CJES
Caspian Journal of Environmental Sciences
Online ISSN: 1735-3866
Print ISSN: 1735-3033

Evaluation of carbon sequestration service in the forest ecosystem (Case study: Hyrcanian Forests, North Iran)

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ABSTRACT
The present study investigates the carbon sequestration service and its economic value in Hyrcanian forests. Eleven Hyrcanian forest communities with different spatial conditions (Guilan, Mazandaran, and Golestan basins) in Northern Iran were studied in 2022-2023. To examine the amount of carbon production, information from the Iranian Forestry and Watershed Management Organization, GIS 10.7, INVEST 3.9, and the replacement cost method were used. The results showed that the level of carbon sequestration varied depending on spatial conditions, species, and other factors. Different species followed distinct growth patterns. In addition, carbon sequestration varied from a minimum of 221 tons ha^{-1} in the mixed forest community of Asalem, Guilan, area 7, to a maximum of 314 tons ha^{-1} in the hornbeam Nur-Chamestan forest community, Mazandaran, area 51, with an average of 261 tons ha^{-1} in all the study areas. The cost of carbon sequestration was calculated based on the costs of carbon capture and storage, approximately $110 per ton. As a result, the average value per ha and the total forests studied were estimated at 12068 and 937451914 million IRR, respectively. By generalizing this figure to the total area of northern Iranian forests (2.3 million hectares), the value of northern forests for carbon sequestration was 27755614523 million IRR, equivalent to $67308 million. Policymakers at national and regional levels should incorporate carbon sequestration values into environmental planning, carbon offset mechanisms, and payment for ecosystem services (PES) schemes to incentivize forest conservation and climate mitigation. This integration should be accompanied by forest management strategies that are tailored to the ecological characteristics and carbon sequestration potential of different forest types, prioritizing high-biomass ecosystems such as beech forests for targeted conservation efforts.

Keywords: Ecosystem services, Carbon sequestration, Hyrcanian Forest, Non-market services
Article type: Research Article.

INTRODUCTION
Forests are globally valuable resources that cover 31% of the Earth's surface (4.06 billion ha). However, the area of forests has been declining, with 420 million ha lost due to deforestation from 1990 to 2020 (FAO 2020). Forest ecosystems are a vital component of global biodiversity, as many forests exhibit greater biodiversity than other ecosystems. Forest coverage is one of the indicators of the 15 sustainable development goals, specifically "life on land." Forests provide habitats for 80% of amphibian species, 75% of bird species, and 68% of mammal species (FAO 2020). Forests play a critical role in controlling climate change and are a key tool for combating its effects. They contain 662 billion tons of carbon, representing more than half of the global carbon reserves stored in soil and vegetation. Despite ongoing reductions in forest area, forests absorbed more carbon between 2011 and 2020 due to forest restoration, improved forest management, and other factors (FAO 2020). Forest ecosystems are the

primary terrestrial carbon sinks, and according to recent international studies, global forests store 22% of the world's carbon reserves. Specifically, 471 petagrams of carbon (where one petagram equals 10^{15} grams), equivalent to 55% of the total forest carbon, is stored in tropical forests, 272 petagrams in deciduous forests, and 119 petagrams in temperate forests (Pan *et al.* 2011). Of the total 862 petagrams of carbon, 44% is stored in soil, 42% in living biomass, and 8% in deadwood (McKinley *et al.* 2011). Forest carbon sinks offset approximately 33% of annual fossil fuel emissions in the atmosphere (Pan *et al.* 2011). However, carbon storage and sequestration in forests vary significantly over time (e.g., annually and over decades) and space (regionally and globally). These processes are directly influenced by natural events (e.g., climate change, droughts, wildfires, pest outbreaks, and diseases) and human activities (e.g., deforestation, afforestation, urban development, and forest management policies) (Mahmoudi Taleghani *et al.* 2007). Carbon storage and sequestration represent one of the most important and well-recognized regulatory ecosystem services, which, through climate regulation at both micro-local and macro-global scales, help mitigate and moderate the pace of climate change (Raihan *et al.* 2021). Carbon sequestration, in forested lands, primarily occurs through the absorption of atmospheric carbon via photosynthesis and its storage in the biosphere (Bostan *et al.* 2018; Bherwani *et al.* 2024). Forest carbon sequestration is widely regarded as a cost-effective solution for controlling the rising concentration of atmospheric CO_2 (Ameray *et al.* 2021; Sevillano *et al.* 2025). Notably, the cost of carbon sequestration in forest-based projects can be up to 40% lower compared to other approaches (Grafton *et al.* 2021; Bostyn & Brunelle 2025). This cost efficiency stems from the fact that the average cost of reducing greenhouse gas emissions through renewable energy sources can exceed double that of forest carbon sequestration (Knopf *et al.* 2013; Vass 2017). Emerging technologies, such as direct air capture of CO_2, are significantly more expensive than the cost-effective forest carbon sequestration methods (Pielke 2009; Keith *et al.* 2018). Forest-based sequestration projects are expected to play a critical role in mitigating climate change in the short to medium term. However, in the long term (e.g. after 2050) forest-based sequestration may face competition from alternative, potentially more cost-effective methods (Minx *et al.* 2018). Specifically, other sequestration approaches, such as Bioenergy with Carbon Capture and Storage (BECCS) and Direct air Carbon Capture and Storage (DACCS), may become economically viable (Minx *et al.* 2018). The Hyrcanian forests in North Iran, as deciduous broadleaf forests, offer ecological functions at both local and global scales. These forests are home to approximately 150 native plant species, 60 mammal species, 340 bird species, 67 fish species, 29 reptile species, and 9 amphibian species (Natural Resources and Watershed Management Organization, 2022). Iran successfully registered these forests as a UNESCO World Heritage Site (UNESCO, 2019). Despite the vital role of the Hyrcanian forests in providing diverse ecosystem services and their direct impact on the livelihoods and welfare of local communities (Panahi 2005; Amirnejad *et al.* 2006), deforestation and forest degradation have intensified in recent decades. Economic incentives and financial motives have driven the conversion of forest lands into other human uses such as settlements, orchards, and farms (Shooshtari *et al.* 2012, 2018; Zarandian *et al.* 2016). Iran's geographic and climatic characteristics exacerbate climate change impacts (Azari *et al.* 2016; Eskandari *et al.* 2016). Native and endangered plant and animal species in the Hyrcanian forests are particularly vulnerable to the cumulative effects of climate change and socio-economic pressures (El-Baha *et al.* 2010). There is broad consensus that the degradation of natural resources and environmental pollution is largely attributable to the absence of markets for ecological goods and services (Stapleton & Garrod 2008). Estimating the true value of ecosystem functions and effects and developing appropriate mechanisms to capture their economic value are critical for optimal resource allocation (Adgers *et al.* 1995; Ninan *et al.* 2007). Several studies have examined the quantitative and economic aspects of carbon sequestration in forest ecosystems. Joshi & Garkoti (2025) investigated ecosystem carbon storage—including plant biomass, deadwood, litter, and soil organic carbon (SOC)—and evaluated carbon sequestration potential and carbon credit values across chir pine, deodar, oak, and Sal forests in the Central Himalaya. Using volumetric equations and field sampling via the quadrat method, they quantified tree biomass and carbon stocks. The findings showed that ecosystem carbon storage ranged from 122.44 to 306.44 Mg C ha^{-1}, with oak forests having the highest and pine forests the lowest carbon stocks. The distribution of carbon among different components varied: trees (21%–34%), soil (64%–77%), deadwood (0.35%–0.9%), and litter (0.46%–1.20%). The Mantel test indicated that environmental factors significantly influenced carbon storage. CO_2 sequestration ranged from 448.98 Mg CO_2 ha^{-1} in pine forests to 1123.16 Mg CO_2 ha^{-1} in oak forests; and the corresponding carbon credit values ranged from €1346.96 to €3379.49 per ha. Lu Xu *et al.* (2025) developed a comprehensive valuation framework to assess the ecosystem services provided by rural forest resources, focusing on Muyun She Nationality

Township in Fuan City, China. Their assessments estimated the annual economic value of forest ecosystem services at 397,899,293.49 Yuan. Direct value accounted for over 63% of the total, with forest by-products making up the largest portion (32%), followed closely by forest-related rural tourism (31%). The study highlighted the significant role of rural forest resources in generating agricultural by-products, promoting rural tourism, supporting local economic development, and advancing rural revitalization initiatives. In their study, Fadaei *et al.* (2020) investigated the changes in land cover/use regarding carbon storage and sequestration in the Jahannama Protected Area (Pilot of Hyrcanian Forests) during the period 2001-2018 and its prediction for the time horizon 2036 in the InVEST software. The amount of carbon available in four carbon storage sources including aboveground biomass, belowground biomass, soil, and dead organic matter was extracted based on land use, through combining IPCC reports with field studies and sampling. The study of the land use change trend showed that over time, the extent of forest and rangeland has gradually decreased, so that in 2036, a 40% decrease in growth will be recorded, which led to a drop in carbon sequestration equivalent to 400,859 tons in the land. Continuing the current trend in land use and land change will lead to a decrease in the ecosystem's function in carbon storage and sequestration. Mohammadi *et al.* (2017) investigated carbon sequestration on land and the economic value of Asalem forests in Northern Iran. In order to estimate the annual carbon sequestration rate, the annual volumetric growth of the stand was determined using diameter growth and tariff data. The carbon sequestration rate was estimated based on wood density and using the allometric equation. The results showed that the annual volumetric growth per ha and stored carbon were 6.023 cubic meters per year and 2.307 tons per ha, respectively. Finally, the carbon sequestration value of the felled trees and the net present value of carbon sequestration were 11023.753 and 790.361 (10000 IRR per ton per ha), respectively. Ghanbari *et al.* (2020) studied carbon stocks in northern Iranian beech forests. The above-ground carbon content of trees and the organic carbon content of soil were determined in three regions in selected forestry projects (in the three northern provinces of Guilan, Mazandaran, and Golestan). The Poncehernanadez method was used to estimate the above-ground carbon content of trees, and the Walky-Block method was used to estimate soil carbon sequestration. The results showed that in general, both the carbon stocks of standing trees and soil carbon sequestration increased at both depths (30 and 60 cm) from east to west; however, the amount of soil carbon stocks declined by increasing depth. The estimates indicated that the carbon storage capacity of the country's beech forests was on average 227475 tons per hectare in the above-ground tree section and 205190 tons per hectare in the underground section (soil). Given the successful international experiences in designing and developing next-generation ecosystem service models such as InVEST, and considering the knowledge gap and the absence of appropriate models in the country, it is essential to utilize and leverage these tools to quantify and map ecosystem services. In addition, understanding the philosophy of valuation and its necessity can influence social decision-making in three ways; Cost-benefit analysis, National income accounting and Raising awareness (Common 2003). This approach can help raise planners' awareness to consider the role of forests in providing ecosystem services when making decisions. It also encourages planning to empower local communities by investing in carbon sequestration capacities and creating alternative livelihoods, reducing their dependence on the meager income derived from converting forests into other land uses. Additionally, local employment can mitigate forest degradation. Given the high economic value of carbon storage by these ecosystems, planners and policymakers can make more comprehensive and accurate decisions while prioritizing among available management options (Pato *et al.* 2017). Consequently, considering the importance of Hyrcanian forests in carbon sequestration at the international level and the importance of using new methods and software in this field; the main objective of the present study was to quantify and map the carbon sequestration service and estimate its economic value using INVEST and GIS in three forest areas of Northern Iran: Watershed 7 of Asalem in Guilan Province, Watershed 51 of Nour-Chamestan in Mazandaran Province, and Watershed 91 of Azadshahr-Minoodasht in Golestan Province.

MATERIALS AND METHODS

Study areas

The study areas encompassed three forestry watersheds in the Hyrcanian (Caspian) forests of Northern Iran:

Watershed 7 of Asalem (Guilan): Located in Hashtpar County, Guilan Province, covering 34,996.89 ha. It is geographically positioned between longitude 28°73'07" to 32°03'86" E and latitude 41°64'436" to 41°81'13886" N; with five rural districts, two divisions, and 20 settlements. The elevation ranges from a maximum of 3,025 meters to a minimum of 32 meters above sea level. Fig. 1 shows the location of the area relative to the Caspian forests and the forest communities within this watershed.

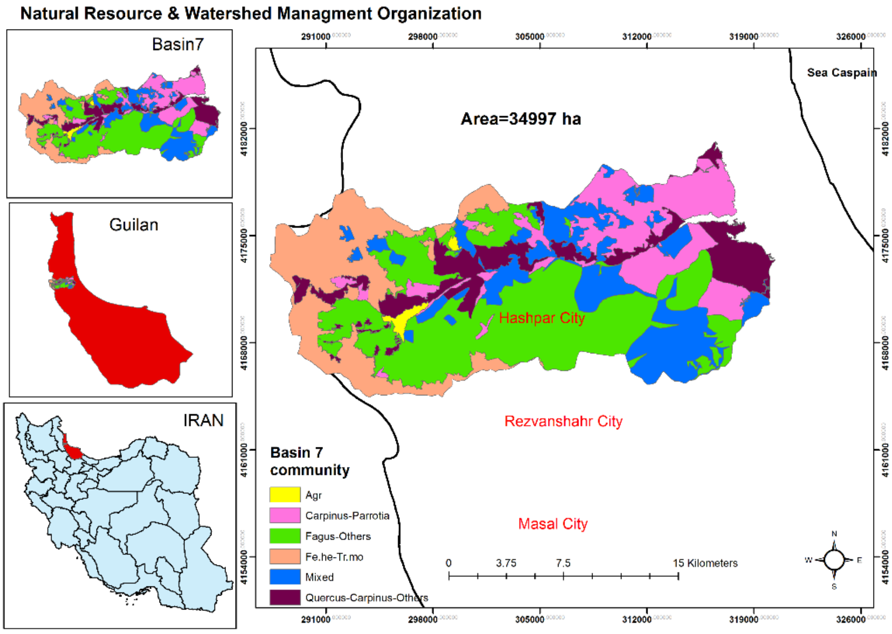

Fig. 1. Location and forest communities in Forestry Basin 7 in Guilan Province, Northern Iran.

Watershed 51 of Nour-Chamestan in Mazandaran Province is geographically located between longitude 52°07'193" to 52°20'57" E and latitude 36°16'259" to 36°29'237" N. The area of this watershed is 27,707 ha. It is bordered to the east by Amol County and to the west by Nour County. The watershed includes three districts: Chamestan, Mianroud, and Imamzadeh Abdullah, along with the villages of Anketa Rud, Naplar, and Sangdarka. The maximum and minimum elevations in the watershed are 2,363 meters and 34 meters above sea level respectively. Fig. 2 illustrated the location of the area relative to the Caspian forests and the forest communities within this watershed.

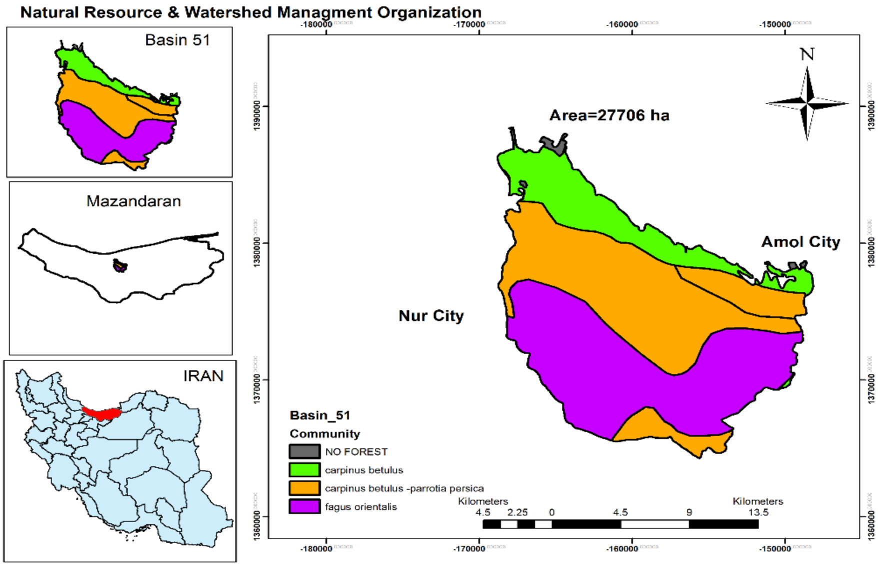

Fig. 2. Location and Forest Communities in Forestry Basin 51 in Mazandaran Province, Northern Iran.

Watershed 91, with an area of 25253.1 ha, is located in Golestan Province, within the counties of Azadshahr and Minoodasht. The study area of Watershed 91 comprises 19 settlements, of which 14 are situated in Chehel-Chay Rural District in the central district of Minoodasht County, and five are located in Kharmaroud-e-Jonoubi Rural District in Cheshmeh-Saran District of Azadshahr County. Geographically, it is positioned between longitude 55°15'13.24" to 55°27'24" E and latitude 36°59'027" to 37°12'51.24" N. The maximum and minimum elevations in this watershed are 1,976 and 102 meters above sea level respectively. Fig. 5 depicts the location of the area relative to the Caspian forests, while Fig. 6 shows the forest communities within this watershed.

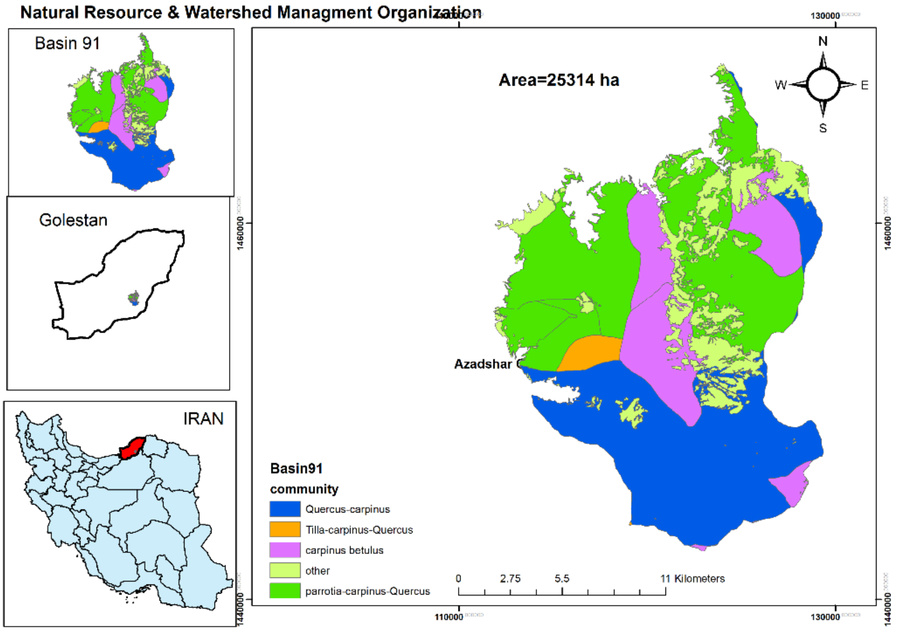

Fig. 3. Location and Forest Communities in Forestry Basin 91 in Golestan Province, Northern Iran.

Research methodology

The carbon storage and sequestration model comprise two key tools: biophysical assessment and economic valuation (Tallis *et al.* 2013; Sharp 2014). The model integrates land cover/land use data (forest communities) with data on the carbon stock inventory in the four main carbon storage pools in forests, including above-ground biomass (tree aerial parts); below-ground biomass (roots); dead organic matter (dead leaves and litter); and soil organic carbon. These inputs are provided by the user to calculate and generate spatial distribution maps of carbon stock and sequestration quantities across the landscape. The most accurate method to determine the data related to carbon stock inventory in the four main carbon pools involves direct field measurements. In this study, data and figures from forestry plans and periodic evaluation reports by the Natural Resources and Watershed Management Organization, available in the Technical Forestry Office in 2023, were employed using INVEST 3.9.

Table 1. Relative growth and wood density of species found in the study areas.

Maple | Sycamore | Oak | Ironwood | Alder | Hornbeam | |

Species Type	Beech	Hornbeam	Alder	Persian Ironwood	Oak	Maple	Tilia
Relative growth (m^3)	2.46	1.36	2.648	0.509	2.267	2.204	2.35
Volume mass of each species (kg/m^3)	575	706	464	850	674	550	520

Source: Forestry and Utilization Office, Iranian Natural Resources and Watershed Management Organization, 2021.

To determine the above-ground biomass (AB), the simplified FAO method (Brown, 1997) was employed. The average standing volume of each forest community within the forestry domain under study was multiplied by the average wood density of the tree species in the forest types or communities and the biomass expansion factor (BEF).

AB=VOB×WD×BEFAB = VOB \times WD \times BEF **(1)**

where ABAB is above-ground biomass (tons per ha); VOB refers to average standing volume of forest cover (tons per ha); WD refers to wood density of the species or the average wood density of species in the forest types or communities; and BEF is biomass expansion factor (ratio of above-ground dry biomass to the dry biomass of standing volume for each forest community). In this study, the standing volume and biomass of forest communities in the forestry domains under investigation were extracted and utilized based on the data available in existing forestry plans, as detailed in Tables 2, 3, and 4.

Table 2. Above- and below-ground biomass of each forest community in watershed 7, Guilan Province.

Row	Forest Community	Average Stock (m^3 ha^{-1})	Density of Species/Types (g cm^{-3})	Biomass Expansion Factor	Aboveground Biomass (tons ha^{-1})	Belowground Biomass (tons ha^{-1})	Deadwood and Litter Biomass ((tons ha^{-1})	Soil Organic Carbon (tons ha^{-1})
1	Hornbeam-Ironwood	209.01	0.778	1.74	283	68	28	82
2	Beech Forest	256.82	0.575	1.74	257	30	26	67
3	Mixed Forest	275.96	0.636	1.74	305	36	31	80
4	Oak-Hornbeam Forest	186.97	0.690	2.66	343	40	34	90

Table 3. Above- and below-ground biomass of each forest community in watershed 51 Mazandaran Province.

Row	Forest Community	Average Stock (m^3 ha^{-1})	Density of Species/Types (g cm^{-3})	Biomass Expansion Factor	Aboveground Biomass (tons ha^{-1})	Belowground Biomass (tons ha^{-1})	Deadwood and Litter Biomass (tons ha^{-1})	Soil Organic Carbon (tons ha^{-1})
1	Hornbeam-Ironwood	177.32	0.706	2.66	333	80	33	96
2	Beech Forest	211.79	0.778	1.74	287	69	29	83
3	Mixed Forest	245.2	0.575	1.74	245	59	25	71

Table 4. Above- and below-ground biomass of each forest community in watershed 91 Golestan Province.

Row	Forest Community	Average Stock (m^3 ha^{-1})	Density of Species/Types (g cm^{-3})	Biomass Expansion Factor	Aboveground Biomass (tons ha^{-1})	Belowground Biomass (tons ha^{-1})	Deadwood and Litter Biomass (tons ha^{-1})	Soil Organic Carbon (tons ha^{-1})
1	Hornbeam Forest	233.14	0.706	1.74	286	69	29	**83**
2	Ironwood-Hornbeam-Oak Forest	213.66	0.778	1.74	289	34	29	**76**
3	Oak-Hornbeam Forest	261.88	0.690	1.74	314	37	31	**83**
4	Lime-Hornbeam-Oak Forest	297.17	0.637	1.74	329	39	33	**86**

The biomass expansion factor (BEF) was determined based on the guidelines of the Intergovernmental Panel on Climate Change (IPCC). For areas with standing forest volume greater than or equal to 190 tons ha^{-1}, a BEF value of 1.74 was used, while for areas with less than 190 tons ha^{-1}, a value of 2.66 was applied (Eggleston *et al.* 2006). Accordingly, the above-ground biomass (AB) of each forest community in the studied forestry domain was calculated as follows:

Eq (1): Aboveground biomass in each forest community = Average stock per ha × Wood density of species or types × Biomass expansion factor

The biomass for each forest community was calculated separately and presented in Tables 2, 3, and 4.
To convert above-ground biomass into elemental carbon (tons of carbon), studies consider 50% of the dry biomass as carbon content (Losi *et al.* 2003; Juwarkar *et al.* 2011; Pearson *et al.* 2013). In this study, a coefficient of 0.49 was applied, which is specific to humid sub-tropical forests (Mokany *et al.* 2006). The carbon contents (tons ha^{-1}) for each forest community are reported in Tables 2, 3, and 4. The below-ground biomass was calculated using the root-to-shoot ratio method (Mokany *et al.* 2006). For forest communities with above-ground biomass greater than 125 tons ha^{-1}, below-ground biomass was estimated at 24% of the above-ground biomass. For forest communities with above-ground biomass less than 125 tons ha^{-1}, below-ground biomass was estimated at 20% of the above-ground biomass.

Eq (2): Below-ground biomass in each forest community = 0.2 × Above-ground biomass

To convert below-ground biomass into elemental carbon, a coefficient of 0.49 was applied. The resulting carbon storages (tons ha^{-1}) are reported in Tables 1, 3, and 5. Additionally, the biomass of deadwood and litter was assumed to be 10% of the above-ground biomass (Delaney et al. 1998). Based on this assumption, the carbon stored in this reservoir for each forest community (tons per ha) was calculated (Tables 2, 3, and 4).

Biomass of deadwood and litter = 0.1 × Above-ground biomass

The calculation of biomass excluded areas covered by herbaceous and non-woody vegetation. This is because the biomass in non-woody vegetation is relatively transient, decomposing and regenerating annually or over a few years (Eggleston *et al.* 2006). As a result, the emissions from decomposition are balanced by carbon uptake during regrowth, creating a long-term stable net carbon stock. The soil organic carbon stock was assumed to be 44% of the total dry biomass weight (above-ground, below-ground, deadwood, and litter) based on McKinley *et al.* (2011). Globally, most forest carbon is found in living biomass (44%) and soil organic matter (45%), with the remainder in litter (6%) and deadwood (4%; FAO 2020). Accordingly, the soil carbon storage for the studied forests was set at 76 tons ha^{-1}, based on previous research in the region (Mesri 2015; Solemani *et al.* 2017; Vahedi 2017). In a separate study in the Darabkola watershed of Mazandaran Province, Northern Iran, this value was calculated as 71 tons ha^{-1} for forested areas. The soil organic carbon stocks for each forest community in the studied forestry domains are reported in Tables 2, 3, and 4.

The economic value of carbon storage and sequestration

The required economic data for the economic valuation include three values that are directly input into the model. The model uses these values and Equation (2) to calculate the value of carbon sequestration over time.

Eq (2)

$$\mathrm{value}_{\mathrm{seq}_x} = V\frac{\mathrm{sequest}_x}{\mathrm{yr}_{\mathrm{fut}} - \mathrm{yr}_{\mathrm{cur}}}\sum_{t=0}^{\mathrm{yr}_{\mathrm{fut}}-\mathrm{yr}_{\mathrm{cur}}-1}\frac{1}{\left(1+\frac{r}{100}\right)^t - \left(1+\frac{c}{100}\right)^t}$$

where V is the monetary value of each ton of sequestered carbon in dollars or any other commonly used currency; r is the discount rate in percentage, which reflects society's preferences for immediate benefits compared to future benefits; and c is the annual rate of change in carbon prices, which adjusts the value of sequestered carbon to account for its emission impact on expected climate change-related damages over time (Tallis *et al.* 2013). In the model, the default value for the discount rate is set at zero. A value greater than zero indicates that the social value of sequestered carbon in the future is lower than its value at present. The monetary value can be estimated using the replacement cost method, based on the social cost of emitting one ton of carbon into the atmosphere, as determined by the user. Alternatively, it can be derived from results of previous environmental economics studies. Market prices, corresponding to the exchange value of carbon credits in common exchanges such as the Chicago and European Climate Exchanges, can also be considered. The discount rate in this model was set to 7%, as recommended by the U.S. government for cost-benefit analysis of environmental projects. This rate can be adjusted based on the country and scope of the study (Badam Firouz *et al.* 2020). If set to zero, no discounting is applied to the monetary value. For the economic valuation of carbon within the study area, data from international and national studies were utilized. Recent international estimates have shown that the social cost of carbon, as the marginal damage cost associated with emitting an additional ton of carbon into the atmosphere, ranged from $32 to $326 per ton in 2010 (Bostan *et al.* 2018). Tol (2009) conducted a comprehensive review and estimated median values between $66 and $130 per ton. The variation in these values stems from differences in the costs and social benefits resulting from carbon emissions or sequestration in different communities and regions, as well as differences in their time discounting. The cost of carbon sequestration in forests varies significantly depending on the location and the project. This high variability results from several factors. First, there are multiple ways to sequester carbon through forestry (FAO 2004). Therefore, costs vary according to how carbon sequestration is implemented. Second, the carbon sequestration of a project is assessed in addition to the amount of carbon that would be sequestered in the absence of the project. Thus, for definitive calculations, additionality and baseline assumptions are necessary (De Jong *et al.* 2000). Third, costs differ depending on the project duration (Stavins 1999). Fourth, there are data limitations regarding the cost and amount of carbon sequestration by a project. Fifth, forest-based carbon sequestration costs vary significantly depending on the methods used and the assumptions made in modeling, and whether co-benefits are included (Nielsen *et al.* 2014). Different assumptions, particularly those regarding carbon absorption by trees, forest age, tree species, geographic location, site characteristics, and the status of forest products, among other factors, also have a significant impact on estimated carbon (van Kooten & Sohngen 2007). Van Kooten & Sohngen (2007) reviewed 68 studies across 30 countries and found that the average cost of forest-based carbon sequestration was approximately $88 per ton of carbon ($24 per ton of CO_2; in 2005 values). Still, individual estimates ranged from $0.46 to about $1,800 per ton of carbon ($0.1 to $490 per ton of CO_2). The differences in types of forest carbon sequestration projects, reference levels used for measurement, additionality, the scale of analyzed projects, cost estimation methods, and project results, among other factors, can explain such wide variability in the global average cost of forest-based carbon sequestration. Estimates by Richards & Stokes (2004) indicated that the costs of forest carbon sequestration are lower in tropical regions compared to temperate ones. According to Manley (2002), assuming all other factors are equal, forestry carbon projects in tropical regions can cost half as much as those in temperate regions. Raihan *et al.* (2019) highlighted the higher tree growth rates and carbon sequestration in tropical regions. Stavins & Richards (2005) estimated a cost range from $25 to $90 per ton of carbon ($7 to $25 per ton of CO_2) in the United States, while Tang *et al.* (2014) estimated that the cost in China is less than $10 per ton of carbon ($3 per ton of CO_2). Valatin (2019) reported long-term cost estimates (up to 2200) in the UK ranging from £21 to £245 per ton of CO_2 ($30 to $346 per ton of CO_2), depending on the type of forest established (e.g., coniferous trees versus broadleaf forests managed for timber and carbon). The most recent report by the International Monetary Fund suggests that if Iran imposes a $35 tax per ton of CO_2 emissions, the country could reduce air pollution and add 5% to its gross domestic product.

RESULTS AND DISCUSSION

The output from InVEST is presented in the tables and figures below.

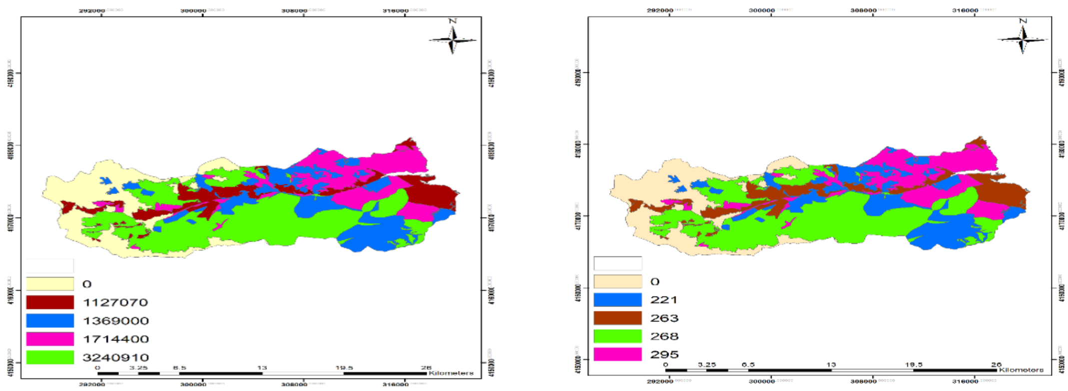

Fig. 4. Average and total carbon sequestration in the forest communities of watershed 7, Asalem, Guilan Province.

According to literature review results, an alternative method for measuring the cost of carbon emissions per ton (or the benefits and economic value of preventing emissions through natural ecosystems) is to calculate the equivalent cost for sequestering each ton of carbon (Metcalf & Stock 2017; Tol 2017). In this method, the cost of capturing and storing carbon in public facilities such as power plants is taken into account. Based on various studies, the cost is approximately $110 per ton of carbon. Since the cost of carbon sequestration is three times the cost of CO_2 absorption, the $110 figure can serve as the basis for calculating the sequestration cost. Therefore, considering the exchange rate of the US dollar versus Iranian Rial (420000 IRR at the official exchange rate), the sequestration cost per ton of carbon was estimated at 46200000 IRR. The average value of each ha of the studied forests was 12068 million IRR. The total value of the studied forests (77683 ha) was calculated equal to 937451914 million IRR. After modeling carbon storage and sequestration using the InVEST model for the studied watershed areas, the following results were obtained.

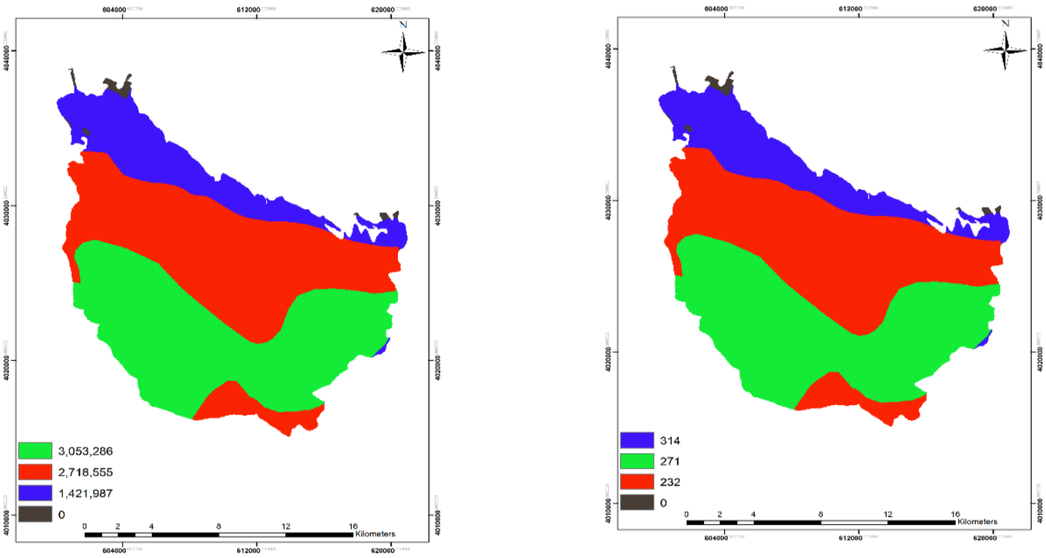

Fig. 5. Average and total carbon sequestration in the forest communities of watershed 51, Nour, Chamestan, Mazandaran Province.

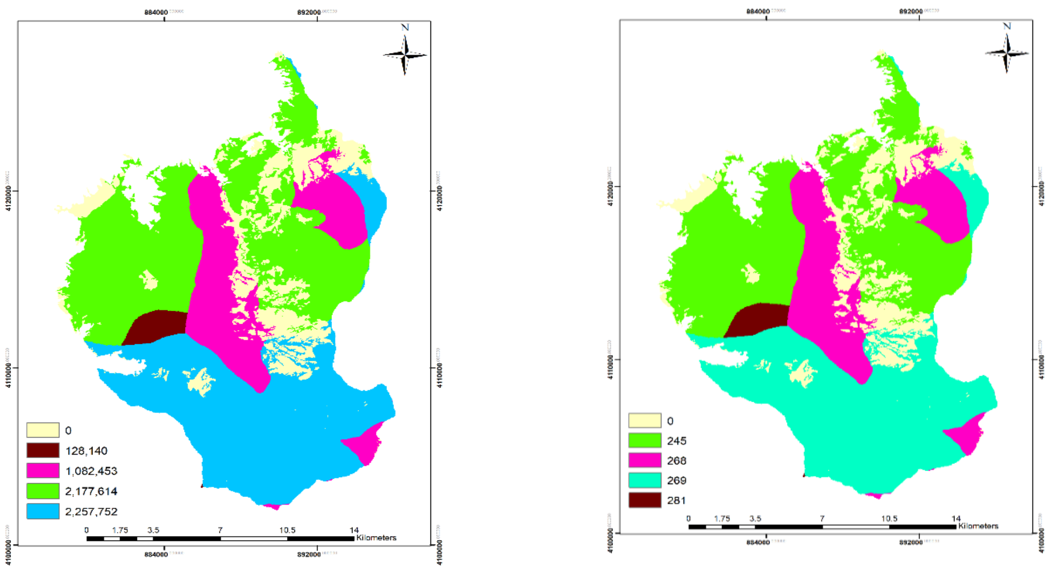

Fig. 6. Average and total carbon sequestration in the forest communities of watershed 91, Azadshahr-Minoodasht, Golestan Province.

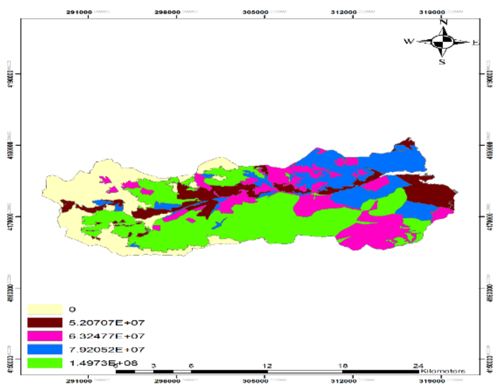

Fig. 7. Spatial map of carbon sequestration value in the forest communities of watershed 7, Guilan.

Table 5. Amount of carbon sequestration in tons per community and overall, in the forest ecosystem of the studied Forestry Basin (million Rials).

Row	Forest Community	Area (ha)	Total Carbon Sequestration (t/ha)	Average Carbon Sequestration per Community (t/ha)	Carbon Sequestration Value (million Rials)
1	Carpinus betulus51	4528	1421987	314	65695785
2	Carpinus -Parrotia 7	5812	1714398	295	79205207
3	Tilia-Carpinus-Quercus91	456	128140	281	5920048
4	Fagus orientalis51	11267	3053286	271	149730197
5	Quercus-Carpinus91	8405	2257752	269	104308151
6	Carpinus betulus91	4044	1082453	268	50009308
7	Fagus orientalis7	12093	3240913	268	141061835
8	Quercus-Carpinus7	4290	1127071	263	52070670
9	Parrotia- Carpinus-Quercus91	8878	2177614	249	100605774
10	Carpinus-Parrotia -Gleditschya51	11718	2718555	232	125597241
11	Mixed7	6194	1368998	221	63247698
12	Overall	77683	20291167	262	937451914

Source: study findings.

Table 6. Amount of carbon sequestration in tons per community and overall, in the forest ecosystem of the studied Forestry Basin (US$).

Row	Forest Community	Area (ha)	Total Carbon Sequestration (t/ha)	Carbon sequestration value (US$)	Average value of each community (US$)
1	Carpinus betulus51	4528	1421987	156418536	34545
2	Carpinus -Parrotia 7	5812	1714398	188583827	32449
3	Tilia-Carpinus-Quercus91	456	1288140	14095353	30911
4	Fagus orientalis51	11267	3053286	335861511	29809
5	Quercus-Carpinus91	8405	2257752	248352740	29548
6	Carpinus betulus91	4044	1082453	119069781	29444
7	Fagus orientalis7	12093	3240913	356500470	29483
8	Quercus-Carpinus7	4290	1127071	123977785	28902
9	Parrotia- Carpinus-Quercus91	8878	2177614	239537557	26981
10	Carpinus-Parrotia -Gleditschya51	11718	2718555	299041051	25520
11	Mixed7	6194	1368998	150589756	24314
12	Total	77683	20291167	2232028367	29264

Source: study findings.

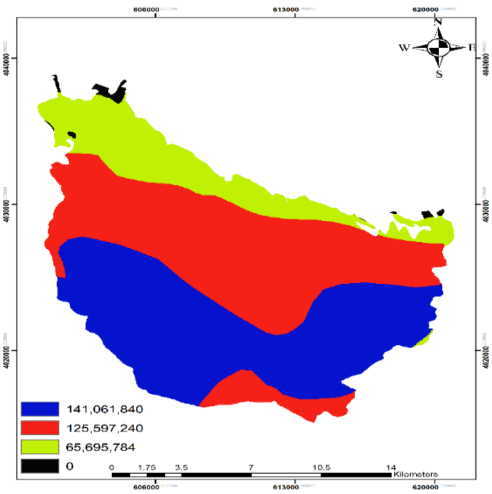

Fig. 8. Spatial map of carbon sequestration value in the forest communities of watershed 51 Mazandaran.

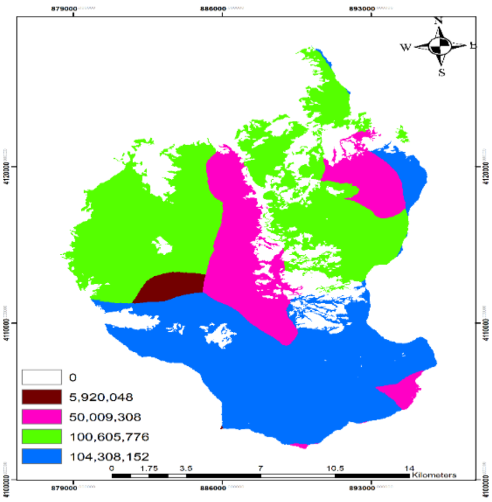

Fig. 9. Spatial map of carbon sequestration value in the forest communities of watershed 91, Golestan.

CONCLUSION

The carbon sequestration potential and economic value of different forest communities within the Hyrcanian forests of Northern Iran were assessed, focusing on three distinct regions with varying ecological conditions, including differences in forest age, elevation, slope, soil type, species composition, and climate. The results revealed significant variation in carbon sequestration across these forest communities, underlining the crucial role of site-specific biophysical characteristics in influencing carbon storage. The estimated carbon sequestration ranged from 221 tons ha^{-1} in the mixed forests of Asalem (Guilan Province) to 314 tons ha^{-1} in the Memarestan forest community in the Noor-Chamestan region of Mazandaran Province, with an overall average of 261 tons ha^{-1} across all sites. Economically, the highest carbon sequestration value was recorded in the Beech Forest community of Asalem, at 149730197 million IRR, while the lowest was observed in the Nemdar-Memarz-Oak Forest community of the Golestan region. The average value per ha was calculated at 12067 million IRR, resulting in a total valuation of approximately 937451914 million IRR for the 77681ha area under study. Extrapolating this value to the full extent of the Hyrcanian forests (2.3 million ha) yields an estimated carbon sequestration value of 27755614523 million IRR, equivalent to approximately 67.3 million USD. These findings are consistent with previous studies conducted in various northern forest regions of Iran. For instance, Mahmoudi Taleghani et al. (2004) reported 283–312 tons ha^{-1} in the Golband watershed, Ghanbari *et al.* (2020) estimated 290–460 tons ha^{-1} in regions such as Asalem, Sardabroud, and Kordkoui, and Dajleri1 *et al.* (2023) recorded 282 tons ha^{-1} in the Lirasar Forest- Tonekabon. Such consistency strengthens the reliability of this study's estimates and reinforces the ecological significance of these forest ecosystems. The results also highlighted the influence of vegetation type, growth period, elevation, and species characteristics on carbon sequestration. Fast-growing species may accumulate carbon more rapidly due to accelerated biomass production; however, often have lower wood density and shorter lifespans, which may limit long-term storage potential. Consequently, understanding forest structure and species dynamics is vital for optimizing carbon sequestration strategies. The carbon sequestration maps generated in this study provide valuable tools for forest management. They can support a range of applications, from fire risk assessment and pest control planning to biodiversity monitoring and evaluating forest sustainability. In the context of climate change, such spatial data are critical for periodic assessments of carbon dynamics and ecosystem resilience. Moreover, carbon sequestration can serve as a key indicator for evaluating the sustainability and health of forest ecosystems. Most importantly, the study underscored the broader ecological role of forests in regulating and supporting other ecosystem services. Higher carbon stocks are often associated with increased biodiversity and biomass, contributing to improved ecosystem functions such as water regulation, climate moderation, and habitat provision. Therefore, recognizing the economic value of carbon sequestration helps emphasize the need to conserve and sustainably manage forest resources. Based on the results of this study, suggestions for preserving Hyrcanian forests are presented below.

1. National and regional policymakers should integrate carbon sequestration values into environmental planning, carbon offset mechanisms, and payment for ecosystem services (PES) programs to incentivize forest conservation and climate action.
2. Forest management plans should be tailored to the ecological characteristics and sequestration capacity of each forest type, prioritizing high-biomass ecosystems such as beech forests for conservation. Implementation of continuous monitoring systems using remote sensing and ground surveys to track changes in biomass and carbon stocks, particularly under climate-induced shifts in vegetation patterns.
3. Promoting the ecological and economic values of forest carbon sequestration through education and outreach to involve local communities and stakeholders in sustainable forest practices.
4. Encouraging interdisciplinary research on belowground carbon pools, long-term sequestration stability, and the socio-economic co-benefits of carbon-rich forests to refine ecosystem service valuation frameworks.

In conclusion, the Hyrcanian forests are not only biodiversity hotspots but also vital carbon sinks that offer significant ecological and economic benefits. Protecting and sustainably managing these forests is critical not only for regional climate adaptation and mitigation but also for preserving ecosystem integrity and enhancing human well-being. Quantifying and valuing ecosystem services such as carbon sequestration provides a strong foundation for evidence-based decision-making and sustainable natural resource governance.

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