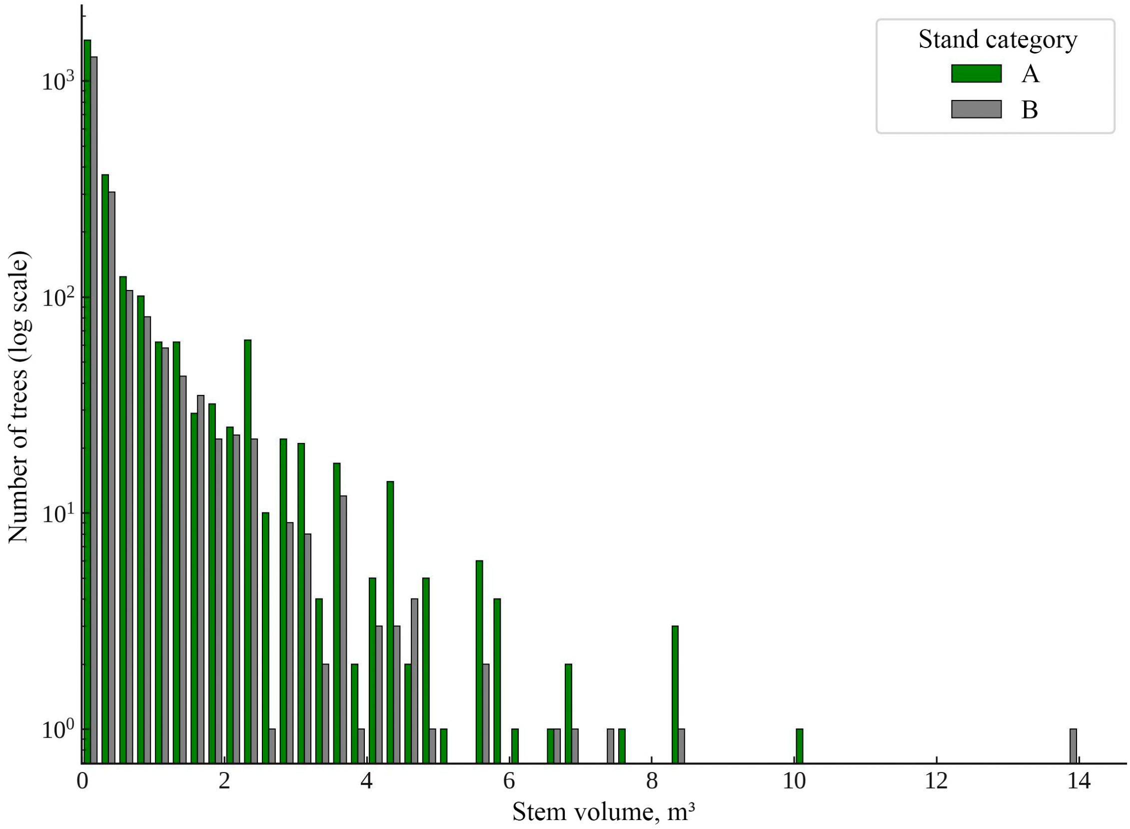

Figure 3. Distribution of trees by stock (the y-axis is logarithmic). A, old-growth stand; B, post-logging stand

Characteristics of individual species. Figure 5 illustrates the differences in diameter at breast height and stem volume among tree species in the old-growth and post-logging plots. *Picea koraiensis* and *Taxus cuspidata* were excluded from the analysis, as there are too few individuals of these species to calculate the average values and their variations. The average values of stem diameter and timber volume per stem vary significantly between tree species, as well as between the old-growth and post-logging plots. The largest stem sizes are typical of *Pinus koraiensis* and *Picea ajanensis*: In *Pinus koraiensis*, the average diameter in the old-growth plots is 40.9 cm, and in the post-logging plots it is 24.5 cm, which is 40% less. A similar trend is observed for the stem volume: 2.42 m^3 versus 1.09 m^3, respectively; the difference is 55%. In *Picea ajanensis*, the average diameter decreases from 26.2 to 21.7 cm (−17%), and the volume decreases from 0.69 to 0.46 m^3 (−33%).

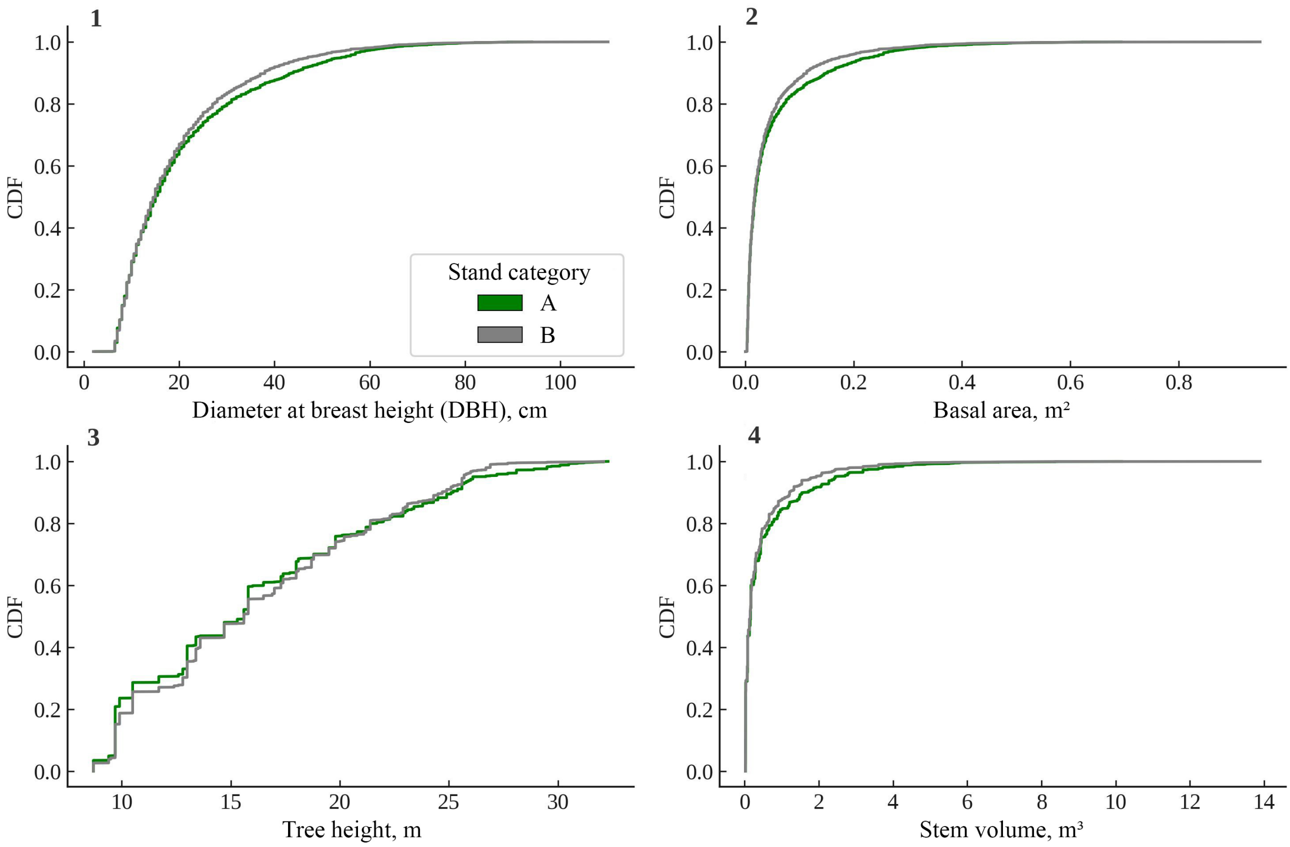

Figure 4. Distribution functions (CDFs) of the main indicators of trees. 1, diameter at breast height (DBH), cm; 2, total basal area, m^2; 3, tree height, m; 4, stem volume, m^3. A, old-growth stand; B, post-logging stand

Similar diameter values were found for *Tilia amurensis* and *Quercus mongolica* in both categories of stands. So, for example, *Tilia amurensis* has an average diameter of 23.2 cm in the old-growth forests and 22.5 cm in the post-logging forests, and a volume of 0.55 and 0.47 m^3, respectively. In *Betula costata*, on the contrary, there is a sharp decrease from 42.0 to 22.0 cm in diameter (−48%) and from 1.66 to 0.48 m^3 in volume (−71%).

In many instances, standard deviations are also higher in the old-growth forests, which indicates a greater heterogeneity and age mosaic pattern of the stand. For some species, data are available only for one of the categories, which is due to their absence or sporadic representation in the other. This applies, in particular, to *Phellodendron amurense*, *Ulmus laciniata*, and *Salix caprea*, which are found exclusively in the post-logging plots.

The nonparametric Mann–Whitney test was used to assess differences in the morphometric indicators of trees (DBH and stem volume) between old-growth and post-logging plots. The analysis included only those species for which there were at least 10 living trees in each category (11 species in total).

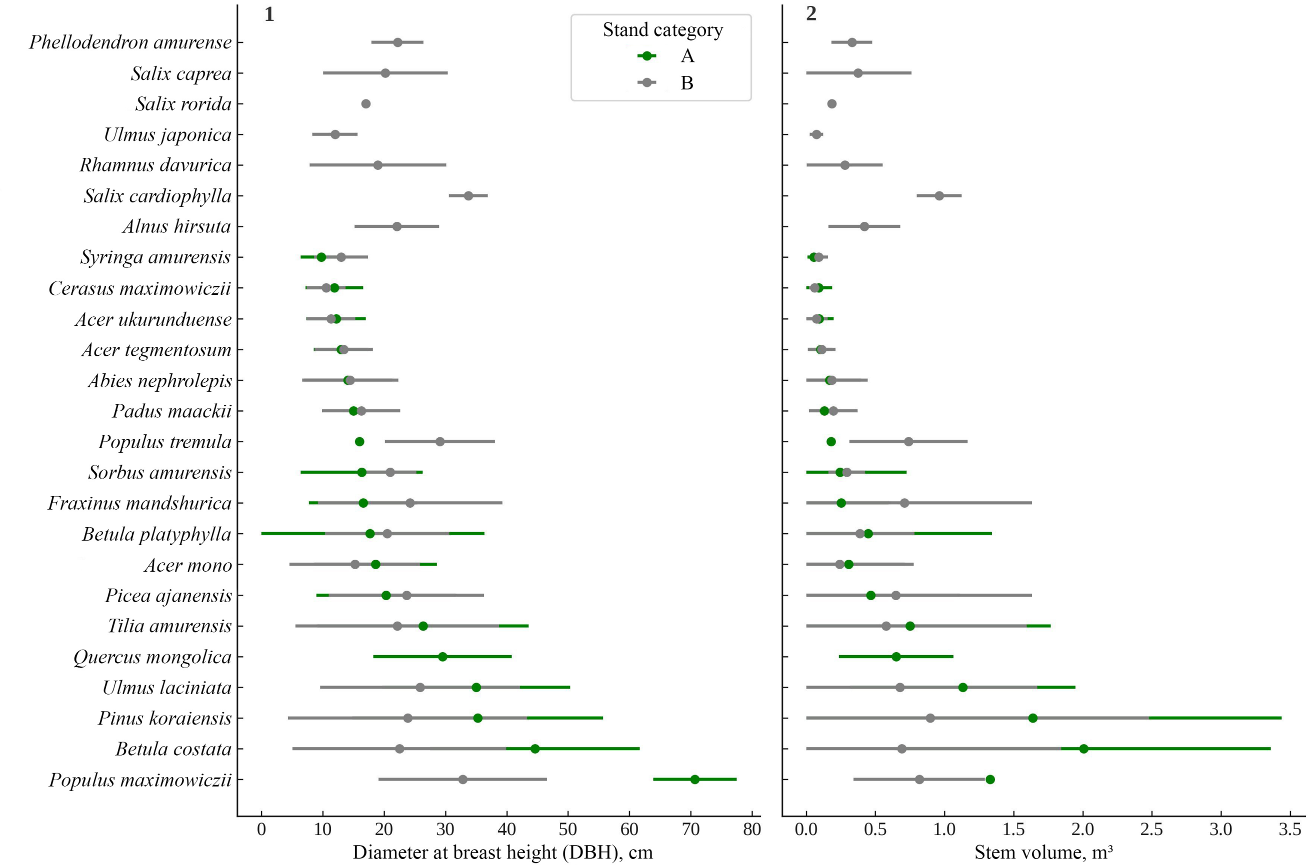

Figure 5. Average values of diameter (DBH) (1) and stem volume (2) of trees of various species in the old-growth (A) and post-logging (B) stands (± SD)

Comparison of median values of diameter at breast height showed statistically significant differences for all five most widespread species: *Betula costata*, *Pinus koraiensis*, *Tilia amurensis*, *Acer mono*, and *Picea ajanensis* ($p < 0.01$ in all cases). In the first four species, the diameter of trees was significantly higher in the old-growth plots, while the opposite trend was observed for *Picea ajanensis*, i.e., larger trees were found in the post-logging plots. A similar pattern was found for the stem volume: in *Betula costata* and *Pinus koraiensis*, the median volume in the old-growth plots was several times higher than in the post-logging plots. Thus, the structure of the stand varies significantly between categories in a number of key species.

Characteristics of stock accumulation in the old-growth and disturbed forests. Figure 6 illustrates the distribution of live timber stock between species in the old-growth and post-logging plots. *Pinus koraiensis* dominates in the old-growth plots, accounting for 32.0% of the total timber stock (146.6 $m^3 * ha^{-1}$). Its contribution to the stock of the post-logging plots is more than ninefold lower, 4.7% (16.6 $m^3 * ha^{-1}$), which indicates weak recovery dynamics of this species after disturbances. *Picea ajanensis* and *Betula costata*, on the contrary, show high stock values in the categories: their total contribution is 29.1% in the old-growth plots and 42.7% in the post-logging ones, reflecting their resistance to disturbance and their ability to form both stable and secondary communities.

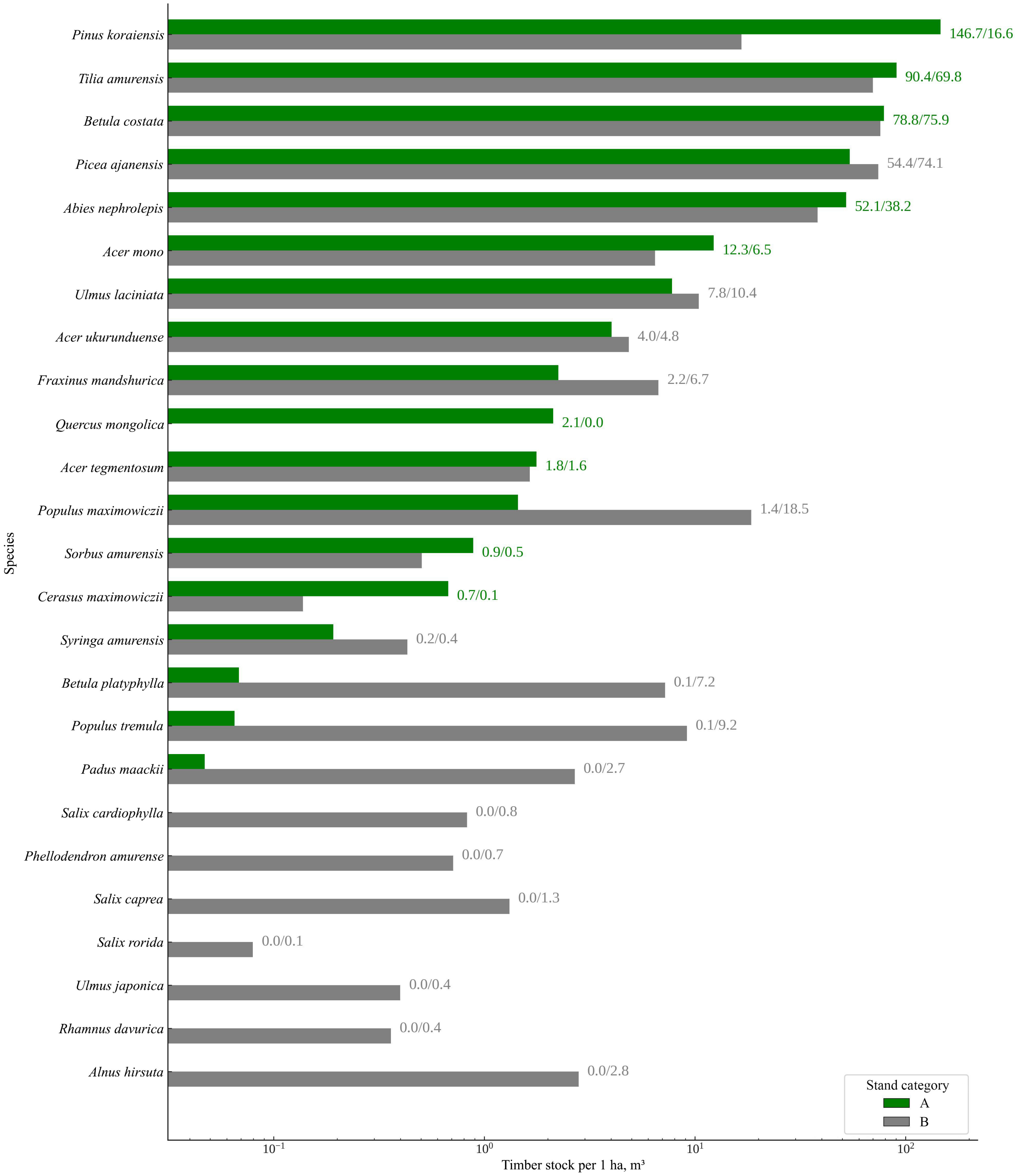

Figure 6. Timber stock per 1 ha by species in the old-growth (A) and post-logging (B) stands

In the post-logging stands, the proportion of pioneer species is noticeably higher, namely *Populus maximowiczii* (5.3% of the stock), *Populus tremula* (2.6%), *Padus maackii* (0.8%), *Alnus hirsuta* (0.8%), and *Betula platyphylla* (2.0%). They hardly participate in the formation of the stock in the old-growth stands. These species, along with the other small-leaved and light-loving species, form the typical structure of the early succession. Thus, as a result of logging, there is a shift towards fast-growing species, and the participation of *Pinus koraiensis* and other late-successional species is significantly reduced.

To assess differences in the structure of timber stock between the old-growth and post-logging plots, a χ^2 test was conducted based on the proportions of tree species in the total stock per 1 ha. For each species, its contribution to the total stock within each plot category was calculated.

The test results showed that the distribution of stocks by species between the two categories significantly differs (χ^2 = 150.66; $p < 0.0001$). This confirms the conclusion that the contribution of individual species to the total stock varies both in size and composition. In general, the structure of dominance in the post-logging stands is formed by faster and more adaptive species, while the participation of primary species is significantly reduced.

State of the stand 60–70 years after logging and the possibility of restoring its original state. The restoration of Korean pine-broadleaf forests after industrial logging is a complex and slow process depending on many biotic and abiotic factors, which is demonstrated in a number of studies, including the review by Manko et al. (2009) and analytical data by Kovalev and Kachanova (2023) indicating the duration and ambiguousness of restoration even after single logging. State assessment of the post-logging stands 60–70 years after single logging makes it possible to assess the direction and degree of successional changes. In our study based on data collected under comparable conditions in the southern Sikhote-Alin, stands that were subjected to logging in the 1960s were compared with old-growth undisturbed stands. This makes it possible to assess the degree of convergence of the forest structure after logging with the initial one and to identify signs indicating a continuing transformation. It should be noted that in the case under consideration, logging was selective: only *Pinus koraiensis* and *Picea ajanensis* were harvested, single large-sized trees being removed, and disturbance to stand structure was minimal.

Assessment of such indicators as the average diameter, height, total basal area and the stock revealed typical differences between the post-logging and old-growth stands. The post-logging plots are dominated by trees with a smaller diameter: the average diameter (19.3 cm versus 20.6 cm) and, especially, the stock per 1 ha (380 m^3 * ha^{-1} versus 496 m^3 * ha^{-1}) are lower as compared to undisturbed plots. Histograms of the stem diameter and volume distribution show the absence of large trees in the post-logging stands, whereas in the old-growth stands all classes are represented, including individual trees with stem volumes of up to 10–14 m^3. These differences are statistically significant, which is confirmed by the results of the Kolmogorov–Smirnov test.

A similar situation has been described in studies of dark coniferous forests after continuous logging. For example, according to Likhanova et al. (2021), in blueberry spruce forests of the middle taiga, no more than 50–60% of the original composition and structure is restored 50 years after logging. At the same time, the authors emphasise that even after 60 years, the structure of phytocenoses remains significantly different from the primary one, and the restoration of a full-sized stand requires a much longer time.

The picture obtained in this study is fully consistent with these conclusions: the time interval of 60–70 years after single logging is insufficient to restore the original size composition of Korean pine-broadleaf forests.

Significant differences between the post-logging and old-growth plots were also identified in the species composition of stands. In the plots that have not been logged, *Pinus koraiensis* remains the main forest-forming species, making the greatest contribution to the total stand timber stock. At the same time, the proportion of the Korean pine in the post-logging plots is drastically reduced, and fast-growing deciduous species, namely birch, poplars, bird cherry, and alder, are predominant.

Similar patterns are described in a study by Kovalev et al. (2021), which highlights that after logging, the Korean pine does not regain a leading position in the stand for a long time, yielding to fast-growing deciduous species, and even in the presence of undergrowth, the rate of Korean pine regeneration is insufficient for substantial participation in stand formation. In a more recent work by Kovalev and Kachanova (2023), it is shown that the restoration of the original structure of Korean pine forests after logging can take more than 150 years, and without active measures to promote Korean pine regeneration, its participation in stands remains marginal. The authors emphasise that under current conditions of economic use, such timescales are as good as unattainable. Similar conclusions were drawn in the studies by A. I. Kudinov (2012, 2014) based on 40 years of monitoring of the post-logging plots in the southern Primorye: despite the preservation of individual coniferous elements in the undergrowth, the stands are dominated by deciduous species. The author assumes that even with the presence of Korean pine undergrowth and the potential for its participation in the formation of a stand, the community structure remains stable and focused on the predominance of deciduous species. The change of dominance of deciduous species to *Pinus koraiensis* occurs within 120–160 years after logging and only if there is an already existing undergrowth in the amount of 400–500 specimens * ha^{-1}. The work of S. G. Glushko et al. (2022) considering successional dynamics of fir-spruce forests demonstrates that the restoration of the original structure occurs unevenly and with high spatial mosaicism, especially in the absence of targeted forestry practices.

Regional surveys (Manko et al., 2009; Manko and Petropavlovskii, 2010) confirm that the transformation of Korean pine forests into secondary forests after economic intervention is ubiquitous, and the restoration of original structure of forests can take centuries. Emerging communities show stable dynamics, often with a shift towards alternative forest types, i.e. oak forests, spruce forests, maple-linden and mixed deciduous stands. These changes are followed by a decrease in productivity, biological diversity, and protective functions.

Similar results were obtained for the dark coniferous forests of the European Russia. According to I. A. Likhanova et al. (2021), even 50–60 years after continuous logging, the restoration of the original structure is incomplete; succession often ends with the formation of stable secondary communities with a different dominant composition. A similar situation is observed in the temperate forests of Scandinavia: Asplund et al. (2020) showed that secondary forests retain differences in species composition, vertical structure, and undergrowth composition even half a century after logging. The authors emphasise the sustainability of the so-called ‘legacy of forest management’, which forms a long-term structure of the forest community which is however different from the original structure; either targeted intervention or a long time is required for the restoration. This phenomenon is less pronounced in the Korean pine-broadleaf forests in the south of the Russian Far East, but the recovery time significantly exceeds the logging period (Kovalev, Kachanova, 2023).

Taking together, the literature data (Kudinov, 2012; Kudinov, 2014; Kovalev et al., 2021, 2023; Manko et al., 2009) and the results obtained in this study allows us to conclude that even after a single and long-ago intervention, the restoration of the original structure of Korean pine-broadleaf forests is extremely slow and remains incomplete even 60–70 years later. The post-logging stands differ significantly from the old-growth stands in terms of timber stock, size structure, and dominant species. They lack large trees; light-loving deciduous species predominate, and the participation of *Pinus koraiensis* is minimal.

Such communities represent a transitional successional stage, where the pioneer species still retain a dominant position, while the late successional *Pinus koraiensis*, *Picea ajanensis*, and *Betula costata* Trautv. are beginning to build up stock. This indicates the slow response of disturbed Korean pine-broadleaf forests and the long-term consequences of even mild impacts, highlighting the need to revisit approaches to their protection, restoration and forest management.

CONCLUSION

The present study showed that 60–70 years after single selective logging, the structure and composition of stands remain significantly different from old-growth Korean pine-broadleaf forests. The post-logging stands are characterised by a lower timber stock, significant participation of pioneer deciduous species and the absence of large trees, which indicates the incompleteness of restoration processes. Although *Pinus koraiensis* remains in the composition, it still does not regain its dominant position: its proportion in the structure and growth rates remain insufficient to compete with fast-growing deciduous species.

Thus, the restoration of the original structure of Korean pine-broadleaf forests is a slow and unstable process that is influenced by many factors and requires a long time. Even with minimal intervention, a return to the original state can take more than 100 years and, as a rule, does not occur within a single logging period without active assistance in terms of forest management.

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