

Quantifying carbon storage decline under land degradation in the Central High Atlas: A case study of the Oued Ahansal watershed (2000–2022)

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Abstract. Carbon sequestration is an essential ecosystem service that contributes to climate regulation and enhances ecosystem resilience. This study evaluates changes in carbon storage in the Oued Ahansal watershed, Central High Atlas, Morocco, from 2000 to 2022 using the InVEST model. Land use and land cover maps derived from Landsat 5 and Landsat 8 images were classified into four categories: dense forest, open forest, agricultural land, and bare soil. Carbon stocks were estimated for aboveground biomass, belowground biomass, soil, and dead organic matter. Results show a marked decline in high-carbon storage areas, which decreased from 55.5% in 2000 to 11.9% in 2022, while low-carbon zones increased from 5.1% to 80.8%. This reflects accelerated land degradation linked to vegetation loss, overgrazing, and recurrent droughts. The findings highlight the urgent need for reforestation, assisted natural regeneration, and sustainable land management to restore the carbon sink capacity of degraded mountain ecosystems.

1 Introduction

Terrestrial ecosystems play a key role in regulating the global climate through their capacity to capture and store atmospheric carbon dioxide (CO₂). This process, known as carbon sequestration, represents a major ecosystem service that helps mitigate climate change [1]. Since the Industrial Revolution, however, atmospheric CO₂ concentrations have been steadily increasing, disrupting the balance between emissions and ecosystem absorption capacity [2]. Carbon is a fundamental component of terrestrial ecosystem functioning. It directly influences soil fertility, biological productivity, biodiversity, and overall environmental quality [3]. Soils and vegetation act as natural carbon sinks, but their storage potential largely depends on land cover type, land use practices, and local climatic conditions [4].

In Morocco's mountainous regions, particularly in the Central High Atlas, increasing anthropogenic pressures such as deforestation, overgrazing, and land conversion have significantly altered vegetation structure and composition [5]. These transformations weaken the ecological stability of watersheds, reduce carbon storage capacity, and accelerate processes of soil erosion and aridification [6].

Spatial assessment of carbon sequestration dynamics provides valuable insights into ecosystem degradation and identifies priority areas for ecological restoration. The InVEST (*Integrated Valuation of Ecosystem Services and Tradeoffs*) model is one of the most widely used tools to quantify and map ecosystem services based on biophysical and remote-sensing data [7, 8]. Its application in the context of the Oued Ahansal watershed allows for an integrated understanding of how land use change and vegetation degradation affect carbon storage over time.

The present study focuses on assessing the dynamics of carbon sequestration in the Oued Ahansal watershed (Central High Atlas, Morocco) over the period 2000–2022, using the InVEST model. The main objective is to quantify the evolution of total carbon storage and to analyze its spatial variability in relation to land use and land cover changes. Particular attention is given to identifying the zones most affected by carbon loss and those showing high restoration potential, in order to support the development of sustainable land management strategies and climate change mitigation actions in mountain ecosystems.

2 Materials and Methods

2.1 Study area

The Oued Ahansal watershed is located in the Central High Atlas of Morocco, upstream of the Bin El Ouidane dam, within Azilal Province (Beni Mellal-Khénifra region). It extends between latitudes 31°40' N and 32°50' N and longitudes 5°55' W and 6°20' W, covering approximately 617 km² (Fig. 1).

The topography is highly rugged, with elevations ranging from 900 to 3200 m A.S.L., and slopes often exceeding 35 %. The climate is semi-arid to sub-humid, characterized by cold winters, dry summers, and annual precipitation varying from 300 to 700 mm depending on altitude.

Vegetation includes *Pinus halepensis*, *Quercus rotundifolia*, *Juniperus phoenicea*, *Juniperus oxycedrus*, *Tetraclinis articulata*, and degraded shrublands subject to intense grazing and wood harvesting. Local communities rely mainly on agro-pastoral systems and forest resources, which exert considerable pressure on natural vegetation and soils.

2.2 Data and preprocessing

Two cloud-free Landsat scenes were selected for analysis: Landsat 5 TM (September 2000) and Landsat 8 OLI (August 2022). Both were obtained from the USGS EarthExplorer platform at Level-1 processing. Radiometric and atmospheric corrections were applied using the *Landsat Surface Reflectance* product in QGIS and ArcGIS (10.x).

A supervised classification based on the Maximum Likelihood algorithm was performed to generate land use/land cover (LULC) maps. Four major classes were identified: dense forest, open forest, agricultural land, and bare soil. Classification accuracy was assessed using 150 validation points derived from high-resolution imagery and field verification, yielding an overall accuracy of 89 % and a Kappa coefficient of 0.83 [9].

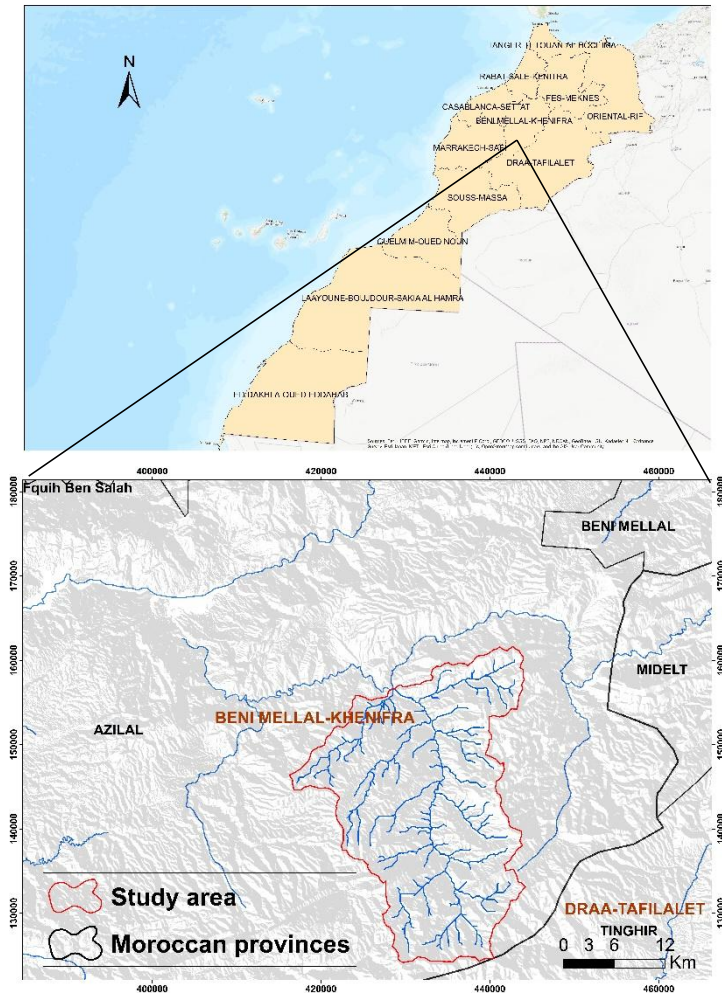


Fig. 1. Location of the Oued Ahansal watershed in the Central High Atlas, Morocco

2.3 Carbon pool data

The *InVEST Carbon Storage and Sequestration* module requires biophysical parameters describing the carbon content of four major pools: above-ground biomass (C_a), below-ground biomass (C_b), soil organic carbon (C_s), and dead organic matter (C_d). Values were compiled from regional and Mediterranean studies [10, 11] and adjusted to the ecological context of the High Atlas forests (Table 1).

Table 1. Carbon stock values used in the InVEST model ($Mg\ C\ ha^{-1}$)

Land cover class	Above-ground (C_a)	Below-ground (C_b)	Soil (C_s)	Dead organic (C_d)
Dense forest	77.1	6.4	27.4	0
Open forest	222.1	0.3	45.9	0
Agricultural land	72.9	4.5	37.2	0
Bare soil	28.2	21.1	25.1	0

C_a = aboveground biomass carbon; C_b = belowground biomass carbon; C_s = soil carbon;
 C_d = dead organic matter carbon.

2.4 InVEST model and spatial analysis

The InVEST Carbon Storage and Sequestration model estimates total carbon stock per pixel as the sum of the four pools. The model was executed for 2000 and 2022 using the respective LULC maps and the biophysical table.

The resulting carbon storage maps were compared to evaluate spatial and temporal variations in carbon density (Mg C ha^{-1}). Three classes were defined: low (< 7), medium (7–14), and high (> 14).

Zonal statistics in ArcGIS (10.x) quantified the surface proportion of each category and identified areas showing carbon loss or gain trends at the watershed scale.

3 Results and Discussion

3.1 Results

3.1.1 Land use and land cover dynamics (2000–2022)

The land use and land cover (LULC) analysis reveals profound transformations in the Oued Ahansal watershed between 2000 and 2022 (Fig. 2 and Fig. 3).

In 2000, bare soils occupied 343.41 km^2 (55.65%), while open forests covered 243.56 km^2 (39.47%). Dense forests and agricultural lands were limited, representing 25.39 km^2 (4.11%) and 6.09 km^2 (0.98%), respectively.

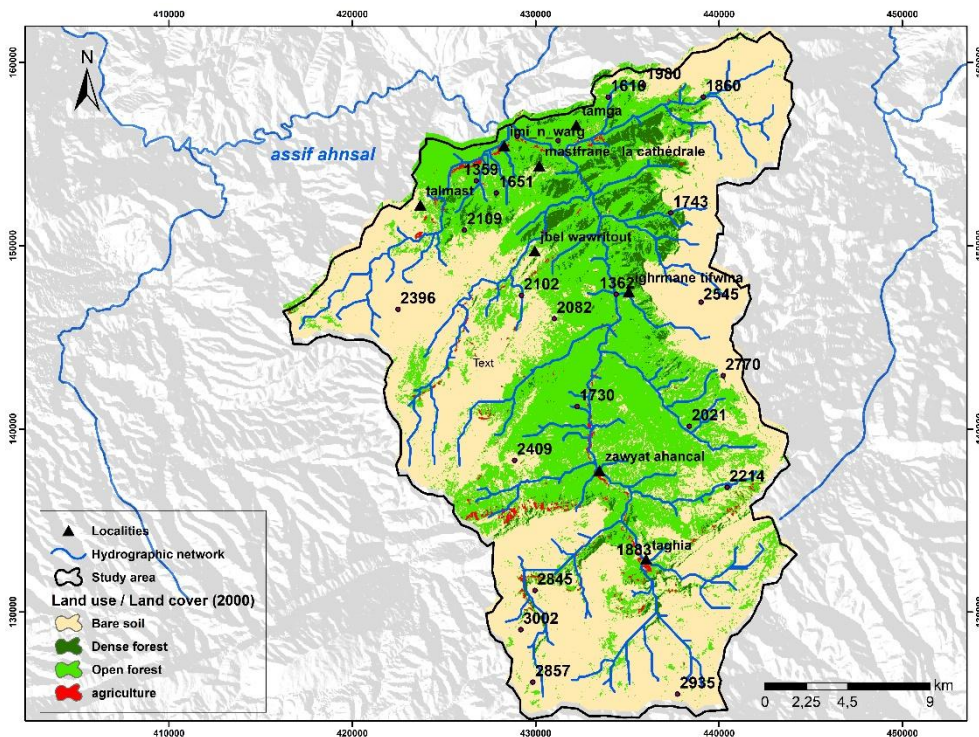


Fig. 2. Land use and land cover map of the Oued Ahansal watershed in 2000

By 2022, the dominance of bare soils became striking, increasing to 515.37 km² (83.53%), indicating an expansion of degraded and unvegetated surfaces. In contrast, open forests declined drastically to 59.56 km² (9.65%), marking a loss of nearly three-quarters of their original extent. Dense forests expanded slightly to 41.45 km² (6.72%), likely due to natural regeneration or localized restoration efforts, whereas agricultural areas decreased to 3.18 km² (0.52%), possibly following abandonment of marginal croplands.

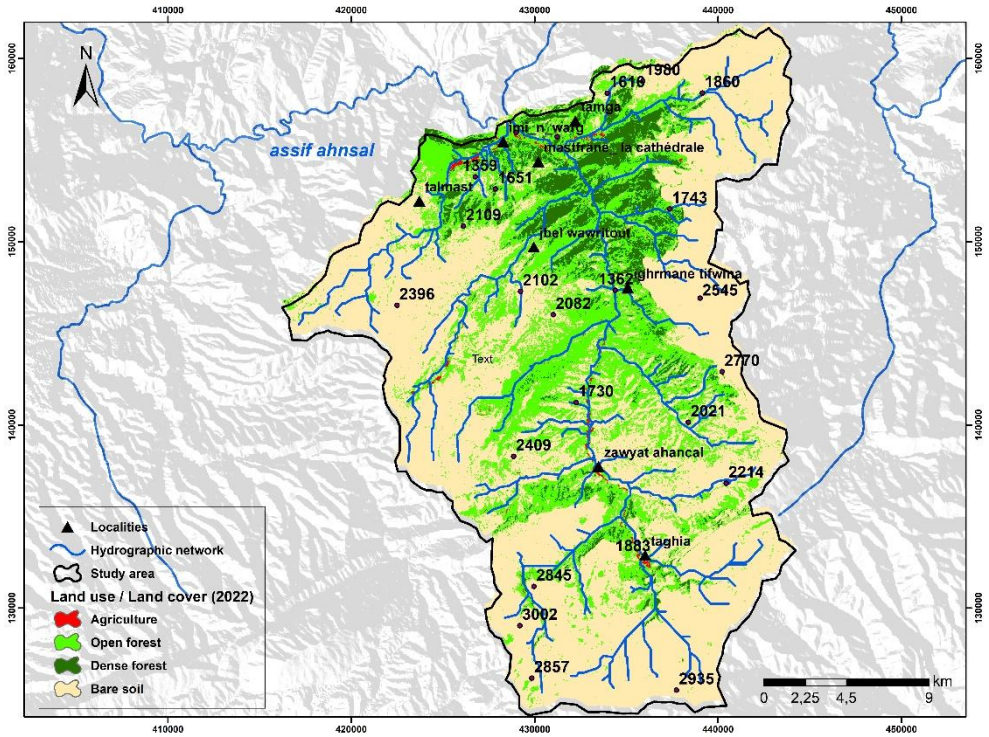


Fig. 3. Land use and land cover map of the Oued Ahansal watershed in 2022

Overall, the 22-year period shows a clear trend of vegetation degradation and soil exposure, consistent with ongoing processes of deforestation, overgrazing, and erosion. The conversion of forested land into bare soil illustrates the intensification of environmental stress in the region, leading to the loss of carbon reservoirs and reduced ecological resilience. These results provide the spatial context necessary to interpret the decline in carbon storage observed in the following sections.

3.1.2 Carbon storage assessment

The InVEST carbon storage model produced spatial maps for 2000 and 2022 (Fig. 4 and Fig. 5), showing clear temporal and spatial contrasts across the Oued Ahansal watershed.

In 2000 (Fig. 4), carbon storage values ranged between $6.68 \text{ Mg C ha}^{-1}$ and $24.10 \text{ Mg C ha}^{-1}$. The highest values were observed in the northern and central forested sectors, where dense and open forest stands dominate, representing about 55.5 % of the total area with high carbon storage ($> 14 \text{ Mg C ha}^{-1}$). Intermediate levels ($7\text{--}14 \text{ Mg C ha}^{-1}$) covered 39.4 %, while low-storage zones ($< 7 \text{ Mg C ha}^{-1}$) accounted for only 5.1 %, mostly in degraded and rocky areas.

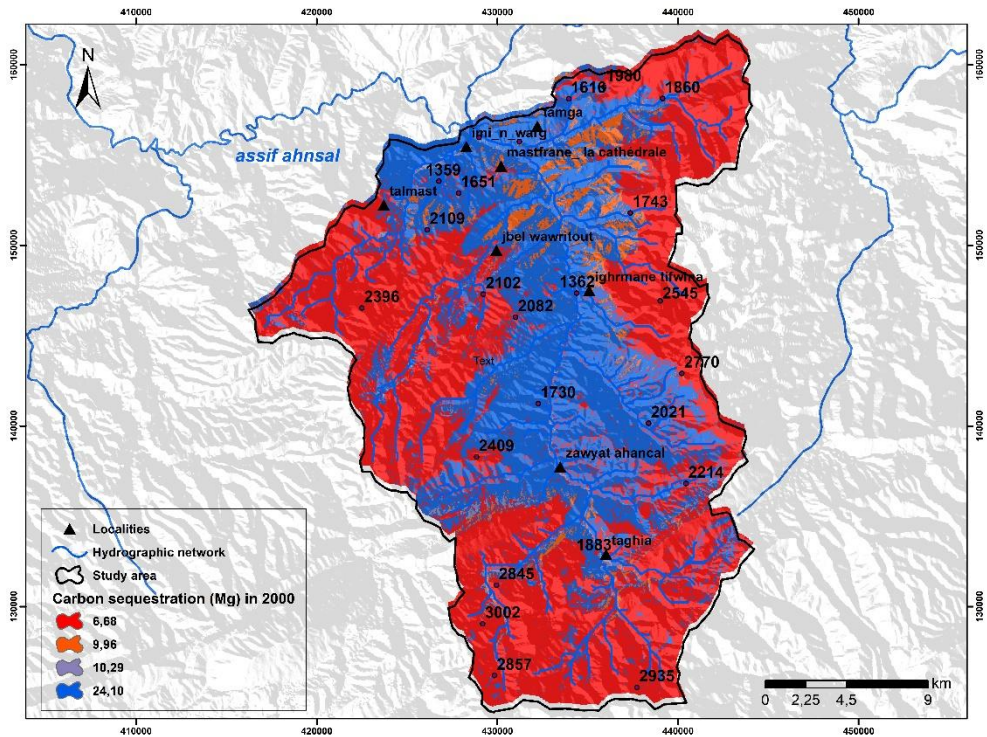


Fig. 4. Spatial distribution of carbon storage in 2000 (Mg C ha⁻¹).

In 2022 (Fig. 5), the spatial configuration changed dramatically. Low-storage areas expanded to dominate 80.8 % of the watershed, while medium-storage zones and high-storage zones shrank to 7.3 % and 11.9 %, respectively. The greatest losses occurred in the southern and eastern slopes, where vegetation degradation and soil exposure have intensified.

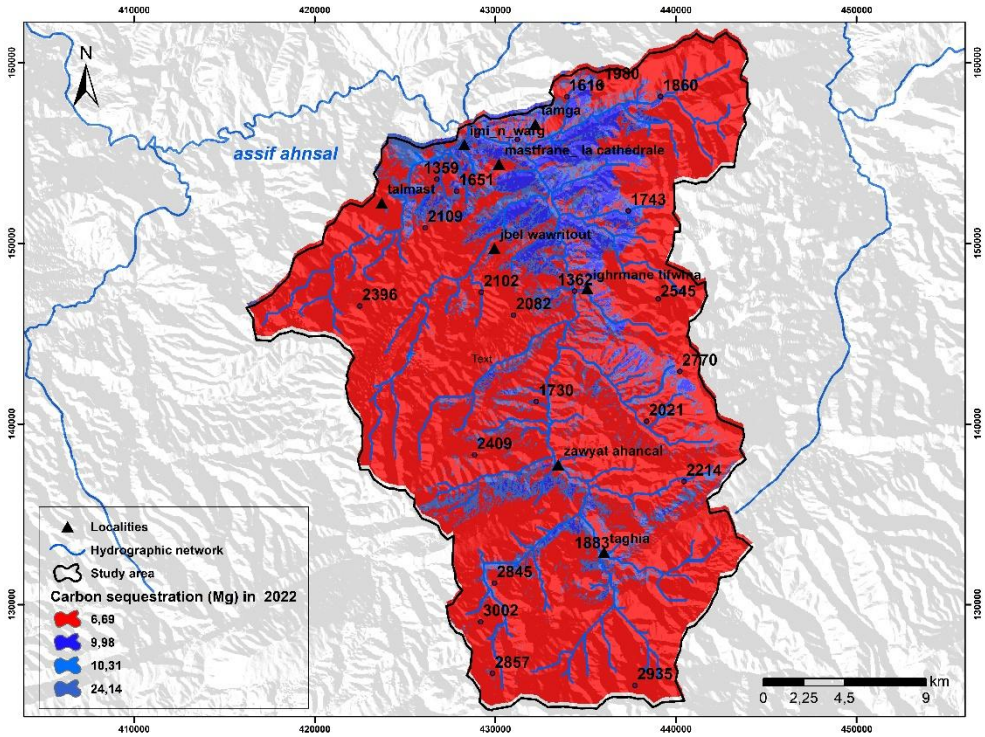


Fig. 5. Spatial distribution of carbon storage in 2022 (Mg C ha^{-1}).

The comparative histogram (Fig. 6) summarizes these variations quantitatively. It illustrates a complete inversion of the distribution of carbon storage classes over the 22-year period: in 2000, high-carbon zones were dominant (55.52 %), whereas by 2022, low-carbon zones accounted for 80.75 %. The medium-storage class also decreased sharply from 39.37 % to 7.26 %.

This evolution confirms a severe decline in the watershed's carbon sequestration potential, directly linked to the loss of vegetative cover revealed in the LULC analysis. The conversion of open forests into bare soil not only reduced aboveground biomass but also weakened soil carbon stocks, illustrating the sensitivity of mountain ecosystems to human and climatic pressures.

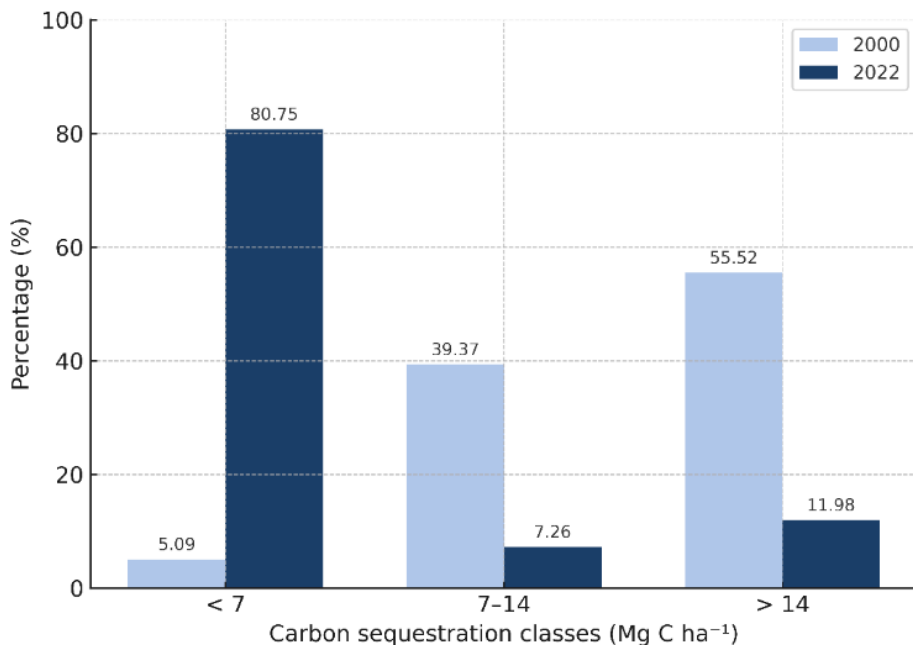


Fig. 6. Comparative distribution of carbon sequestration classes in 2000 and 2022.

3.2 Discussion

The marked decline in carbon storage observed between 2000 and 2022 illustrates a progressive degradation of ecosystem functions within the Oued Ahansal watershed (Central High Atlas, Morocco). The sharp increase in low-storage areas (Fig. 6) reflects a substantial reduction in both biomass and soil organic matter, which is consistent with the expansion of bare soils and the retreat of open forests evidenced by the LULC analysis (Fig. 2 and Fig. 3). This finding confirms the strong link between vegetation cover dynamics and the ability of mountain ecosystems to retain carbon stocks.

These patterns mirror the broader processes of land degradation and deforestation occurring in Morocco's semi-arid and mountainous regions, where overgrazing, fuelwood harvesting, and land conversion to marginal uses have considerably weakened vegetation structure and soil stability [12, 13]. The conversion of forested and shrub-dominated landscapes into degraded or sparsely vegetated surfaces leads to a loss of above- and belowground carbon pools, accompanied by enhanced erosion and nutrient depletion [10].

Mountain ecosystems are particularly sensitive to climatic variability. In the High Atlas, recurrent droughts, increased evapotranspiration, and rising temperatures exacerbate soil desiccation and carbon loss from the upper horizons [14]. The combined impact of climate stress and land use intensification contributes to a substantial decline in ecosystem productivity and carbon sequestration potential, as similarly reported in Mediterranean and semi-arid catchments across the globe [8]. The InVEST model outcomes confirm this tendency, revealing that more than 80 % of the Oued Ahansal watershed is now characterized by low carbon storage, compared with only 5 % in 2000.

Globally, semi-arid ecosystems have been identified as major regulators of the interannual variability of the terrestrial carbon sink [1]. Therefore, the contraction of high-carbon zones from 55.5 % to 11.9 % in the study area not only signals a local ecological imbalance but

also reflects a regional trend of declining carbon sink capacity under cumulative human and climatic pressures [2, 7, 8].

To mitigate these effects, ecological restoration and adaptive land management are urgently needed. Priority actions should include reforestation and assisted natural regeneration in degraded forest zones, the stabilization of erodible slopes through soil and water conservation measures, and the promotion of agroforestry and rotational grazing systems to enhance soil organic carbon storage and landscape resilience [9, 14]. The integration of these measures into regional forest and land use planning frameworks would strengthen carbon sequestration potential, mitigate the impacts of climate change, and sustain the ecosystem services that underpin local livelihoods in Morocco's mountain regions.

4 Conclusion

This study quantified and analyzed the spatio-temporal evolution of carbon sequestration in the Oued Ahansal watershed (Central High Atlas, Morocco) over the 2000–2022 period using the InVEST model. The results reveal a drastic decline in carbon storage capacity, driven by extensive vegetation loss and land degradation. High-carbon storage areas decreased from 55.5 % to 11.9 %, while low-storage zones expanded to more than 80 % of the watershed, reflecting the growing dominance of bare and eroded surfaces.

These findings highlight the combined influence of human and climatic pressures on mountain ecosystems, where deforestation, overgrazing, and recurrent droughts have accelerated the depletion of biomass and soil organic carbon. The Oued Ahansal watershed thus exemplifies the fragile balance between ecosystem productivity and land use intensification in Morocco's semi-arid mountains.

Restoring the carbon sequestration potential of such degraded environments requires integrated management strategies that couple ecological restoration with sustainable land use planning. Priority actions should focus on reforestation and assisted natural regeneration in forest remnants, slope stabilization through soil and water conservation practices, and the adoption of agroforestry and rotational grazing systems to reinforce carbon storage and improve ecosystem resilience.

Incorporating carbon monitoring into regional planning frameworks would provide a robust basis for tracking restoration progress and supporting Morocco's commitments to climate change mitigation. Overall, this work demonstrates the value of spatial modeling tools such as InVEST in assessing ecosystem degradation and guiding adaptive management policies toward more sustainable and carbon-resilient landscapes.

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