

ASSESSING CARBON STORAGE AND GREENHOUSE GAS RISK REDUCTION IN MIXED BROADLEAF- CONIFER AND PURE PINE FORESTS NEAR AKHALTSIKHE, GEORGIA (2019-2025)

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Abstract

*This study evaluates the accumulation of aboveground carbon from 2019 to 2025 in two forest types near Akhaltsikhe in Georgia (at an altitude of approximately 1,500 meters): an uneven-aged mixed broadleaf-conifer forest and a pure *Pinus sylvestris* stand. The analysis focused on four native species — *Carpinus orientalis*, *Quercus petraea* subsp. *iberica*, *Quercus macranthera* and *Pinus sylvestris* — to evaluate their responses to stand composition and their respective contributions to carbon storage in relation to mitigating the risk of greenhouse gases. In the mixed stand, *C. orientalis* exhibited the highest carbon gain (59.2%), followed by *Q. macranthera* (34.2%) and *Q. petraea* subsp. *iberica* (6.3%). *Pinus sylvestris* showed limited carbon accumulation in the mixed forest, but performed better in monoculture with an average height of 18.8 meters and a 19.6% increase in carbon. These variations highlight species competition and their differing capacities to sequester carbon, which is critical for understanding forest ecosystem functions in carbon cycling. Conducted in Georgia's mountainous region, the study quantifies the amount of harmful greenhouse gas CO₂ absorbed and stored by native forest ecosystems, thereby mitigating the risks posed by rising atmospheric carbon concentrations and global climate change. The study emphasizes the crucial role that forest structure and species diversity play in enhancing the potential for carbon sequestration and mitigating greenhouse gas risks.*

Keywords: carbon sequestration, above ground biomass, species composition, mixed vs. pure stands, temperate forest ecosystems

I. Introduction

Forest ecosystems are key regulators of the terrestrial carbon cycle, sequestering atmospheric CO₂ in aboveground and belowground biomass and thereby functioning as important long-term carbon sinks [1]. However, the efficiency of carbon storage depends significantly on forest structure, species composition, and management practices [2].

In boreal and temperate regions, *Pinus sylvestris* often forms monospecific stands characterized by fast growth and high biomass density [3]. The regional variant *Pinus sylvestris* var. *caucasica*, native to the Caucasus Mountains, is adapted to nutrient-poor, rocky soils and can reach heights of 25–35 meters with a lifespan extending over several centuries [4, 5].

Yet, mixed-species forests, especially those involving conifer, broadleaf combinations, have shown enhanced carbon storage capacity compared to monocultures due to complementary resource use and structural diversity [6, 7]. In Georgian mountain forests, broadleaf species such as *Carpinus orientalis*, a small understory tree reaching 6–8 meters in height and adapted to dry,

shallow soils [8], and oaks like *Quercus macranthera* and *Quercus petraea* subsp. *iberica*, which grows up to 25–30 meters in height and thrives in humid and dry montane conditions, respectively, contribute to vertical forest stratification and increased carbon accumulation [9, 10].

Regional studies within Georgia are limited but highlight the importance of land-use change on carbon budgets [11]. While prior work has explored national-scale carbon dynamics, long-term, plot-based investigations of native mixed and pine forests in the Georgian mountain zone remain scarce. By remeasuring permanent sample plots in mixed and pine-dominated stands between 2019 and 2025, our study will allow for a longitudinal assessment of species-level carbon dynamics.

Through this approach, we aim to:

1. Quantify aboveground carbon accumulation across two forest types,
2. Understand interspecific competition and structural development,
3. Provide data applicable to greenhouse gas risk assessment in Georgia’s mountain ecosystems.

This research not only extends existing regional knowledge but also contributes to broader climate-relevant policy and sustainable forest management strategies.

II. Methods

Study areas are located near Akhaltsikhe. Figure 1 shows the study areas on the map, while Table 1 summarizes the geographical data for study plots. Akhaltsikhe is situated in the Samtskhe–Javakheti region of southern Georgia, serving as the administrative center of Samtskhe–Javakheti and Akhaltsikhe Municipality. The town lies within a mountain depression known as the Akhaltsikhe Hollow, typically at elevations ranging from 900 to 1,500 m above sea level [12].

Topographically, Akhaltsikhe occupies a mid-elevation zone within a broader mountainous landscape: the Trialeti and Meskheti Ranges to the north, and the Javakheti Plateau to the south and east. The terrain supports a transition between the valley flood-plain (of the Kura/Mtkvari River) and the surrounding uplands, with local elevation between approximately 950 m and 1,575 m.

Climatically, the region has a continental mountain climate, with mean annual temperatures near 9.5 °C, average January temperatures around -1.4 °C, and July averages near 19.5 °C [12]. Precipitation ranges from 400 mm to 1,400 mm annually, with lower values in the Akhaltsikhe basin and higher rainfall on elevated slopes; transitional zones receive roughly 508–654 mm/year, peaking in May–June and lowest in December–January [13]. The pure pine plot observed no significant structural changes compared to earlier measurements. The only differences were the death of one tree and a slight loss of height in several others, caused by snow damage. In the mixed-species plot, changes were more notable: five trees were cut during management activities, four died naturally, and seven new trees were added to the dataset after reaching the minimum measurement size.

Table 1: *The summarized geographical data for study plots*

Plot Type	Longitude (°, ', ")	Latitude (°, ', ")	Exposition	Inclination (°)	Altitude (m)
Mixed Forest	41.6077	42.9771	E	7	1559
Pure pine Forest	41.6078	42.9769	E	6	1499

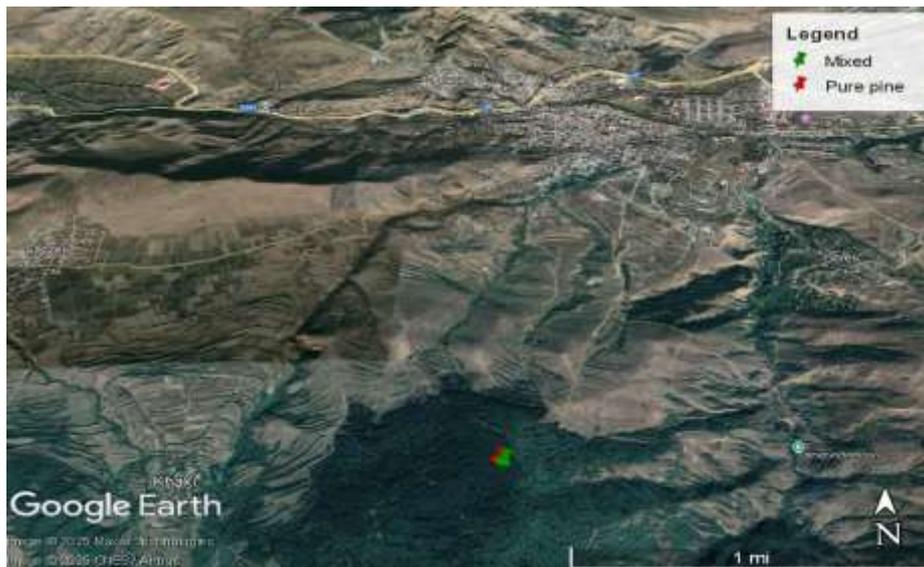


Figure 1: Location of the study plot south of Akhaltsikhe, Georgia. The image shows the forest area used for research, situated near the town in the Samtskhe–Javakheti region.

Field Measurements and Data Processing.

In 2025, a remeasurement was carried out in the same pure *Pinus sylvestris* and mixed stands previously surveyed in 2019 within the Akhaltsikhe municipality. During this fieldwork, updated values for diameter at breast height (DBH) and total tree height were recorded for all trees with a DBH of 7 cm and higher, as the usual DBH caliper was used for tree Diameter at breast height measurement, and the vertex clinometer was used for tree height measurement. These two parameters were sufficient to reassess stand structure, estimate growth over time, and update aboveground carbon estimates.

No new wood samples were collected in the current phase. Instead, previously obtained data, such as wood density and carbon content percentage, were used. Pure pine stands showed 51% while mixed stands showed 53%, from 2019 measurements through oven-dried mass and laboratory combustion methods. This approach provided consistency and allowed for a reliable comparison of changes over a five-year interval [14].

The basal area (BA) of each tree was calculated using the standard formula (1) [15, 16]:

$$G = \frac{\pi \times (DBH/2)^2}{10000} \tag{1}$$

To estimate stem volume, a taper-based volume equation was used, adapted from Bettinger:

$$V = F \times H \times G \tag{2}$$

where *H* is tree height and *F* is a form factor (species-specific), derived from local growth conditions.

Stem biomass was estimated as:

$$\text{Biomass} = V \times P \tag{3}$$

where *P* is the wood density (kg/m³), obtained from the 2019 sampling.

To estimate stem carbon content, the following equation was applied:

$$\text{Carbon} = \text{Biomass} \times C \% \tag{4}$$

where *C%* is the carbon concentration in oven-dried biomass, previously measured for this stand.

After this, the averaged data was multiplied by 3,65 to find the exact number of carbon sequestration. All data were scaled to a per-hectare basis using the plot area and expansion factor. A slope correction was applied to adjust for terrain inclination. The resulting metrics included tree density, total stem volume, biomass, and carbon stock per hectare [17, 18].

III. Results and Discussion

Morphometric and Carbon Changes in Mixed and Pure Pine Plots

This section presents the changes in tree morphometric characteristics and carbon-related variables between 2019 (or 2020 for pure pine) and 2025. The mixed-species and pure pine plots exhibited positive growth trends in DBH, height, volume, biomass, and carbon sequestration. The mixed forest plot includes broadleaf (*Carpinus orientalis*, *Quercus petraea iberica*, *Quercus macranthera*) and conifer (*Pinus sylvestris*) species, while the pure plot consists mainly of *Pinus sylvestris*.

General Growth Trends are given in Tables 2, 3, and 4.

Table 2: Average Tree Morphometric and Carbon Data per Species

Tree No.	Species	Year	DBH, cm	H, m	Volume 2019, m ³	Biomass 2019, kg	Dry Bio 2019, kg	Carbon 2019, kg	Carbon Seq. 2019, kg
Mixed forest plot									
7	Carpinus orientalis	2019	20.46	15.3	0.4134	211.29	163.52	76.85	280.51
		2025	21.58	15.42	0.4866	248.74	192.46	90.46	330.16
44	Quercus petraea ssp. iberica	2019	18.31	14.35	0.2935	152.25	116.52	54.77	199.9
		2025	19.58	14.73	0.3389	176.01	134.51	63.22	230.74
15	Quercus macranthera	2019	22.2	16.58	0.4762	243.57	188.18	88.45	322.82
		2025	24.61	17.69	0.5873	300.07	231.87	108.98	397.77
98	Pinus sylvestris	2019	19.81	14.69	0.3309	172.02	131.43	61.77	225.47
		2025	21.27	15.16	0.3908	203.17	155.24	72.96	266.31
Pure pine forest plot									
1	Prunus avium	2019	7	5.9	0.0132	7.13	5.56	2.95	10.75
		2025	8.5	6.2	0.0157	8.45	6.59	3.49	12.76
4	Picea orientalis	2019	9.5	7.33	0.0272	28.41	22.16	6.08	22.18
		2025	12.7	9.2	0.0526	42.87	33.98	11.74	42.87
59	Pinus sylvestris	2019	24.63	20.45	0.4998	269.89	210.52	111.57	407.24
		2025	25.88	21.73	0.5577	301.15	234.89	124.49	454.4

Table 3: Percentage Change in Parameters from 2019/2020 to 2025

Tree No.	Species	DBH % ↑	H % ↑	BA % ↑	Volume % ↑	Biomass % ↑	Dry Bio % ↑	Carbon % ↑	Carbon Seq. % ↑
Mixed forest plot									
7	Carpinus orientalis	5.48%	0.78%	12.89%	17.69%	17.71%	17.71%	17.71%	17.71%
44	Quercus petraea ssp. iberica	6.90%	2.64%	12.80%	15.49%	15.60%	15.43%	15.44%	15.44%
15	Quercus macranthera	10.83%	6.70%	18.11%	23.37%	23.16%	23.25%	23.23%	23.23%
98	Pinus sylvestris	7.36%	3.43%	13.33%	18.09%	18.10%	18.13%	18.13%	18.13%
Pure pine forest plot									
1	Prunus avium	21.43%	5.08%	12.90%	18.94%	18.54%	18.53%	18.53%	18.53%
4	Picea orientalis	33.68%	25.59%	53.57%	93.75%	50.89%	53.39%	93.75%	93.31%
59	Pinus sylvestris	5.07%	6.25%	5.26%	11.60%	11.59%	11.58%	11.58%	11.58%

The updated data clearly demonstrate a consistent increase in tree growth and carbon storage across all species over the six-year period. Among the broadleaf species, *Quercus macranthera* exhibited the highest relative growth, with increases exceeding 10% in DBH, 6.7% in height, and over 23% in volume, biomass, and carbon-related metrics. These findings underscore its strong adaptive growth potential in mixed-species stands. In the mixed forest plot, *Pinus sylvestris* showed stronger growth performance (18.09% volume increase) compared to the same species in the pure pine plot, which only achieved an 11.60% increase.

This supports the idea that mixed-species stands can enhance individual tree growth and ecosystem productivity. Such patterns align with global research indicating that species richness enhances forest productivity and carbon sequestration potential [19].

Interestingly, trees in the pure pine plot, particularly *Picea orientalis*, showed extreme growth rates—with a 33.68% increase in DBH and a 93.75% increase in volume and carbon sequestration. While this may reflect species-specific growth dynamics or microsite advantages, it also suggests that particular species can thrive in monocultures under favorable conditions. *Pinus sylvestris* in the pure stand had a greater height increase (6.25%) than in the mixed stand (3.43%), likely due to intense vertical competition common in even-aged monocultures. This behavior is well-documented in silvicultural studies, where trees grow taller and thinner in dense stands to access light [20]. Overall, the findings highlight the ecological and climate benefits of species-diverse forests, showing that mixed-species plots not only support greater biomass accumulation but also enhance carbon sequestration. These results prove that biodiversity promotes resource-use efficiency, ecosystem resilience, and long-term forest sustainability [21, 22].

Table 4: *Tree number, volume, biomass, carbon content, and carbon sequestration for mixed forest and pure pine stands in 2019 and 2025*

Forest type	Year	Tree number (trees/ha)	Volume (m ³ /ha)	Biomass (kg/ha)	Carbon content (kg/ha)	Carbon sequestration (kg CO ₂ -eq/ha)
Mixed forest	2019	720	234.90	121,682.53	43,799.61	159,868.59
	2025	807	298.67	154,880.69	55,698.66	203,300.12
Pure pine forest	2019	787	364.11	196,621.54	81,283.35	296,684.21
	2025	787	406.88	219,716.91	90,830.97	331,533.05

Between 2019 and 2025, mixed forests increased by 12.1% in tree density, 27.1% in volume, 27.3% in biomass, 27.2% in carbon content, and 27.2% in carbon sequestration.

Between 2019 and 2025, the mixed broadleaf–conifer forest demonstrated stronger relative growth than the pure even-aged pine stand. The mixed stand’s tree density increased by approximately 12%, while volume, biomass, carbon content, and CO₂-equivalent sequestration all rose by about 27%. In contrast, the pure pine stand maintained constant tree density but still achieved around 11–12% gains in volume, biomass, carbon, and sequestration. This contrast reflects the structural differences between the stands. The mixed forest is uneven-aged, composed of both mature trees and younger recruits that emerged during the six-year period, enabling vigorous growth. Meanwhile, the pure pine stand is even-aged, limiting recruitment and therefore displaying slower relative growth, though its biomass and carbon stocks remain high.

Such patterns align with global experiment findings that mixed-species and uneven-aged stands often outperform monocultures in productivity and carbon sequestration, mainly due to complementary resource use and structural diversity. mixed-species forests were about 15% more productive than average monocultures, particularly in climates with adequate rainfall [23]. From a carbon-risk perspective, both stand perform essential but different roles. The mixed forest acts as a “growth engine,” sequestering carbon rapidly through active recruitment and fast-growing young trees. The pine stand functions more like a “carbon reservoir,” storing large amounts of carbon in mature biomass. This dual role—rapid uptake and long-term storage—enhances the forest landscape’s resilience to climate-related disturbances.

Forest age dynamics are crucial to understanding carbon fluxes. Younger and mid-aged stands sequester carbon more rapidly per hectare, whereas aging forests contribute more to carbon storage than removal rates. Regrowing forests currently contribute more to global carbon uptake than old-growth systems, though the latter remain vital as stable carbon stores [24]. Simulations in New Brunswick showed that older hardwood-dominated forests continued accumulating carbon over time, underlining the value of mature stands [25]. Moreover, old forests—though slower in growth—possess substantial carbon reserves and provide ecosystem stability.

Mature and old-growth stands act as long-standing carbon pools, reinforcing the importance of preserving such structures [26, 27, 28, 29].

Risk mitigation is another benefit of mixed and uneven-aged stands. Structural and species diversity tends to buffer forests against disturbances such as pests, fires, and droughts, reducing the likelihood of abrupt carbon release. For example, mixed-species forests in Europe have been shown to sustain less storm damage than monocultures. These insights suggest that this regional forest system performs both roles essential to climate mitigation: the mixed stand accelerates carbon uptake, while the pine stand secures long-term carbon. The combination enhances ecosystem resilience and mitigates greenhouse gas risk effectively.

V. Conclusion

With the growing risks from greenhouse gas emissions and climate change, healthy forests are more essential than ever. They are natural carbon sinks, helping to remove CO₂ from the atmosphere and store it for long periods. Understanding exactly how much carbon different forests can store and how these changes over time is key to protecting and managing them effectively. Even small-scale studies can provide valuable insights. Though limited to only two study plots, the data collected here adds another piece to the puzzle. Comparing measurements from different years shows how carbon sequestration potential changes as trees age. Such information can help predict biomass and carbon trends in forests with similar species composition and climatic conditions.

While this study covers a small area and cannot represent all forest types in the region, it is an informative starting point. Our next research stage will expand to more plots, species, and repeated measurements over time. This will strengthen the accuracy of the data and allow for more meaningful comparisons. Forests are our allies in slowing climate change, but only if we understand and protect them. Even small, focused research projects like this contribute to that knowledge, helping to build the larger picture, one study at a time.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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