

Spatial and temporal analysis of land use and carbon storage dynamics in forest ecosystems: The case of Reşadiye

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Abstract: This study aims to analyze land cover changes and the associated biomass and carbon stocks between 1971 and 2022 in the Reşadiye Forest Enterprises, located within the borders of the Reşadiye district of Tokat Province. Forest management plans, stand maps, and 1:25000-scale topographic maps for four periods (1971, 1991, 2012, 2022) were used as materials. According to the Intergovernmental Panel on Climate Change (IPCC) guidelines, carbon stock conditions have been calculated based on the differences between successive inventory periods. The analysis, supported by biomass and carbon conversion coefficients, was mapped with ArcGIS Desktop 10.2™ software. These results show that the proportion of pure coniferous forests increased from 6.9% to 19%, and the proportion of deciduous forests increased from 2.0% to 7.6% between 1971 and 2022. During the same period, degraded forest areas decreased from 34.2% to 15.7%; total carbon stock increased by 101.7% from 924.310 tons to 1864.306 tons. However, there was a significant decrease in biomass between 2012 and 2022. This situation highlights the impact of management practices on forest dynamics, the carbon cycle, and natural succession processes. The study highlights the importance of sustainable land use policies and the necessity of monitoring the continuity of carbon stocks. The results provide valuable data for updating carbon inventories and planning climate change mitigation strategies for the Reşadiye region.

Keywords: Carbon storage, Forest planning, Reşadiye, Spatial analysis, Temporal change

Orman ekosistemlerinde arazi kullanımı ve karbon depolama dinamiklerinin mekânsal ve zamansal analizi: Reşadiye örneği

Özet: Bu çalışma, Tokat ili Reşadiye ilçesi sınırları içerisinde yer alan Reşadiye Orman İşletme Şefliği'nde 1971-2022 yılları arasında arazi örtüsü değişimlerini ve bu değişimlerle ilişkili biyokütle ve karbon stoklarını analiz etmeyi amaçlamaktadır. Materyal olarak dört döneme (1971, 1991, 2012, 2022) ait orman amenajman planları, meşcere haritaları ve 1/25000 ölçekli topografik haritalar kullanılmıştır. Hükümetlerarası İklim Değişikliği Paneli (IPCC) kılavuzuna göre, karbon stoku durumları ardışık envanter dönemleri arasındaki farklar temel alınarak hesaplanmıştır. Biyokütle ve karbon dönüşüm katsayıları ile desteklenen analiz ArcGIS Desktop 10.2™ yazılımı ile haritalanmıştır. Bulgular, 1971'den 2022'ye kadar saf iğne yapraklı ormanların %6.9'dan %19'a, geniş yapraklı ormanların ise %2.0'den %7.6'ya yükseldiğini göstermektedir. Aynı dönemde bozuk orman alanları %34.2'den %15.7'ye düşmüştür; toplam karbon stoku %101.7 artarak 924.310 tondan 1864.306 tona yükselmiştir. Ancak 2012 ve 2022 yılları arasında biyokütlede önemli bir düşüş yaşanmıştır. Bu durum, yönetim uygulamalarının orman dinamikleri, karbon döngüsü ve doğal süksesyon süreçleri üzerindeki etkilerini ortaya koymaktadır. Çalışma, sürdürülebilir arazi kullanım politikalarının önemini ve karbon stoklarının sürekliliğinin izlenmesi ihtiyacını vurgulamaktadır. Elde edilen bulgular, Reşadiye yöresi için karbon envanterlerinin güncellenmesi ve iklim değişikliği azaltım stratejilerinin planlanmasında değerli veri sağlamaktadır.

Anahtar kelimeler: Karbon depolama, Mekânsal analiz, Orman planlaması, Reşadiye, Zamansal değişim

1. Introduction

Forest ecosystems provide a wide range of ecosystem services beyond timber production, including biodiversity conservation, regulation of soil and water resources, erosion control, and climate change mitigation. These ecosystem services are directly linked to the United Nations Sustainable Development Goals (SDG 13 and 15) (United Nations, 2022). Among these services, the sequestration of atmospheric CO₂ and its storage in biomass is significant. The carbon storage capacity of forests plays a crucial role in reducing the impacts of global warming and stabilizing the climate system (Intergovernmental Panel on Climate Change, 2019a; Food and

Agriculture Organization of the United Nations, 2020). Recent studies have shown that forests, through their role as a net carbon sink, represent one of the most cost-effective natural climate solutions in the ongoing climate crisis (Griscom et al., 2017; Bastin et al., 2019).

However, land use and land cover changes (LULC) significantly affect the role of forests in the carbon cycle. LULC-related emissions are considered the second-largest anthropogenic carbon source, after fossil fuels (Houghton et al., 2012; Friedlingstein et al., 2022). The impacts of LULC reduce existing carbon stocks and decrease carbon sequestration rates, thereby constraining the adaptive capacity of ecosystems under climate change (Song et al., 2018; Pugh et al., 2019).

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These processes introduce substantial uncertainties when calculating and monitoring regional carbon budgets.

Recent studies from various countries have demonstrated that LULC is one of the key drivers of terrestrial carbon stock dynamics (Tang et al., 2018; Yu et al., 2018; Chang et al., 2022). Long-term monitoring data indicate that both natural forest succession and forest management policies are decisive factors shaping carbon storage dynamics (Pan et al., 2011; Forzieri et al., 2021), while recent global-scale assessments have revealed emerging signals of declining forest resilience under climate change (Forzieri et al., 2022). Longitudinal studies based on forest inventory data from Europe and Asia have confirmed the importance of these drivers (Luyssaert et al., 2008; Forzieri et al., 2021). Several studies have been conducted on the changes in forest carbon stocks in Turkey, and a significant portion of them are based on comparisons covering two periods (Bulut, 2012; Kadioğulları and Karahalil, 2013; Sivrikaya et al., 2013; Seki et al., 2017; Karahalil et al., 2018; Günlü et al., 2019; Kocaman and Durkaya, 2020; Çelik and Şahin, 2023). In addition, studies are addressing three periods (Durkaya et al., 2014; Kaptan and Durkaya, 2019; Mumcu Kucuker, 2020; Kucuker and Tuyoglu, 2021; Seki and Atar, 2021; Kucuker and Tuyoglu, 2021; Bulut and Bulut, 2024) and four periods (Mısır, 2013; Durkaya et al., 2016; Değermenci and Zengin, 2016; Mumcu Kucuker, 2020). However, the vast majority of studies in the literature are limited to two or three periods, while studies on four periods are both fewer in number and primarily based on datasets spanning less than 50 years.

In this context, our study spans approximately 52 years (1971-2022) and comprises four distinct periods. Additionally, spatial and temporal changes were assessed holistically using the most recent (2022) planning data. In particular, the increasing impacts of climate change and the impacts of recent large-scale forest fires on land cover and carbon storage capacity were evaluated alongside the increase in production activities. This enables us to demonstrate the temporal effects of production activities on carbon stocks, highlighting the importance of this relationship for sustainable forest management. In this respect, our study provides a current and long-term dataset that can contribute to the development of forest management strategies, policies, and action plans to combat climate change. This gap constitutes an essential source of uncertainty in updating regional carbon budgets (Sun and Liu, 2019). The present study provides a rare case of a multi-decadal, spatially explicit analysis of carbon stock dynamics in Turkey.

In Türkiye forestry, forest management plans, stand type maps, and topographic data serve as fundamental tools for the sustainable management of forest resources and for meeting international reporting obligations. The IPCC Special Report on Climate Change and Land (2019) explicitly emphasizes the importance of reliable inventory data for local and regional carbon accounting (Intergovernmental Panel on Climate Change, 2019b). Therefore, comparative evaluation of historical management plans is critical for tracking ecosystem dynamics and supporting national climate change mitigation strategies.

This study analyzes land cover change and the associated variations in biomass and carbon stocks using four consecutive forest management plans (1971, 1991, 2012, and 2022)

for the Reşadiye Forest Sub-district in Tokat Province. The research provides a multi-decadal (52-year) spatio-temporal assessment of carbon stock dynamics in the Reşadiye forests, thus filling a notable gap in the literature. These results are expected to contribute to updating regional forest carbon inventories and to provide scientific support for Turkey's nationally determined contribution (NDC) and climate change mitigation policies (Republic of Türkiye, 2023).

2. Materials and methods

This study utilized forest management plans for the Reşadiye planning unit for the years 1971, 1991, 2012, and 2022, as well as stand maps derived from these plans and 1:25000 scale standard topographic maps, as the primary materials. Topographic maps numbered G38d3, G38c4, G38a2, G38b1 (Karaçam series), G39d3, G38c4, G38c3, G39d4, H38a2, H38b1, H38b2, H39a1 (Çaltepe series), G39d4, G39d3, H38b2, H39a1, H39a2 (Delicedere series), H38b1, H38b2, H39a1, H38b3, and H39a4 (Güneşdağ series) covering the study area were evaluated during the analysis process. Topographic maps were used only for georeferencing and boundary verification purposes, while forest types and carbon classes were determined directly based on management plan maps and databases. Stand volume data obtained from stand maps for the relevant years were used to calculate the amounts of above-ground biomass (AGB) and below-ground biomass (BGB) and the amounts of carbon stored in these biomass. These materials constituted the primary data source for analyzing long term forest ecosystem dynamics and monitoring changes in carbon stocks.

2.1. Study area

This study covers the Reşadiye district of Tokat province, located in the inland region of Türkiye's Black Sea Region. Located approximately 90 kilometers east of Tokat city center, Reşadiye is situated at a transitional point between the Black Sea and Central Anatolia regions, a characteristic that significantly impacts both its natural environment and human development. The district is bordered by Koyulhisar in Sivas to the east, Hafik, Doğanşar, and Almus to the south, Niksar to the west, Aybastı, Başçiftlik, and Gököy to the north, and Mesudiye to the northeast. The Reşadiye Forest Enterprises, selected as the study area, represents a district region rich in forest resources and reflects its mountainous structure. Located in the Kelkit Valley, the district has historically served as a vital transportation and settlement corridor, rich in both traditional and cultural heritage. Its mountainous and rugged terrain, river valleys, and forest cover are decisive in shaping activities such as agriculture, animal husbandry, and forestry.

The study area is between 37° 09' 01"- 37° 38' 33" east longitudes and 40° 38' 29"- 40° 19' 36" north latitudes. The average elevation of the study area is 1285 m. The average annual temperature of the study area is 12.4°C, and the average annual precipitation is 434.8 mm. The dominant tree species in the study area are red pine (*Pinus brutia*), scots pine (*Pinus sylvestris*), cedar (*Cedrus*), fir (*Abies*), juniper (*Juniperus*), beech (*Fagus*), oak (*Quercus*), and hornbeam (*Carpinus*). The map showing the location of the study area in Türkiye is given in Figure 1.

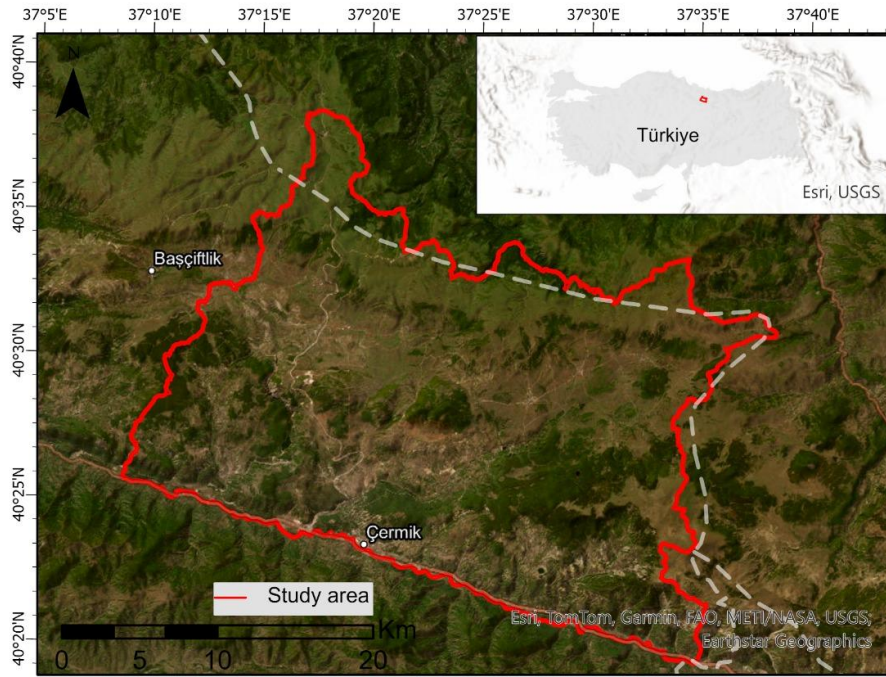


Figure 1. Location of the study area

The forests of the planned units were managed in the 1970s according to definitive management plans for the Karaçam, Çaltepe, Deliceredere, and Güneşdağ series. These series have been managed according to the age class method and consist of forest stands of the same age and coppices. These series plans were combined at the forest planning unit level between 1991 and 2012, and the unit was renamed the Reşadiye Forest Planning Unit. The area boundaries of the forest planning unit were updated in 2012 (the research area encompasses these boundaries). Finally, the same forest planning unit was divided into the Reşadiye and Suluçorak Forest Planning Units in 2022.

There are 76 villages and six municipalities within the boundaries of the Reşadiye Forest Planning Unit. The district's total population, which was 61802 in 1970, decreased by 47.3% to 32600 people by 2022. During the period in question (1970-2022), a large portion of the population resided in rural areas; the share of the rural population in the total population decreased from 88.4% to 71.6%, representing a decline of approximately 16.8%. During this period, the rural population also experienced a significant decrease in total numbers; the rural population, which was 54643 in 1970, decreased by 57.3% to 23340 people in 2022. Population data of the Reşadiye district by year are presented in Table 1 (Türkiye İstatistik Kurumu, 2025).

Table 1. Population change of the Reşadiye district (persons)

	Years	1970	1990	2012	2022
Reşadiye	Center	7159	12321	8835	9260
	Rural	54643	48845	33530	23340
	Total	61802	61166	42365	32600

2.2. Determination of biomass and carbon storage capacities

To determine changes in carbon stocks, the IPCC guidelines recommend two basic approaches for calculating the annual change for each carbon pool. The first approach is based on the difference between carbon input and output. This

method calculates net carbon change by subtracting the amount of carbon entering the pool in a given year from the amount of carbon leaving the pool in the same year. In the guidelines published by the IPCC, this method, particularly for monitoring the carbon cycle in land use and forest ecosystems, is expressed as the following equation (Intergovernmental Panel on Climate Change, 2006, 2019b):

$$\Delta C = \sum_{i,j,k} [A_{ijk} \times (C_I - C_L)_{ijk}] \quad (1)$$

In the equation: ΔC : net annual change of carbon stock in the pool in a particular year (ton C), A_{ijk} : pool area (ha), depending on i : climate type, j : forest type, and k : management intensity, C_I : the amount of carbon entering the pool in the same year (ton/ha/year), C_L : the amount of carbon leaving the pool in the same year (ton/ha/year).

The second approach calculates the change in carbon stock based on the difference between two consecutive inventory periods. This method uses the differences between carbon stocks measured at specific intervals to determine the net change. This calculation is formulated as follows in the IPCC guide (Intergovernmental Panel on Climate Change, 2006, 2019b):

$$\Delta C = \sum_{i,j,k} [(C_{t2} - C_{t1})_{ijk} / (C_I - C_L)_{ijk}] \quad (2)$$

In the equation: ΔC : change in carbon stock (ton C), C_{t1} and C_{t2} : total carbon stock (ton C) measured at t_1 and t_2 , C_I : average annual carbon amount entering the pool in the specified period (ton/ha/year), C_L : average annual carbon amount leaving the pool in the specified period (ton/ha/year), i,j,k : Represents climate type, forest type and management-operation type subclasses, respectively.

The first of these two approaches calculates carbon change based on carbon input and output (increase and decrease) data on an annual basis; the second method is based on the change in the carbon stock directly between periodically performed inventories.

In this study, the second method outlined in the IPCC guidelines was employed to monitor changes in carbon stock in the study area. The guideline defines carbon stored in forest ecosystems as “carbon pools,” which are categorized into three main groups and five subgroups. These subcategories are AGB and BGB, dead wood, litter, and soil organic matter (Intergovernmental Panel on Climate Change, 2003; Asan et al., 2005). Carbon stock changes across four periods were analyzed spatially and temporally in this context.

In determining the carbon storage capacity of the planning unit, forest types were classified as coniferous, deciduous, and mixed forests; the distinction between productive and degraded forests was made according to the official management plan classification of the General Directorate of Forestry. In mixed forests, carbon stocks were calculated using the weighted average method, taking into account the spatial shares of species. Species were not separated into distinct classes, and calculations were based on the dominant tree species in the forest. This choice was made to maintain consistency with the management plan classification and to avoid disrupting the spatial integrity of the forest stand maps. This study employs LULC as a standard concept to describe land-use and land-cover changes. The development stage codes used in the Turkish forestry system (a, ab, b, bc, c, cd, d, de, and e) are defined as follows for international readers: a = juvenile developmental stage (< 8.0 cm diameters at breast height (DBH)), b = young developmental stage (8.0-19.9 cm DBH), c = mature developmental stage (20.0-35.9 cm DBH), d = old developmental stage (36.0-51.9 cm DBH), e = over-mature developmental stage (> 51.9 cm DBH) (Orman Genel Müdürlüğü, 2015). These codes are associated with diameter classes and standing timber values in assessing carbon stock dynamics.

To determine the carbon storage capacity of the planning unit, forest types were first classified into coniferous, deciduous, productive, and degraded forests. First, the stem biomass was calculated by multiplying the standing volume (with bark) by the basic wood density (BWD); then, the branch, foliage, and root biomass components were added using expansion factors and root-to-shoot ratios (R) proposed

by Tolunay (2011). The total carbon stock was determined by multiplying the AGB and BGB values by the carbon conversion coefficients (Sivrikaya and Bozali, 2012).

The calculation of carbon stocks in forests was based on coefficients developed by Asan (1995) and Tolunay (2011), which were included in the IPCC's 2010 Forest Resources Assessment (FRA) guidelines. The five-stage method outlined in Table 2 was used to calculate carbon stocks by period. Total carbon stock was calculated as the sum of above-ground (AGC) and belowground carbon (BGC), deadwood carbon (DWC), litter, and forest soil carbon amounts for tree species groups (Değermenci and Zengin, 2016).

2.3. Estimation and mapping of carbon stocks

Stand type maps for the years 1971, 1991, 2012, and 2022 were used to determine and map the carbon storage capacity of the study area. The 1971 and 1991 stand maps were scanned in TIFF format at high resolution using an A0 scanner and placed on 1:25000 scale topographic maps using the ArcGIS 10.2™ program, with an RMS (Root Mean Square) error of less than 1 meter. Stand maps for the years 2012 and 2022 were obtained digitally from the Niksar Forest Enterprises. For each stand map, standing volume information for stand types was taken from the relevant forest management plans and transferred to the database. To calculate the carbon storage capacity, the following attributes were added to the attribute data table of the stand map: stand type, division number, crown closure, developmental stage, and standing volume amounts per hectare (ha). Using these data, the quantities of AGB, BGB, AGC, and BGC for the years 1971, 1991, 2012, and 2022 were calculated using biomass and carbon conversion coefficients with the help of ArcGIS 10.2™ software, and carbon maps were created (Sivrikaya and Bozali, 2012; Değermenci and Zengin, 2016). The same classification template and consistent layer structure were used for all periods to ensure comparability across years. This enabled the reliable presentation of temporal and spatial changes in carbon stocks across planning units.

Table 2. Calculation of biomass and carbon in the plan unit

Categories		PF	DF
		Biomass (t)	Biomass (t)
Stage 1			
Aboveground Biomass	Coniferous	SV*0.446*1.212	SV*0.446*1.212
	Deciduous	SV*0.541*1.310	SV*0.541*1.310
Belowground Biomass	Coniferous	AGB*0.29	AGB*0.40
	Deciduous	AGB*0.24	AGB*0.46
Stage 2			
Carbon in Aboveground Biomass	Coniferous	AGB*0.51	AGB*0.51
	Deciduous	AGB*0.48	AGB*0.48
Carbon in Belowground Biomass	Coniferous	BGB*0.51	BGB*0.51
	Deciduous	BGB*0.48	BGB*0.48
Stage 3			
Dead Wood Biomass	Coniferous	AGB*0.01	AGB*0.01
	Deciduous	AGB*0.01	AGB*0.01
Carbon in Dead Wood	Coniferous	DWB*0.47	DWB*0.47
	Deciduous	DWB*0.47	DWB*0.47
Stage 4			
Carbon in Litter	Coniferous	F1(Area ha)*7.46	F3(Area ha)*1.86
	Deciduous	F2(Area ha)*3.75	F4(Area ha)*0.93
Stage 5			
Forest Soil Organic Carbon	Coniferous	F1(Area ha)*76.56	F3(Area ha)*19.14
	Deciduous	F2(Area ha)*84.82	F4(Area ha)*21.20

AGB: above ground biomass, AGC: above ground carbon, BGB: below ground biomass, BGC: below ground carbon, DWB: dead wood biomass, DWC: dead wood carbon, LC: litter carbon, SOC: forest soil organic carbon, PF: productive forest, DF: degraded forest, SV: stem volume, F: area in ha

3. Results and discussion

3.1. Results of land use land cover change

Significant changes in land cover occurred in the research area between 1971 and 2022. Coniferous forests increased approximately threefold, rising from 4259.34 ha to 14239.51 ha, while deciduous forests reached 5144.07 ha. Degraded coniferous forests declined steadily between 1971 and 2012 but showed an increase again in 2022. Degraded deciduous forests, on the other hand, continued to fall throughout the entire period. This trend parallels the increase in the productive forest (PF) area observed across Turkey. Indeed, while the proportion of productive forests nationwide was 53% in 2012, it rose to 59% by 2023 (Orman Genel Müdürlüğü, 2023). This increase observed locally parallels the approximately 6% increase in PF areas at the national level, revealing the regional effects of forestry policies. While forest land decreased from 4495.43 ha to 1946.90 ha, non-forested areas increased slightly from 30806.19 ha to 31235.01 ha. These results indicate significant increases in coniferous and deciduous forest areas within the study area. At the same time, there has been a decrease in degraded forest (DF) areas and forest soil areas (Table 3).

Between 1971 and 1991, productive forest (PF) areas increased by approximately 94.7%, rising from 6163.15 ha to 11999.4 ha; in contrast, DF areas decreased by 39.6%, falling from 20876.78 ha to 12600.43 ha. Non-forest (NF) areas increased by 19.2% during this period, reaching 36738.06 ha from 30806.19 ha. Between 1991 and 2012, PF areas increased by 62.5% to reach 19496 ha, while DF areas decreased by 43.6%. During this period, NF areas also decreased by 3728 ha, indicating that afforestation efforts were carried out in both DF and NF areas. During 2012-2022, the PF area remained largely stable, declining from 19496 ha to 19383.58 ha. In contrast, the DF area increased by 37.6% to reach 9776.07 hectares. Over the 52 years, the PF area increased by 214.5%, while the DF area decreased by 53.2% (Table 3).

This significant decrease is considered an indicator of a general improvement trend in forest ecosystems. This observed development indicates that natural regeneration and rehabilitation programs have yielded effective results. However, it has also been observed that recovery is uneven and fragmented, particularly in some degraded coniferous forest areas, meaning that ecosystem integrity has not been fully achieved in every region (Chazdon, 2008; Holl and Aide, 2011). Information on mixed forest types is not included in the 1971 data. Still, as of 2022, mixed coniferous-deciduous forests account for 3.8% of the total area, while mixed deciduous-coniferous forests account for 0.6%. Thus, mixed forests cover a total area of 4.6% (Table 5). This development

suggests that the importance attributed to species diversity in forest management is increasing, and that the resilience of ecosystems may have strengthened accordingly (Felton et al., 2010). Indeed, species diversity can increase not only resilience but also carbon productivity. Pretzsch et al. (2013) noted that stands composed of mixed species can exhibit higher productivity and carbon sequestration capacity than monoculture forests.

In addition to changes in land cover, significant transformations have also occurred in the structure of the developmental stages. These transformations reveal that both rejuvenation and rehabilitation efforts, as well as structural changes in planning approaches, have been decisive in the study area over the past 50 years. While only a few development stages ('a', 'b', 'bd') were defined in 1971, the use of detailed classifications such as 'ab', 'bc', 'c', 'cd', and 'd' in subsequent periods demonstrates the development of the forest planning system. In 1991, the 'c' development stage became dominant with 5602.08 ha, while the 'ab' and 'bc' development stages were recorded as 1505.99 ha and 799.57 ha, respectively. During the 1971-1991 period, the 'a' development stage decreased from 2009.12 ha to 1130.77 ha, and the 'b' development stage decreased from 3824.22 ha to 2335.46 ha, thus showing a significant decrease in both stages. This change indicates that the forests have transitioned from young classes to older classes. In 1991-2012, the 'bc' development stage increased rapidly, reaching 6196.60 ha, while decreases were observed in the 'c' and 'b' development stages. The 'a' development stage increased slightly to 1486.83 ha (Table 4).

During the 2012-2022 period, the 'bc' development stage remained the most common class at 6692.20 ha, while the 'cd' development stage reached 3631.35 ha with a notable increase. In contrast, the 'c' and 'd' development stages declined to 2431.61 ha and 942.77 ha, respectively, revealing a decrease in forest areas in the older development stage. The 'a' and 'b' development stages remained relatively stable. These periodic data indicate a reduction in degraded areas in forest ecosystems over the last 52 years, along with a trend towards diversification and balance in development stages. These changes appear to be consistent with the combined effects of forestry practices, forest area conversions, and natural regeneration processes (Table 4).

These results indicate that reforestation and rehabilitation practices have led to a more balanced 'c' and 'd' development stage structure in forests, with a significant portion of the forests reaching optimal production stages and thereby increasing their carbon storage capacity. However, the decline in older development stages highlights the need to develop additional strategies for conserving old-growth forest ecosystems.

Table 3. Land cover change from 1971 to 2022 (ha)

Land Cover	1971	1991	2012	2022
Con.	4259.34	10552.59	13577.27	14239.51
Dec.	1903.81	1446.81	5918.73	5144.07
Deg.-Con.	14336.19	7004.49	2839.45	6354.05
Deg.-Dec.	6540.59	5595.94	4264.26	3422.02
OFA.	4495.43	1003.68	2732.58	1946.90
NF.	30806.19	36738.06	33009.26	31235.01
PF	6163.15	11999.4	19496	19383.58
DF	20876.78	12600.43	7103.71	9776.07
Total	62341.56	62341.56	62341.56	62341.56

Con.: coniferous, Dec.: deciduous, Deg.-Con.: degraded coniferous, Deg.-Dec.: degraded deciduous, OFA.: open forest area, NF.: non-forest areas, PF: productive forest, DF: degraded forest

Table 4. Change in stand development stages according to the plan period (ha)

Stand development stage	1971	1991	2012	2022
a	2009.12	1130.77	1486.83	1388.43
ab	-	1505.99	1739.97	2122.45
b	3824.22	2335.46	1992.09	2541.61
bc	-	799.57	6196.60	6692.20
bd	329.81	-	-	-
c	-	5602.08	4737.55	2431.61
cd	-	-	1804.60	3631.35
d	-	625.53	1538.37	942.77
DF and NF	56178.41	50342.17	42845.55	42591.14
Total	62341.56	62341.56	62341.56	62341.56

DF: degraded forest, NF: non-forest areas, a: juvenile developmental stage (< 8.0 cm DBH), b: young developmental stage (8.0-19.9 cm DBH), c: mature developmental stage (20.0-35.9 cm DBH), d: old developmental stage(36.0-51.9 cm DBH), e: overmature developmental stage (> 51.9 cm DBH)

Table 5 data also reveal that the increase in mixed forests occurred primarily through conversion from degraded coniferous forests (23.3% to 10.2%) and degraded deciduous forests (10.9% to 5.5%). This situation demonstrates the effectiveness of rehabilitation efforts and natural regeneration processes, particularly in degraded forest areas. Only a limited increase of 0.5% was observed in non-forest areas (NF), most of which originated from open and low-yield areas; this indicates that agricultural and settlement pressures are low. The most significant decrease occurred among forest categories in DF, while OFA declined partially as well. These results indicate that deforestation in the study area primarily originated from low-coverage forest categories and that productive forest cover largely offset this loss.

According to land cover data for the study area, forest soils accounted for 7.3% of the total land area in 1971, but this ratio declined to 3.1% by 2022. Although there appears to be a 57.5% decrease in percentage terms, it is evident that a significant portion of this transformation occurred in the direction of expanding productive and mixed forest areas. Indeed, the productive forest area (both pure and mixed forests), which was only 8.9% in 1971, increased to 41.0% in 2022, showing a remarkable rise (Table 5). This indicates that some areas classified as forest land have been converted into active forest cover, becoming more productive and functional. Although the decline in forest land indicates a negative picture regarding ecosystem functions, only 0.5% of the area has been converted to NF land use. This shows that the transformation is towards forest cover with high ecological value. Therefore, it is understood that this is a reclassification consistent with the trend towards afforestation rather than a deterioration in soil functions. This land-use transformation can

be viewed as a positive development that aligns with the objectives of sustainable forest management (Lamb et al., 2005; Intergovernmental Panel on Climate Change, 2022). Furthermore, the fact that planned changes in land use have limited the increase in NF areas to a relatively small level (from 49.6% to 50.1%) suggests that urbanization and agricultural pressures are under control, and that policies aimed at preserving ecosystem integrity can be effective (Lal, 2001; Food and Agriculture Organization of the United Nations, 2020).

In general, although the expansion of productive forest areas has supported quantitative increases in land cover, some challenges remain regarding the quality and functionality of forest ecosystems. While the decrease in DF areas is viewed as a positive development, the decline in forest soils primarily reflects the conversion to more productive forest cover. This situation demonstrates the effectiveness of both natural regeneration processes and rehabilitation efforts. However, comprehensive monitoring and management strategies must be implemented to preserve ecosystem integrity for sustainable forestry (Chazdon, 2014; Food and Agriculture Organization of the United Nations, 2020; Intergovernmental Panel on Climate Change, 2022).

The data presented in Figure 2 demonstrates significant changes in land cover between 1971 and 2022. The analyses reveal complex transitions between different land-use types. The most important changes appear in transforming degraded areas and other land types. Transitions to NF regions are also significant. These changes are thought to be influenced by natural processes and human activities. The data reveal that certain land types, in particular, have undergone more transformation than others. These results offer valuable insights into understanding the dynamics of land use in the region.

Table 5. Land cover change between 1971 and 2022 (ha)

1971	2022								Total	%
	Con.	Dec.	Con.-Dec.	Dec.-Con.	Deg.-Con.	Deg.-Dec.	OFA.	NF.		
Con.	3276.6	27.6	209.8	66.1	322.8	6.7	134.9	234.1	4278.5	6.9
Dec.	150.2	673.0	46.3	-	119.9	107.9	9.0	115.9	1222.3	2.0
Con.-Dec.	-	-	-	-	-	-	-	-	-	-
Dec.-Con.	-	-	-	-	-	-	-	-	-	-
Deg.-Con.	5562.2	1721.1	1618.5	221.4	3072.0	562.7	388.0	1396.2	14542.2	23.3
Deg.-Dec.	948.6	1372.5	206.4	63.3	779.6	1342.8	296.2	1790.8	6800.3	10.9
OFA.	491.6	130.3	50.5	31.6	359.4	36.1	452.4	3013.2	4565.2	7.3
NF.	1415.6	816.8	262.4	20.3	1700.4	1361.2	666.3	24677.9	30921.0	49.6
Total	11844.9	4741.3	2394.0	402.6	6354.1	3417.5	1946.9	31228.2	62329.4	
%	19.0	7.6	3.8	0.6	10.2	5.5	3.1	50.1		100.0

Con.: coniferous, Dec.: deciduous, Dec.-Con.: mixed deciduous-coniferous. Dec.-Dec.: mixed deciduous-deciduous, Deg.-Con.: degraded coniferous. Deg.-Dec.: degraded deciduous, OFA.: open forest area, NF.: non-forest areas

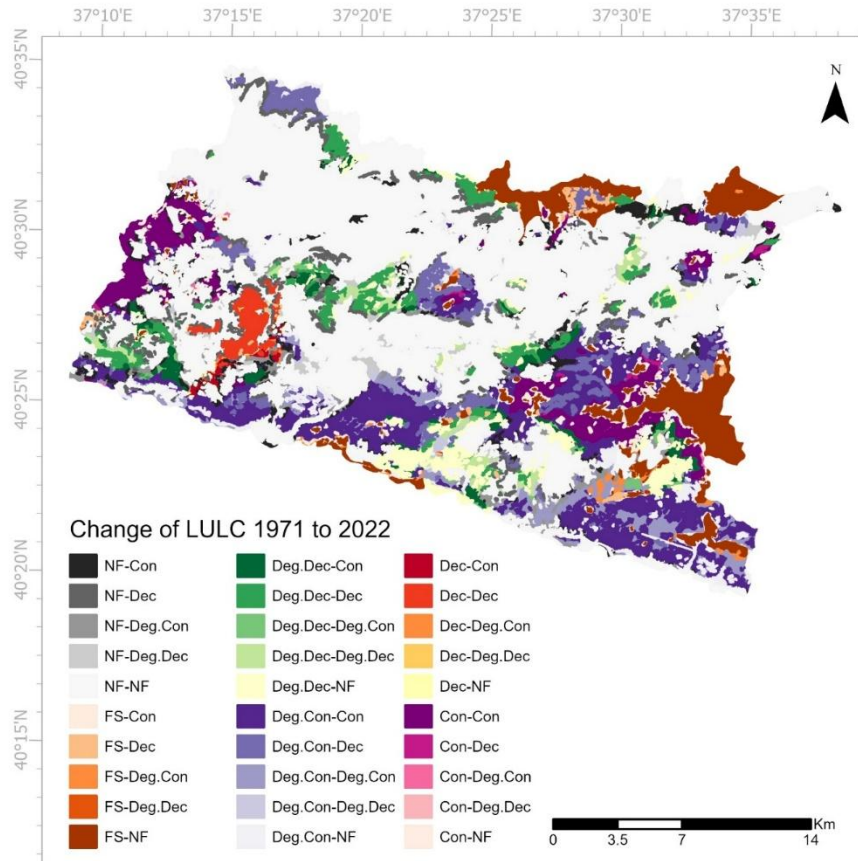


Figure 2. Land cover change between 1971 and 2022

(Con-Con: coniferous-coniferous, Con-Dec: coniferous-deciduous, Con-Deg.Con: coniferous-degraded coniferous, Con-Deg.Dec: coniferous-degraded deciduous, Con-NF: coniferous-non-forest areas, Dec-Con: deciduous-coniferous, Dec-Dec: deciduous-deciduous, Dec-Deg.Con: deciduous-degraded coniferous, Dec-Deg.Dec: deciduous-degraded deciduous, Dec-NF: deciduous-non-forest areas, Deg.Con-Con: degraded coniferous-coniferous, Deg.Con-Dec: degraded coniferous-deciduous, Deg.Con-Deg.Con: degraded coniferous-degraded coniferous, Deg.Con-Deg.Dec: degraded coniferous-degraded deciduous, Deg.Con-NF: degraded coniferous-non-forest areas, Deg.Dec-Con: degraded deciduous-coniferous, Deg.Dec-Dec: degraded deciduous-deciduous, Deg.Dec-Deg.Con: degraded deciduous-degraded coniferous, Deg.Dec-Deg.Dec: degraded deciduous-degraded deciduous, Deg.Dec-NF: degraded deciduous-non-forest areas, FS-Con: forest soil-coniferous, FS-Dec: forest soil-deciduous, FS-Deg.Con: forest soil-degraded coniferous, FS-Deg.Dec: forest soil-degraded deciduous, FS-NF: forest soil-non-forest areas, NF-Con: non-forest areas-coniferous, NF-Dec: non-forest areas-deciduous, NF-Deg.Con: non-forest areas-degraded coniferous, NF-Deg.Dec: non-forest areas-degraded deciduous, NF-NF: non-forest areas-non-forest areas)

3.2. Land cover, forest development, and carbon storage dynamics

The carbon storage capacity of a study area is directly related to the dynamics of land cover and developmental stage. Therefore, changes in carbon stocks reflect increases in biomass and structural transformations in forests.

Significant changes occurred in AGB and BGB, as well as associated carbon stocks, in the study area between 1971 and 2022. According to the data, the total carbon stock was 924310.83 tons in 1971, increasing to 1864306.25 tons in 2022 (Table 6; Figure 3). This represents an increase of approximately 101.7%. However, this increase did not occur linearly over the years; seasonal differences are significant.

Between 1971 and 1991, AGB increased from 315.87 tons to 687.83 tons, while AGC increased from 160.69 tons to 347.37 tons. BGB and BGC also approximately doubled during the same period. This increase indicates the expansion of forest areas and increased carbon sequestration. An increase is also observed in slowly changing carbon pools, particularly litter carbon (LC) and forest soil carbon. During this period, the total carbon stock increased by 39%. This increase is likely explained by the effects of afforestation activities

and natural growth (Pan et al., 2011). The carbon accumulation observed during this period may have been significantly contributed to by the reduction in anthropogenic pressure (fuelwood collection and clearing for agriculture) on forests, a factor supported by the population data in Table 1, which shows a decrease in the rural population (from 54643 to 48845).

Even more striking increases in biomass and carbon stocks were observed between 1991 and 2012. AGB increased approximately tenfold, reaching 6916.15 tons, and AGC reached 3442.90 tons. Similarly, BGB and BGC significantly increased (1887.15 tons and 941.73 tons, respectively). Total carbon increased by 42% during this period. This increase is related to natural forest succession processes, favorable climatic conditions, and the effectiveness of forest management policies (Luyssaert et al., 2008). The ecological and social 'gap' created by the sharp decline in the rural population during this specific period (from 48845 to 33530) should be considered a key socio-economic factor that facilitated this remarkable carbon accumulation by increasing the recovery rate of forests and the effectiveness of natural succession.

However, between 2012 and 2022, a significant decrease occurred in AGB and AGC values. This decline is quantitatively evident, as AGB decreased from 6916.15 tons to

4335.34 tons and AGC decreased from 3442.90 tons to 2155.09 tons (Table 6). Spatial and structural analyses indicate that this reduction was primarily concentrated in mature forest development stages. In particular, the contraction of the c (mature) and d (overmature) development stages, as defined in the forest management plans used in this study, led to a disproportionate loss of stand volume and associated carbon stocks (Table 4). These stages represent forest stands with higher basal area and larger tree diameters, and therefore store a greater proportion of AGB and AGC. This result is consistent with the preferential removal of large diameter trees through production oriented harvesting and regeneration practices, which disproportionately affect high carbon density pools, as reported in previous forest carbon studies (Pan et al., 2011; Keith et al., 2014). In addition, increasing climate related stressors after 2012, including prolonged drought periods, elevated temperature anomalies, insect outbreaks, and wildfire events, likely amplified the observed carbon losses by reducing growth rates and increasing tree mortality (Allen et al., 2010; Forzieri et al., 2021). Together, this result indicates that the observed decline in carbon stocks between 2012 and 2022 reflects the combined effects of production focused forest management practices and climate change related stressors, rather than changes in land cover extent alone.

This decline over the past decade demonstrates that carbon stocks are not only increasing but can also experience periodic fluctuations. Therefore, sustainable forestry policies should aim to increase carbon stocks, protect existing stocks, and prevent biomass losses. In particular, the rehabilitation of DF areas, the promotion of mixed-species forests, and the development of adaptation strategies against stress factors such as drought/fire are critical to reducing these risks (Griscom et al., 2017; Intergovernmental Panel on Climate Change, 2022). However, more stable carbon pools, such as LC and soil carbon, continued to increase. This suggests that carbon continues to accumulate in the soil system. This increase in soil carbon is particularly related to factors such as microbial activity, input of dead organic matter, and soil structural integrity (Jandl et al., 2007). This allows carbon to remain in the soil for extended periods, increasing the system's resilience.

The net increase between 1971 and 2022 is 101.7% in total carbon content. This increase is a positive development in terms of carbon accumulation in the ecosystem; however, the decline in the last decade poses a risk to the sustainability of this positive trend. These results demonstrate the importance of restoring DF areas and sustainable land use policies (Erb et al., 2018; Food and Agriculture Organization of the United Nations, 2020). In conclusion, the passive conservation effect

resulting from the decline in anthropogenic pressure due to rural population decline contributed significantly to the increase in carbon stock between 1971 and 2012. However, this effect appears to have been offset by the impact of climatic and managerial stress factors after 2012. The decrease in biomass observed in the last decade, in particular, could reduce carbon sequestration capacity, negatively impacting regional climate regulation functions and the global carbon balance. In this context, the increase in carbon stocks and their sustainability should be taken into consideration. Land use decisions should be reformed with approaches that are not only based on economic benefits but also on the holistic management of the carbon cycle (Griscom et al., 2017). These results underscore the crucial role of forest ecosystems in regulating the carbon cycle and mitigating climate change (Intergovernmental Panel on Climate Change, 2019b).

On the other hand, global assessments indicate a general improvement in the structural quality of forests, despite net decreases in forest area. According to Food and Agriculture Organization of the United Nations (2020) data, the total tree stock worldwide was approximately 560 billion m³ in 1990, but this value decreased to 557 billion m³ by 2020. However, the stock per unit area increased from 132 m³ to 137 m³ during the same period. This increase reflects the positive impact of sustainable forestry practices and quality-oriented approaches to wood production. This trend provides context for understanding the structural transformations and changes in carbon storage capacity that can be observed in the study area as well.

While a general upward trend in biomass and carbon stocks is observed between 1971 and 2022, this change did not follow a linear course; the significant decrease, particularly between 2012 and 2022, reveals a fluctuating character. This demonstrates that carbon storage capacity does not simply grow; it can fluctuate under the influence of dynamics such as land use, forest degradation, and management practices. Furthermore, the continuous increase in more stable pools, such as those of LC and soil carbon, indicates that carbon accumulation is not limited to biomass but also continues in soil systems, contributing to a more comprehensive understanding of the carbon cycle. In our study, soil carbon and litter carbon accounted for the most significant proportion of total forest carbon, similarly to the findings of Ren et al. (2014), Cui et al. (2015), and Chen et al. (2019), confirming that stable carbon pools play a critical role in forest carbon sequestration. This perspective emphasizes the importance of considering not only quantitative increases but also the continuity of the increase and the diversity of carbon pools for sustainable forest management and the protection of carbon sinks.

Table 6. Changes in forest biomass and carbon pools between 1971 and 2022 (tons)

Year	AGB	AGC	BGB	BGC	DWB	DWC	LC	SOC	Total Carbon
1971	315.87	160.69	97.83	49.71	3.16	1.48	69908.47	854190.48	924310.83
1991	687.83	347.37	201.90	102.02	6.88	3.23	102281.13	1183580.69	1286314.44
2012	6916.15	3442.90	1887.15	941.73	69.16	32.51	130335.51	1691698.36	1826451.01
2022	4335.34	2155.09	1175.89	586.03	50.20	23.60	140551.92	1720989.61	1864306.25

AGB: above-ground biomass, AGC: above-ground carbon, BGB: below-ground biomass, BGC: below-ground carbon, DWB: dead wood biomass, DWC: dead wood carbon, LC: litter carbon, SOC: soil organic carbon

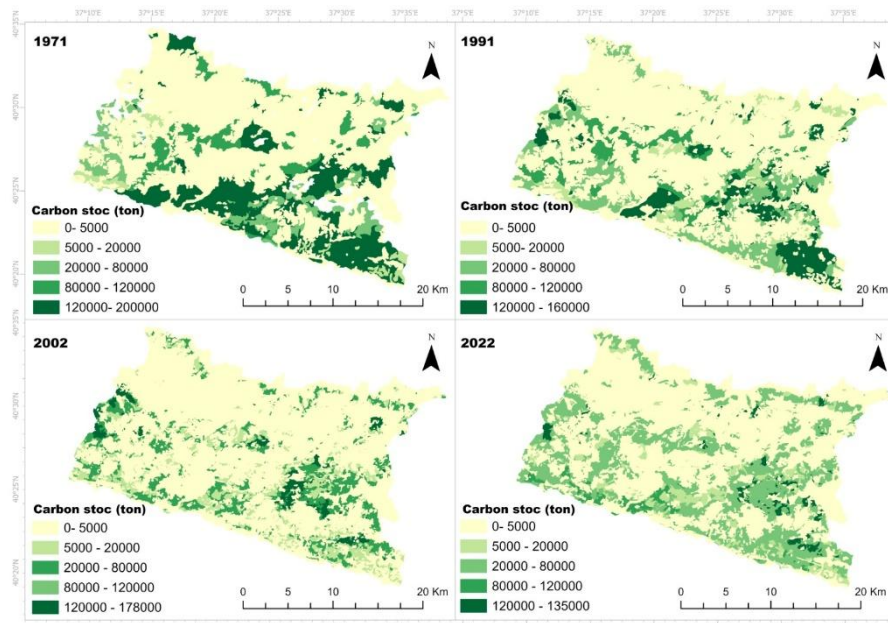


Figure 3. Spatial distribution of carbon storage (1971-2022)

Biomass accumulation in forest ecosystems directly relates to stand structure and developmental stages. This study evaluated the spatial distribution and the resulting changes in AGB and BGB across developmental stages between 1971 and 2022. The results show that biomass accumulation and carbon stocks increase significantly as the diameter class increases in forest areas.

According to 1971 data, the 'a' and 'b' developmental stages, representing earlier stages of development, covered 5833 ha. This area decreased to 3511 ha in 2022. In contrast, a significant increase was observed in the 'c', 'cd', and 'd' developmental stages, which contain larger-diameter individuals. The expansion of transitional classes such as 'bc' and 'cd', in particular, reveals that the stands have evolved into a more mature structure. This change has resulted in a direct increase in volume and, consequently, in biomass. This trend is also reflected in the AGB and BGB values. AGB, which had only 315 tons in 1971, reached approximately 4335 tons in 2022. Similarly, the amount of BGB increased from 9783 tons to 117589 tons in the same period. This significant increase can be attributed to the increased planted standing volume (SV) and growth in developmental stages. The SV value is a key variable in empirical biomass calculation formulas, and increases in diameter cause this value to increase, directly affecting the AGB and BGB calculations.

Composite development stage symbols, such as 'bd,' used before 1971, are considered indicators of structural heterogeneity within the stand (Aksoy, 1978; Avşar, 1999). This structural heterogeneity is a significant factor determining the future carbon stock and biomass trends of the stand. Indeed, in such a stand, either young individuals will be cut to ensure rapid growth and high carbon stocks of older trees (d), or older individuals will be harvested to rejuvenate the stand and restart the carbon absorption flow from scratch (Asan, 1995).

These results are consistent with results reported by Nabuurs et al. (2017) in studies conducted on European forests, which indicate that the carbon storage capacity of forests increases with advancing developmental stages. Furthermore, Pilli et al. (2017) examined the effects of developmental

stages on the carbon cycle within management scenarios, demonstrating that carbon accumulation increases as the diameter class increases. However, a partial decrease in AGB and BGB amounts was observed between 2012 and 2022. This decrease is directly related to the shrinkage of stand areas in large developmental stages ('c' and 'd'). This can be explained by factors such as production in forest areas, regeneration practices, or area losses. Such fluctuations may also reflect temporary renewal periods as a natural part of the stand cycle. Kurz et al. (2013) suggest that these periods of reduced mature individuals may have a long-term effect on carbon stocks. This area loss led to a decrease in mature individuals and, consequently, a reduction in SV values, resulting in a decrease in total biomass and carbon stocks. These results were also emphasized by Kilpeläinen and Peltola (2022), indicating that carbon accumulation may be interrupted if diameter growth stops or reverses.

As a result, progress in developmental stages increases stand volume and, consequently, biomass and carbon content; diameter class growth strengthens the carbon sink potential of forests in terms of ecosystem services. Therefore, preserving mature stands and supporting diameter growth is critical for sustainable forest management policies.

4. Conclusions

This study examined changes in land cover and carbon stocks in the Reşadiye Forest Management Unit between 1971 and 2022. The findings indicate an overall improvement in carbon stocks, driven by an increase in productive forest areas and a decrease in degraded areas. However, the observed decline in biomass during the 2012-2022 period emerges as a critical risk factor that requires careful monitoring for sustainable forest management. The study's original contribution lies in the use of a rare long-term (52-year) dataset in Turkey to analyze the relationship between land cover changes and carbon stocks at both spatial and temporal scales. This approach not only highlights increases in carbon stocks but also reveals the dynamics affecting their continuity. In

particular, the biomass loss observed over the past decade highlights the vulnerability of carbon sinks and underscores the importance of ongoing monitoring efforts.

The results provide direct data for updating carbon inventories specific to the Reşadiye region and contribute to the development of carbon-based management strategies for forest ecosystems in Turkey. The findings support strategies aimed at strengthening climate change adaptation through the rehabilitation of degraded forests and the promotion of mixed-species stands. Furthermore, the protection and maintenance of large-diameter, mature trees emerges as a priority strategy to enhance carbon storage capacity and sustain ecosystem services. The significant share of soil and litter carbon in total carbon stocks underscores the importance of preserving these pools in land-use planning and forest management practices. Reforestation efforts, the promotion of mixed-species plantations, and sustainable regeneration policies should consider stand development stages. Meanwhile, proactive measures against natural disturbances, such as drought, fire, and insect outbreaks, are crucial for maintaining the sustainability of carbon stocks. Beyond economic considerations, integrating carbon cycle management and climate change mitigation strategies into planning and implementation provides decision-makers with a concrete roadmap. In this context, the findings provide a scientific basis for developing policies and strategies that enhance carbon accumulation and climate regulation functions in Reşadiye and similar regions. Decision-makers can use this evidence to optimize short-term forestry operations while achieving long-term ecosystem service and carbon balance objectives.

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