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STRUCTURAL PROPERTIES AND GROWTH DYNAMICS OF A UNEVEN-AGED PURE PINE FOREST STAND

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ABSTRACT: This study examines the growth dynamics and structure of an uneven-aged pure Scots pine (Pinus sylvestris) stand in the alpine zone at elevations between 1800 and 2200 meters in Georgia, with the forest ending at 2188 meters. The research site was centered at 2056 meters, where a one-hectare plot was selected. To avoid edge effects, we chose a denser part of the forest rather than the border, ensuring natural resource distribution. Data on tree height, diameter at breast height (DBH), and annual growth increments were collected from a randomly selected plot. Dendrochronological analysis showed younger trees (<40 years) had a mean growth rate of 1.588 mm/year (±0.1505 mm) over five years, while trees aged 40–70 years and over 70 years exhibited rates of 1.173 mm/year (±0.0723 mm) and 1.166 mm/year (±0.2245 mm), respectively. Findings highlighted correlations between age, height, and DBH, showing distinct growth patterns tied to tree age and size. The uneven-aged structure influenced light availability and competition, impacting growth rates. Regeneration analysis revealed diverse age distribution, suggesting ongoing recruitment. Relationships between DBH increment and average DBH indicated faster growth until trees reached a specific size threshold. These insights enhance understanding of growth processes in uneven-aged pine stands, with implications for sustainable forest management. Findings on growth dynamics and recruitment patterns can guide conservation strategies, balancing forest productivity with ecosystem health.

Keywords: Pure pine stand, Uneven-aged Forest, Growth dynamics, Annual increment, Dendrochronology.

1. INTRODUCTION

Forest ecosystems are essential for maintaining ecological balance, providing habitats for diverse species, and serving as vital resources for human use. Uneven-aged forests, characterized by their structural complexity and resilience, are crucial in sustaining biodiversity and ecological stability. These forests contain trees of various ages and sizes, contributing to their ability to regenerate and support diverse habitats continuously [1]. Pure pine stands, such as Pinus sylvestris, are prominent in temperate regions and hold significant ecological and economic value.
However, modern forest policies now emphasize sustainable management of forest ecosystems rather than merely viewing them as sources of wood products. This shift in perspective has led to considerations of converting pure coniferous forests to near-natural and mixed broadleaved-coniferous forests, which offer multiple benefits, including greater diversity, enhanced disease resistance, and improved stability against disturbances. This aligns with the broader trend of optimizing ecosystems for both economic and environmental sustainability, as seen in the utilization of coastal mangrove ecosystems for multiple purposes [2].

Understanding the dynamics and structural characteristics of uneven-aged stands is essential for developing sustainable management practices. These practices aim to mimic natural processes, ensuring continuous growth, regeneration, and resource availability. Key aspects of this understanding include growth dynamics, which involve patterns of tree growth and the factors influencing these patterns, and structural characteristics such as tree size distribution and age structure.

This study investigates an uneven-aged pure pine stand located between an elevation of 1800 and 2200 meters in Georgia. By examining tree height, diameter at breast height (DBH), annual growth increments, wood density, and moisture content, the research aims to uncover the intricate relationships between these variables and their impact on forest dynamics. Utilizing dendrochronology, which studies/ tree-ring patterns, we measure annual growth increments to provide a detailed historical record of growth trends [3].

The objectives of this research are as follows: analyzing the growth dynamics of pine trees within the stand and identifying how growth rates vary with age and size. Additionally, the research aims to investigate the structural characteristics of the stand, including tree density, basal area, and the distribution of different age classes.

The hypothesis posits that younger trees exhibit faster growth rates compared to older trees due to reduced competition and greater access to resources. Furthermore, examining the relationship between DBH increment and tree size will enhance our understanding of how growth rates change as trees mature. The findings offer a framework for managing uneven-aged pine stands in mountainous ecosystems worldwide, where such systems are vital for biodiversity and climate resilience [4].

Existing research on uneven-aged pine stands has disproportionately focused on lowland forests, leaving a gap in understanding their growth patterns in high-altitude environments such as those in Georgia [5]. This study aims to bridge this gap by analyzing growth increments, structural properties, and regeneration patterns in a mountainous, uneven-aged pine stand. By quantifying these relationships, our research contributes to the global understanding of forest stand dynamics, particularly in challenging terrains where microclimatic stressors and steep slopes influence growth trajectories.

This study aims to explore the growth dynamics and structural characteristics of a mixed-aged Scots pine stand located in the Erusheti Highlands of Georgia. The forest's diversity, ranging from young saplings to mature trees, offers a unique opportunity to examine how trees of different ages respond to environmental factors like temperature and precipitation. Understanding these growth patterns can provide valuable insights for improving forest management practices, especially in regions like Akhaltsikhe, where steep slopes and challenging terrain complicate traditional forestry methods[6].

Moreover, this research holds significant potential for both the engineering and construction industries. By analyzing the structural properties of wood from these trees, we can develop more sustainable building materials that not only offer strong, renewable resources but also help mitigate climate change. When used in construction, wood products act as a carbon sink, effectively storing carbon that would otherwise be released into the atmosphere. This creates a natural cycle where wood products help offset emissions, contributing to a more environmentally friendly approach to development while promoting the use of materials that support a sustainable, low-carbon future.

2. RESEARCH SIGNIFICANCE

This study on the growth dynamics and structure of an uneven-aged pure pine stand at high elevation provides key insights for sustainable forest management. Analyzing tree age, size, and growth rate informs strategies to maintain forest health, biodiversity, and productivity amid climate change. The findings connect to Sustainable and Smart Environmental Engineering through precision forestry, adaptive management, and technology like remote sensing and GIS. These tools optimize ecosystem services and enhance resilience, supporting eco-friendly practices for sustainable resource use and climate change mitigation.

3. MATERIALS AND METHODS

3.1 Study Area

The study area is located in Georgia's south-western region of Samtskhe-Javakheti, specifically within the Akhaltsikhe municipality, on the northern slope of the Erusheti Highlands, near the Akhaltsikhe town – an administrative center of the municipality. It borders the Borjomi and Aspindza municipalities to the east, the Adigeni municipality to the west, the Imereti region to the north, and Turkey to the south. Akhaltsikhe is located on both banks of the Potskhovistskali River, at an altitude of 1000 m above sea level, 214 km from Tbilisi (the capital of Georgia). Akhaltsikhe is characterized by a mountain steppes climate with cold, snow-free winters and long warm summers, with significant rainfall even in the driest month. The average temperature in January is 10°C; in August, it is 20°C. According to multi-year meteorological observations, the average annual precipitation in the region ranges from 400 to 700 mm [7].

Akhaltsikhe municipality features diverse soil types, including skeletal Brown Forest (according to WRB – Cambisol Dystric) and Mountain-Medow (Leptosols Umbric) soils [8].

A single 100 m × 100 m plot was selected based on its representativeness of the broader forest structure in the region, ensuring a balance between young, mature, and older trees. The sample size of 456 trees was determined to achieve statistical robustness, following the methods outlined by the Georgian National Forest Agency's National Forest Inventory (NFI). Given the challenging terrain, slope stability was accounted for by selecting trees across a range of inclinations, ensuring that growth data were not biased by erosion-prone zones.

3.2 Study Plot Description

The study plots were established on the Erusheti Highlands near Akhaltsikhe (Fig. 1).

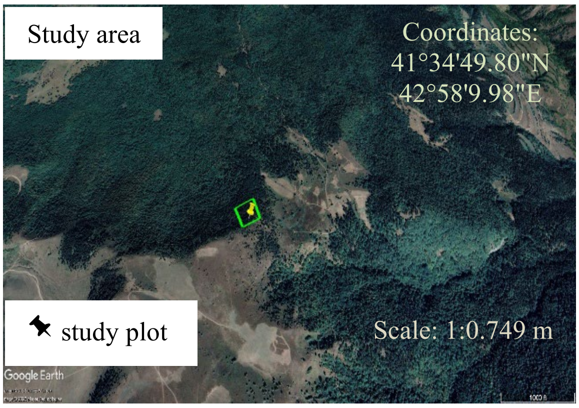

Fig. 1. Geographic Location of the Study Area in Akhaltsikhe, source: Google Earth.

All plots are situated on Brown Forest soils (Cambisol Dystric) within a subalpine zone at an elevation of approximately 1800-2045 meters above sea level.

Soil-forming parent materials of Cambisols Dystric in this region are presented as tertiary volcanic and sedimentary parent materials and their weathering products (porphyries, andesite basalts, sandstones, conglomerates, etc.). The humidity coefficient is more than 1, making for the wash-down water regime. The morphological structure of the soil profile is 0–A–Bm–BC–C. They are characterized by a well-established forest litter, rust color, profile skeleton (in their lower layers, particularly), and acid reaction, which reduces at greater depths. Cambisols Dystric soil is moderately or deeply containing soil organic matter. It has a strongly pronounced organic material of a dark color. Its profile is cloddy and partly granular in the upper profiles. With their mechanical texture, the soils are classified as loamy soils. They get heavy in the lower layers. The profile is characterized by intense weathering.

Cambisols Dystric soils are provided with nitrogen. The type of soil organic matter is fulvous. The properties of humic acids and fulvoacids are quite similar. Alumosilicates decompose easily, thus contributing to the formation of secondary clay minerals (e.g., a group of montmorillonite). One of the typical features of these soils is the accumulation of SiO_2 in the upper horizons. Calcium dominates in the exchange cations. The sum of absorbed cations is average. Accumulation of Fe_2O_3 and Al_2O_3 takes place in the middle part of the soil profile. More detailed information on the study area is provided in Table 1.

Table 1: Characteristics of the Study Plot

Plot Coordinates	Elevation (meters)	Inclina-tion (°)	Expo-sition	Average Tem-perature (°C)
41°34'49.8"N 42°58'9.984"E	1932	45	North Slope	July: 12, January: -11

The plot is an uneven-aged forest containing young, mature, and older trees, some of which may be over 200 years old. Many trees in this area exhibit snow damage, visible on their crowns. This damage is likely due to the higher elevation, resulting in heavier snowfall, The image was taken by a camera with high definition 4896 x 3672 pixels (Fig. 2).

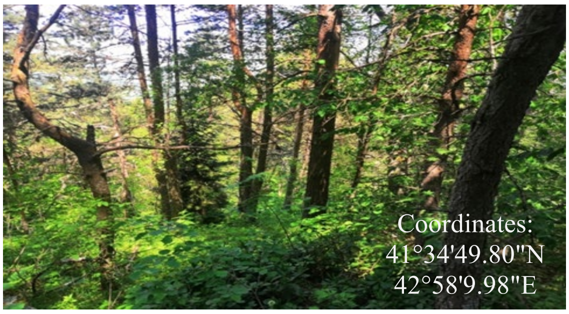

Fig. 2. Uneven-Aged Pine Forest in Akhaltsikhe

3.3 Data Collection

In this study, we established a single plot of 100 square meters with 796 trees. All trees with a diameter at breast height (DBH) equal to or greater than 8 cm were tallied according to species. Measurements were recorded for DBH, total height, and the most recent five-year radial increment, determined by coring at breast height Table 2 [9]. Following the Georgian National Forest Agency (NFI) methods, we used a random sampling method to ensure a representative sample. DBH was measured at 1.3 meters above ground using a diameter tape. Tree height was calculated with a Sunnto clinometer, and the Geographical coordinates of each tree were recorded with a GPS device. Additional measurements included canopy width and tree health indicators, such as disease presence and damage. All data were meticulously documented for subsequent analysis, providing a detailed assessment of forest structure and health. Its level of data precision ensures the reliability of our findings, contributing significantly to our understanding of forest dynamics. The methodology focused on capturing detailed measurements and maintaining consistency in data collection, allowing for accurate analysis.

Table 2: Tree attributes of Scots pine

Variable	Diameter at breast height	Total height
Unites	Cm	M
Symbol	DBH	HT
Max	32.4	20.7
Min	8.5	7
Mean	23.10385	14.92692
STD	5.604247	3.247837

3.4 Sample Analysis

Collected samples were analyzed using Dendrochronology, the scientific method of measuring and dating tree rings to the exact year they were formed [10, 11]. The samples were obtained by using an increment borer,

In the lab, the cores were analyzed to calculate the tree samples, which initially oven-dried at 105 °C for 72 hours to determine their dry mass. For this a special drying tool was used. While oven-drying samples at 105°C for 72 hours was necessary to determine dry mass, this process may have caused a slight shrinkage of growth rings. However, studies on coniferous species like Scots pine (Pinus sylvestris) suggest that radial shrinkage typically remains below 5%, ensuring minimal distortion in recorded increment values. In contrast, total mass loss due to moisture evaporation in such species can range from 30% to 50%, depending on initial moisture content and environmental conditions [12]. Once dried, the analysis proceeded using the software applications CooRecorder and CDendro. To enhance reproducibility, each core was scanned using a high-resolution flatbed scanner at 1200 dpi, and the images were saved in TIFF format to maintain quality. The scanned images were then imported into CooRecorder software, where measurement points were manually placed from the leftmost edge of a tree ring to the rightmost edge. If ring boundaries were unclear, contrast adjustments and zoom functions were used for precision. The extracted ring-width sequences were then exported to CDendro software, which cross-matched individual samples against a reference chronology to identify missing or false rings. Any flagged discrepancies were manually reviewed, and corrections were made if necessary. The combination of CooRecorder and CDendro provided reliable tree-ring measurements, allowing for accurate growth analysis. CooRecorder was employed to measure tree-ring widths and accurately determine the age of each tree. This application provided precise measurements of distances between tree rings. CDendro was used for organizing and crossdating the tree-ring data, ensuring a comprehensive analysis of the samples. The methodology for using these tools followed the procedures outlined by R. Stockton Maxwell and Lars-Ake Larsson [13]. The analysis involved recording each tree twice: initially, before drying, where the average ring width was 2.56 mm ± 0.16 mm without age categorization, and again after drying. Post-drying, the trees were classified into three age groups: below 40 years, between 40 and 70 years, and above 70 years. The increment of the last five years for each tree was then calculated, and average growth rates were documented, as detailed in Table 3.

Table 3: Average Growth Increment by Age Group after drying to constant weight

Age Groupe (year)	Tree number N =796	Mean increment (mm/yy)	Standard deviation (mm)
< 40	201	1.588	0.1505
40 - 70	481	1.173	0.0723
> 70	114	1.166	0.2245

4. RESULTS

The analysis of tree growth dynamics revealed significant variations across different age groups and sizes within the uneven-aged pure pine stand. Younger trees (<40 years old) exhibited the highest average growth increment over the last five years, with a mean increment of 1.588 mm/year (±0.1505 mm). In contrast, trees aged 40-70 years and those over 70 years showed slightly lower growth rates, with mean increments of 1.173 mm/year (±0.0723 mm) and 1.166 mm/year (±0.2245 mm), respectively (Fig. 3).

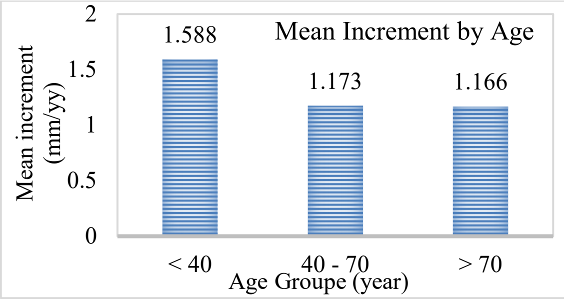

Fig. 3. Tree growth dynamics variations across different age groups.

Figure 4 illustrates the distribution of mean and growth increments over the last five years across different age groups of pine trees in the stand. This visualization provides a comprehensive view of how the average growth varies annually. This analysis not only highlights the annual variability in growth rates but also provides insights into how these dynamics differ across different age classes within the uneven-aged pine stand. Understanding these variations is crucial for effective forest management strategies aimed at sustaining biodiversity and optimizing resource use in similar forest ecosystems.

Younger trees often compete intensely for light and nutrients, while mid-age categories exhibit higher resilience to inter-tree competition due to their well-established canopy positions and root systems. Such patterns have been explored through simulation studies, revealing how recruitment and competition interact to shape the structure and dynamics of uneven-aged stands [15].

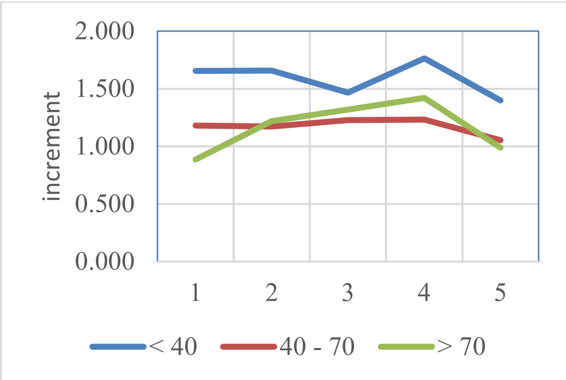

Fig. 4. Average Growth Increment Over the Last Five Years by Age Group

Table 4 offers insights into the growth patterns of Scots pine trees across three age groups: under 40 years, 40-70 years, and over 70 years, using data from 2019 to 2023. The table tracks the average growth increment, standard deviation, and standard error, providing a clear view of growth trends.

Table 4. Age-Dependent Growth Increments of Scots Pine Trees (2019–2023)

Age	year	2019	2020	2021	2022	2023
< 40	Avg	1.398	1.763	1.467	1.657	1.655
	SD	0.327	1.004	0.600	0.637	0.638
	SE	0.134	0.410	0.245	0.260	0.260
40-70	Avg	1.181	1.172	1.228	1.232	1.053
	SD	0.389	0.456	0.471	0.403	0.529
	SE	0.094	0.111	0.114	0.098	0.128
> 70	Avg	0.885	1.218	1.320	1.420	0.988
	SD	0.236	0.527	0.487	0.367	0.355
	SE	0.105	0.236	0.218	0.164	0.159

For young trees (under 40), growth is rapid and consistent, peaking at 1.763 in 2020 and stabilizing between 1.467 and 1.657 in subsequent years. The mid-age group (40-70 years) shows slower, stable growth, starting at 1.181 in 2019 and remaining between 1.172 and 1.232 until a slight drop to 1.053 in 2023. The oldest trees (over 70) start with a lower growth rate of 0.885 in 2019, peak at 1.420 in 2022, and then drop to 0.988 in 2023. This group shows more uneven growth, with variability decreasing after the peak. Using a 1.96 confidence interval for standard deviations ensures the data's reliability, showing that younger trees grow quickly and consistently, mid-aged trees grow steadily, and older trees grow more slowly and erratically. This data provides valuable insights for forest management and ecological studies.

The relationship between temperature and increment in different age categories of trees over the last five years is shown in Figure 5. The blue bars represent the annual average temperatures, while the red, yellow, and green lines represent the increment in tree growth for age categories <40 years, 40-70 years, and >70 years, respectively.

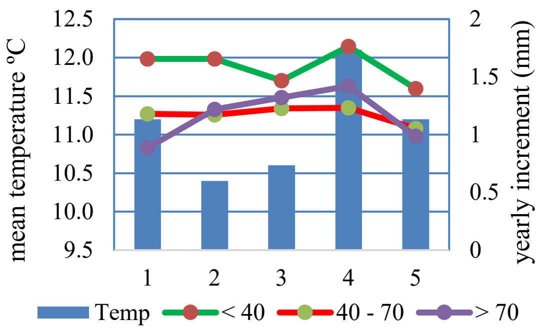

Fig. 5. Impact of Temperature on Tree Growth Increments Across Different Age Categories Over Five Years

The temperature fluctuates over the five-year period. Overall, the data suggests that younger trees (<40 years) exhibited a more significant growth response to rising temperatures compared to older trees (>70 years). This trend may be attributed to the higher physiological activity of younger trees under favorable thermal conditions, as suggested by a study on the temperature sensitivity of tree-ring growth increments in pine species [16]. In contrast, mid-age trees (40–70 years) demonstrated stable growth increments across varying temperature conditions, reflecting potential adaptive resilience to temperature fluctuations.

These findings are consistent with dendroclimatic studies that have identified a positive correlation between warmer temperatures and increased photosynthetic activity in younger pine trees. However, such effects are often modulated by soil moisture availability, which remains a critical factor in sustaining growth.

Figure 6 illustrates the relationship between precipitation and tree growth increments over five years. Green bars represent annual average precipitation, while blue, red, and yellow lines indicate growth increments for age categories <40 years, 40-70 years, and >70 years, respectively. Precipitation fluctuates between 1200 mm and 2200 mm. Overall, younger trees show more significant growth increases, mid-age trees are more stable, and older trees are more sensitive to precipitation changes. These insights are valuable for forest management and conservation efforts. These findings highlight the differential impact of temperature and precipitation on tree growth across various age categories, providing valuable insights for forest management and conservation efforts.

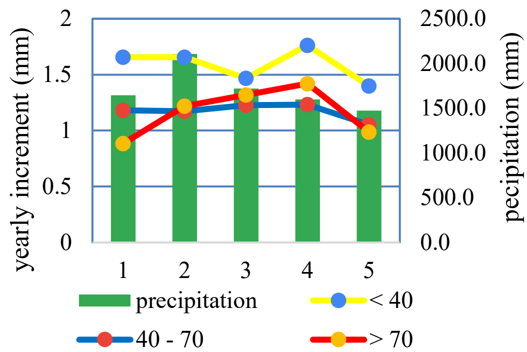

Fig. 6. Impact of Precipitation on Tree Growth Increments Across Different Age Categories Over Five Years

Younger trees responded more positively to higher precipitation levels, showing greater growth increases compared to mid-age or older categories. This differential response could reflect the greater dependence of younger trees on soil moisture availability, as explored in drought-precipitation interaction studies on forest stands [17]. The mid-age category remained relatively stable, whereas older trees (>70 years) displayed increased sensitivity to both excessive and reduced precipitation, likely due to declining physiological efficiency with age.

5. DISCUSSION

This study explores the growth dynamics and structural characteristics of an uneven-aged pure pine stand, focusing on Scots pine (Pinus sylvestris) at an elevation of 1800 meters in Georgia. Our findings shed light on how size-class uniformity and dominance affect stand growth dynamics and efficiency.

5.1 Growth Dynamics Across Age Groups

Younger trees (< 40 years old) showed the highest average growth increment over the last five years, indicating vigorous growth in the early stages of development. This is due to rapid height and diameter growth as these trees establish themselves in the forest canopy with less competition and light.

Older trees (>70 years) exhibited lower growth rates, reflecting competition for resources and age-related physiological limitations. This variability highlights the need for age-specific management strategies to ensure sustained productivity.

Younger trees (<40 years) exhibited a more pronounced response to increasing temperatures, while older trees (>70 years) showed greater sensitivity to fluctuations in precipitation levels. This aligns with existing studies on pine species, which indicate that younger trees rely more heavily on soil moisture availability, making them more vulnerable to seasonal drought stress. Conversely, mid-aged trees (40-70 years) displayed more stable growth patterns, suggesting greater resilience to climate variability. The uneven-aged structure of the pine stand influenced light availability and competition among trees, affecting individual growth rates. This structural complexity supports biodiversity by creating diverse habitats within the forest ecosystem. The presence of multiple age classes, from young saplings to old trees, enhances resilience against environmental disturbances and promotes long-term stability [18].

5.2 Implications for Sustainable Management

Adaptive management practices tailored to the specific needs of uneven-aged forests are crucial. Strategies should prioritize maintaining structural diversity, promoting natural regeneration, and mitigating human impacts to enhance overall forest health and resilience. Maintaining a diverse age structure can help the forest better withstand climate variability, ensuring that younger trees are available to replace older, declining ones. These findings can help optimize ecosystem services, conserve biodiversity, and mitigate climate change impacts. From the viewpoint of water resource management, forested areas are considered to be water sources and are closely linked to downstream ecosystems. Thus, when establishing policies for water resource management, forests play a significant role [19]. Also, the root system of vegetation not only anchors soil but also plays a critical role in stabilizing slopes, enhancing soil structure, and effectively preventing landslides [20]. Steep terrains present logistical challenges for mechanized thinning operations. In such areas, manual thinning using hand tools or lightweight equipment is a feasible alternative to minimize soil disturbance. Furthermore, tree selection should prioritize removing competition-heavy individuals while maintaining root stability, reducing the risk of soil erosion [21]. These approaches align with best practices in high-altitude forest management, ensuring that thinning operations do not compromise slope integrity [22].

5.3 Size-Class Uniformity and Growth Efficiency

Our study found that greater size-class uniformity negatively impacts the growth of Scots pine. This aligns with findings by Bravo and Guerra [23] in Pinus pinaster stands in Central Spain. Contrary to Binkley's hypothesis [24], which suggests that increased size-class differentiation leads to greater growth efficiency, our results do not support this. Instead, initial size inequalities, expressed as dominance and reverse dominance, significantly influence stand growth dynamics. A greater number of similarly sized trees can lead to intense competition, reducing the overall growth potential of the stand.

5.4 Management Implications

Effective forest management strategies should consider these findings to optimize growth and sustainability. Intensive thinning can enhance water yield and concentrate growth among fewer trees, promoting ecosystem services such as biomass production and carbon sequestration [25]. Additionally, careful thinning practices can improve light availability for younger trees, promoting their development and ensuring the continuity of forest regeneration processes [26]. Thinning strategies, while beneficial for reducing competition and improving stand structure, must be carefully designed to avoid unintended biodiversity loss. Selective thinning should retain a mix of age classes and structural diversity, ensuring that habitat conditions for understory species are maintained. Similar studies in mixed-aged forests in Spain have shown that moderate thinning enhances light penetration without negatively impacting species diversity [27].

5.5 Forest Structure, Climate Change, and Management Strategies

The findings from this study highlight the importance of maintaining uneven-aged forest structures for enhancing resilience under climate change. Uneven-aged stands support biodiversity by providing diverse microhabitats, which can help forests adapt to shifting environmental conditions. By promoting age diversity through selective thinning, forests can become more resilient to stressors like pests and extreme weather. However, thinning in steep, remote terrains presents economic challenges, including high costs for labor and equipment. Despite these costs, the long-term benefits of improved forest health and reduced risk of catastrophic events may outweigh the expenses [28]. Furthermore, diverse, healthy forests offer opportunities for non-timber products and ecotourism, which can provide additional economic value as described in FAO.

6. CONCLUSIONS

This study explored the growth dynamics and structural characteristics of a pure Scots pine stand at elevations above 1800 meters in Georgia, focusing on three age groups: younger trees (< 40 years), middle-aged trees (40-70 years), and older trees (> 70 years). Younger trees exhibited the highest growth rates, reflecting vigorous yearly growth, while middle-aged trees had moderate growth, and older trees showed slower growth due to increased competition and age-related limitations. These findings highlight the importance of age-specific management strategies to balance growth, biodiversity, and ecosystem resilience. On steep slopes, where mechanized equipment may not be feasible, manual thinning with low-impact tools is recommended to minimize soil disturbance and maintain slope stability. This study also underscores the need for forest managers to carefully plan thinning and regeneration strategies in challenging terrains. Future research should address additional structural variables and expand these findings to other forest types and locations to confirm and broaden the conclusions.

7. ACKNOWLEDGMENTS

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