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Carbon Storage in Biomass and Soil after Mountain Landscape Restoration: *Pinus nigra* and *Picea abies* Plantations in the Hyrcanian Region

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Abstract: Forest plantations have significantly more potential for carbon storage than non-forested areas. In this study, the amount of carbon stored in the biomass (trees, shrubs, herb, litter, and deadwood) and soil of 25-year-old plantations with *P. nigra* and *P. abies* species was measured and compared with the non-planted adjacent area (control) in a mountainous region of northern Iran. The results show that the amount of carbon stored in the biomass of *P. nigra* and *P. abies* plantations was 4.4 and 3.3 times higher than the value of the control (4.59 C Mg ha^{-1}), respectively. In addition, the amount of carbon stored in soil was 1.5 and 1.2 times higher than the value at the control site (47.91 C Mg ha^{-1}), respectively. Of the total carbon stored in the biomass of plantations, the highest level was observed in trees (86.5–88.5%), followed by shrubs (4.6–6.5%), litter (2.7–2.8%), the herbaceous layer (1.8–2.5%), and deadwood (1.7–2.4%), while 45.5%, 34.6%, 10.8%, 5.8%, and 3.3% of the total carbon stored in the biomass of the control site were in shrubs, trees, the herbaceous layer, litter, and deadwood, respectively. The soil carbon sequestration rate (SCSR) in soil depths of 0–10 and 10–20 cm was 0.46 and 0.44 C Mg ha^{-1} yr^{-1} in the *P. nigra* plantation and 0.15 and 0.23 C Mg ha^{-1} yr^{-1} in the *P. abies* plantation, respectively. According to the results, we conclude that the restoration of the landscape by tree plantation has a substantially determining impact on the acceleration of carbon sequestration.

Keywords: coniferous plantation; biomass; carbon storage; carbon sequestration

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1. Introduction

One of the major challenges on a global level that is environment-related is climate change [1]. It is highly likely that increased concentrations of greenhouse gases (GHGs) in the atmosphere are contributing to an increase in global warming. Global warming is directly affecting ecosystems and their biodiversity in different parts of the world [2,3]. In particular, CO_2 concentrations have become a problem related to global warming due to the fact that CO_2 is a critical GHGs component [1]. Forests are seen as a mitigative strategy to reduce global warming. Plantation forests play a crucial role in forest management due to their high productivity and large contribution to carbon sequestration. Increasing global carbon sequestration through enlargement of the proportion of planting forests on non-forested lands on the planet has been suggested to be an effective measure to lessen elevated concentrations of atmospheric carbon dioxide [4–7].

Plant biomass forms an important carbon stock in many ecosystems. Shrubs and trees can accumulate more than hundreds of tons ha^{-1} of carbon over their lifespan [2]. Among terrestrial ecosystems, forests have the highest level of potential to combat climate change due to the extensive amount of wood and fertile soil [4,5]. Almost one third of the Earth's surface is covered by forests. These complex ecosystems have up to 80% of the total above-ground terrestrial C and 40% of the below-ground C [6]. Forests have the potential to store 20 to 50 times more carbon than barren lands [7], acting as a sink of carbon.

Large-size trees are important components of forest ecosystems, which are fundamental in the C cycle, storing large amounts of carbon in their tissues thanks to photosynthesis [8–12]. Forests are also important in regulating atmospheric CO_2 levels [11]. Artificial forest plantations have two main purposes: timber production and ecological restoration. They account for 7% of the global forest area and positively affect the global C cycle [13]. These particular forests play an important role in C sequestration thanks to their high rate of growth [14].

Forests positively affect soil physicochemical properties and soil communities (animal and microbial communities) [15–17]. Soil contains the world's largest terrestrial active C pool; for this reason, it is considered fundamental in the global C cycle [18]. The assessed amount of organic C stored in soils is about 1100–1600 petagrams (Pg), more than twice the C in living vegetation (560 Pg) or in the atmosphere (750 Pg) [19]. Jackson et al. [20] examined the impact on carbon sequestration of a plantation in a region of the United States with an annual rainfall of about 230 to 660 mm and found that the total ecosystem carbon storage increased from 2.9 to 10.1 Mg C ha^{-1}. In addition, a study by Zou and Bashkin [21] showed that afforestation with eucalyptus trees in degraded lands resulted in carbon sequestration of about 3 tons ha^{-1} $year^{-1}$ in a 25 cm layer of soil.

The forests in Iran cover about 12.4 million ha, 7.3% of the national surface, and the forest plantations represent approximately 944,000 ha, with a share of broadleaves and conifers at 61% and 39%, respectively [22]. Given that Iran is located in arid and semi-arid zones and has poor forest cover (less than 10%), plantations play a crucial role in mitigating wood demand pressure on natural forests. The purposes of plantations are wood production, the protection of biological diversity, and soil and water conservation in watershed basins. The fixation of sand dunes by vegetation is another important reason for tree plantation in arid and semi-arid regions of the country in order to combat desertification.

Black pine (*Pinus nigra*) and Norway spruce (*Picea abies*) are non-native coniferous species planted at different sites and under different climate conditions in Iran. These plantations were established to increase soil and water, biodiversity, and landscape protection. Forestation and reforestation remain the most effective strategies to combat climate change [2,23] and are also the most commonly applied [24,25]. The specific objectives of our study were to determine the (1) plant biomass by category (tree, shrub, grass, deadwood, and litter) and (2) vegetation and soil C storage in plantations with two species of conifers (*P. nigra* and *P. abies*) and at natural sites in a mountainous region in northern Iran. Therefore, the aim of this research was to estimate the differences in afforestation with conifers and the degraded natural sites to evaluate the performance of management (plantation) and the alternative of abandonment.

2. Materials and Methods

2.1. Study Area

This research was conducted on the northern slopes of the Alborz mountain range in the Ardebil province, northern Iran (latitude 38°26′51″ N to 38°27′11″ N, longitude 47°36′10″ E to 47°36′57″ E). The average annual rainfall is 350 mm. The average temperature of the hottest and coldest months is 15.5 and 3.6 °C, respectively. The average annual humidity value is 51.4% to 67.3% in summer and 83.1% in winter. The climate is cold mid-arid (aridity index, I = 16.1) according to the De Martonne climate classification [26]. Most days of the year have a lot of wind, and most of the precipitation is in the form of snow. The number of frost days is relatively high (130 frost days per year). The soil of the

area is relatively shallow with a loamy texture and the bedrock is typically limestone. The main type of vegetation in the area is grassland (pasture) with scattered shrubs and short trees. Caucasian oak (*Quercus macranthera* Meyer) and Oriental hornbeam (*Carpinus orientalis* Miller) are the main tree species in this area. The main woody species of shrubs and short trees include [27]: *Corylus avellana* L. (*Corylaceae*), *Rosa canina* L. (*Rosaceae*), *Mespilus germanica* L. (*Fagaceae*), *Pyrus syriacus* Boiss. (*Rosaceae*), *Prunus spinosa* L. (*Rosaceae*), *Rubus hirtus* Waldst and Kit. (*Rosaceae*), *Prunus divaricate* Ledeb. (*Rosaceae*), *Malus orientalis* Ugl. (*Rosaceae*), *Sorbus orientalis* Schon. (*Rosaceae*), *Viburnum lantana* L. *(Caperifoliaceae*), *Sorbus torminalis* (L.) Crantz. (*Rosaceae*), *Crataegus melanocarpa* M.B. (*Rosaceae*), *Cratageus mdyeri* A. Pojark (*Rosaceae*), *Ilex spinigera* Leos. (*Aquifoliaceae*), *Salix eegyptiaca* L. (*Salicaceae*), and *Lonicera coucasica* Pall. (*Caprifoliaceae*).

Plantations with the black pine (*Pinus nigra* J.F. Arnold) and Norway spruce (*Picea abies* (L.) H. Karst.) tree species, each in an area of 20 hectares, were planted in 1997 at altitudes of 1500 to 1700 m in this area. These plantation areas were protected by barbed wire fences against animal grazing and human disturbance. During this period, neither timber nor firewood was extracted from the plantations [27]. Detailed characteristics of the study site are shown in Table 1.

Table 1. Description of geographical characteristics of the study sites.

Site Properties	Site I	Site II	Site III
Altitude (m above sea level)	1800	1750	1700
Land use	Plantation	Plantation	Control
Vegetation type	Forest	Forest	Grassland
Tree species	*Pinus nigra*	*Picea abies*	Scattered *Quercus macranthera* and *Carpinus orientalis*
Soil type	Clay loam	Clay loam	Clay loam
Area (ha)	20	20	20
Slope (%)	22–25	20–24	23–27

2.2. Study Design

Three sites, including the *Pinus nigra* and *Picea abies* plantations, were selected, and adjacent natural habitats were used as a control (Table 1). In order to collect plant biomass data, a systematic plot sampling method with a random starting point was used. The dimensions of the network were 100 m by 200 m and the area of each plot was 400 m^2 (20 m by 20 m). There were 10 plots at each site. Each plot was divided into 4 10 m × 10 m quadrats, and each quadrat was further divided into 25 sub quadrats (2 m × 2 m).

2.3. Tree Biomass

The biomass of the whole tree was calculated by summing the biomass of the trunk, branch, leaf, and root.

2.3.1. Above-Ground Biomass (AGB)

AGB is mainly estimated in forest stands by the allometric method with high accuracy. The method proposed by the FAO, which is a faster and easier-to-use method than the allometric method, is also used to estimate AGB in plantations. In order to increase the accuracy when estimating the AGB value and to evaluate the accuracy of the FAO method, AGB in this study was estimated using both methods, as described in the following paragraphs.

Allometric Method

The diameter at breast height (*DBH*) and height (*h*) of trees were measured by a dendrometric caliper and clinometer, respectively, in each plot. Two trees were selected randomly in each plot (20 trees at each site) to estimate the biomass of the tree leaf, branch, trunk, and root. The number of branches (B_n) of each tree was counted and one branch was randomly taken from the mid-point of the stem as a sample of the tree crown. Then, all the leaves of the sample branch were collected and weighed. Sample branches were cut into

30-cm pieces and weighed. The fresh mass of the tree leaf was estimated by multiplying the fresh mass of the leaves of the sample branch by the number of branches. Additionally, the fresh mass of the tree branches was estimated by multiplying the fresh mass of the sample branch by the number of branches. For the estimation of the fresh mass of the tree trunk, the first tree trunk volume (TV, m^3) was calculated from Equation (1).

$$TV = \left(\frac{\pi}{4}\right)\left(DBH^2\right) \times h \times f \quad (1)$$

where DBH is the diameter at breast height in m, h is the tree height in m, and f is a constant stem form factor. The calculated values for f were 0.3925 for *P. nigra*, 0.4163 for *P. abies*, 0.3640 for *Q. macranthera*, and 0.3520 for *C. orientalis* [28].

Approximately 500 g of fresh samples of tree leaves and branches was randomly collected for moisture determination. In addition, one core sample was collected from each sample tree trunk at 1.30 m from ground level for basic density determination. Cylindrical samples of wood were collected using a drill with cylindrical coring and subsequently processed in the laboratory following the procedures described in Lo Monaco et al. [29]. For splinted or irregular fresh samples, the volume was calculated with the water-displacement method [28]. Wood dry mass was determined by a gravimetric method after drying to constant mass in an oven at a temperature of 103 ± 2 °C [29].

The total biomass of leaves and branches was calculated through multiplying the fresh mass by the dry/wet ratio. The biomass of the trunk was calculated through multiplying the trunk volume by the wood basic density. Allometric equations between the tree component biomass and the independent variable (squared *DBH* multiplied by the tree height (D^2H)) were developed using curve fitting. The optimum equations were selected to calculate the tree component biomass at the plantation sites.

FAO Method

For the estimation of the AGB of trees, the model developed by the FAO Forest Resources Assessment was used, applying Equation (2).

$$\text{AGB} = \text{VOB} \times \text{WD} \times \text{BEF} \quad (2)$$

where AGB is the above-ground biomass in Mg/ha, VOB is the volume over bark (m^3/ha), WD is the wood density (kg m^{-3}), and BEF is the biomass expansion factor (the ratio of above-ground oven-dry biomass of trees to oven-dry biomass of the inventoried volume).

2.3.2. Below-Ground Biomass (BGB)

Due to the fact that measuring the root biomass of trees is destructive, time consuming, and costly, as well as the fact that the roots have a highly variable distribution in the soil, many studies use a conservative and cautious fitting method of trunk-to-root ratio [30] to estimate the root biomass. The BGB of trees was calculated by multiplying the AGB of trees by a default value (DV) of 0.2.

2.4. Understory Biomass

All understory vegetation (shrub and herb) was harvested from two sub quadrats randomly located in each quadrat. Shrubs were separated into leaves, branches, and roots; herbs were separated into above-ground and below-ground parts [31].

The fresh mass of each component (leaves, branches, and roots) was measured to the nearest 1.0 g by using an electronic balance. About 500 g of fresh samples of shrub and herb components was randomly collected for moisture determination. Samples were dried at 65 °C until they reached a constant mass [31]. The total biomass of leaves and branches was calculated through multiplying the fresh mass by the dry/wet ratio.

2.5. Deadwood Biomas

The volume of deadwood (DW) was estimated in two components: standing (standing dead tree, snag) and downed (log or branch). Every snag with a minimum *DBH* of 5 cm and every piece of downed woody debris with a minimum diameter of 5 cm at the base (wider end) was included for measurement in each plot. The biomass of snags was estimated by allometric equations as described for live trees. Each snag and piece of downed DW encountered was assigned to a decay class based on the observed extent of decomposition. These ratings varied on a scale from 1 to 5, with 1 being sound wood and 5 being highly friable wood with little structural integrity remaining [32]. Within each plot, one piece of downed DW representing each decay class present was sampled by a handsaw. Samples were dried at 103 °C until they reached a constant weight. For estimation of the biomass of downed DW, the volume of each piece was calculated by Huber's equation for regular samples using Equation (3), and by the water displacement method for irregular samples; then, the volume of DW was multiplied by the basic density of downed DW.

$$V = \left(\frac{d_m^2}{4}\right)\pi L \tag{3}$$

where V is the volume (m^3), d_m is the diameter under bark at the middle of the stump or short snag (m), and L is the height of the stump or short snag (m).

2.6. Litter Biomass

All litter was collected from three sub quadrats randomly located in each quadrat. About 500 g of fresh samples of litter was randomly collected for moisture determination. Samples were dried at 65 °C until they reached a constant mass. The total biomass of litter was calculated through multiplying the fresh weight by the dry/wet ratio.

2.7. Carbon Stock in above-Ground Biomass (AGB), below-Ground Biomass (BGB), Litter, Deadwood (DW), and Soil

2.7.1. Carbon Stock in AGB, BGB, Litter, and DW

Considering that the allometric method is probably more accurate than the FAO method in estimating the AGB value, to estimate the carbon stock in AGB, the AGB value calculated by the allometric method was used.

In order to obtain accurate estimates of stand-level C sequestration in living tree biomass, litter, and DW, we multiplied the stand-level estimates of dry mass by the appropriate conversion factors. We estimated the C sequestration in living woody biomass by multiplying stem, branch, and root dry mass by 0.531 [33]. Leaf dry mass was multiplied by 0.47 to estimate the C in leaves [34]. Estimates of DW dry mass were multiplied by 0.50 to estimate the C stored in DW. The C in whole-tree and DW biomass was summed to estimate the total C sequestration (Mg C ha^{-1}) in both living and dead biomass. Litter dry mass was multiplied by 0.37 to estimate the C in litter as recommended by the protocol of the Intergovernmental Panel on Climate Change [2].

2.7.2. Carbon Stock in Soil

Ten soil samples were randomly collected for each plot (20 m × 20 m) at depths of 0–10 cm and 10–20 cm using a soil corer (5 cm in diameter). Then, the 10 soil samples from the same layer in each plot (respectively for each plantation-type plot and control plot) were mixed for a more representative sample for the measurement of soil C stock. In addition, soil cores (5 cm in height, 5 cm in diameter) with two replications of each plot were sampled for bulk density measurement. Soil core samples were oven dried for 24 h at 105 °C. Soil organic carbon (OC) was determined by the Walkley and Black method [35].

Soil C storage was calculated from the OC multiplied by the bulk density and the thickness of the soil layer using Equation (4).

$$\mathrm{SCS} = 100 \times \mathrm{BD} \times \mathrm{OC} \times \mathrm{e} \tag{4}$$

where SCS is the soil carbon stock (Mg ha^{-1}), BD is the soil bulk density (g cm^{-3}), OC is the soil organic carbon (%), and e is the soil depth (m).

The soil C sequestration rate was calculated by subtracting the SC storage of the control site from that of the plantation and then dividing the result by the stand age using Equation (5).

$$SCS_R = (SCS_P - SCS_C)/t \quad (5)$$

where SCS_R is the soil carbon sequestration rate in the plantation (Mg C ha^{-1} yr^{-1}), SCS_P is the soil carbon storage in the plantation (Mg C ha^{-1}), SCS_C is the soil carbon storage in the control area (Mg C ha^{-1}), and t is the plantation age (year).

2.8. Statistical Analysis

Statistical analysis was performed by the software SPSS, ver. 19.0 (SPSS Inc., Chicago, IL, USA). ANOVA analyses were used to determine the statistically significant differences between species for the biomass and C storage; multiple comparisons were carried out by Duncan's test, with differences at the $p < 0.05$ significance level.

3. Results

The tree density and live and deadwood volume in the plantation stands were significantly higher than in the control stand (Table 2). The density and volume of live trees and snags in the *P. nigra* plantation were significantly higher than the values in the *P. abies* plantation.

Table 2. Structural characteristics (mean ± SD) of the study stands.

Parameter	*Pinus nigra* Plantation	*Picea abies* Plantation	Control
Tree density (stem ha^{-1})	307.1 ± 13.9 a	233.5 ± 14.4 b	62.4 ± 5.1 c
Tree DBH (cm)	16.2 ± 2.0 a	14.6 ± 1.9 ab	11.1 ± 1.9 b
Tree height (m)	7.4 ± 0.8 ab	8.3 ± 0.8 a	6.9 ± 0.5 b
Stand basal area (m^2 ha^{-1})	6.40 ± 0.61 a	4.08 ± 0.50 b	0.64 ± 0.02 c
Standing volume (m^3 ha^{-1})	27.05 ± 2.31 a	19.45 ± 2.07 b	2.10 ± 0.29 c
Fallen DW volume (m^3 ha^{-1})	1.47 ± 0.15 a	0.88 ± 0.05 b	0.19 ± 0.04 c
Standing DW (m^3 ha^{-1})	0.71 ± 0.06 a	0.58 ± 0.06 b	0.10 ± 0.02 c
Total DW volume (m^3 ha^{-1})	2.18 ± 0.20 a	1.46 ± 0.21 b	0.29 ± 0.05 c

Significant differences among structural characteristics in different sites are indicated with lowercase letters (a–c) by Duncan's test at $\alpha = 0.05$.

The wood basic densities of natural broadleaved trees were significantly higher than those of coniferous plantation species (Table 3). The wood basic density value decreased with increasing decay stage in all tree species.

Table 3. Wood basic density (mean ± SD, g cm^{-3}) of trees species and decay classes.

Tree Species	DC0-Live	DC1	DC2	DC3	DC4	DC5
P. nigra	0.55 ± 0.04 b	0.40 ± 0.03 b	0.35 ± 0.03 b	0.31 ± 0.03 b	0.26 ± 0.03 b	0.17 ± 0.03 a
P. abies	0.51 ± 0.03 b	0.37 ± 0.03 b	0.33 ± 0.03 b	0.29 ± 0.03 b	0.25 ± 0.03 b	0.17 ± 0.03 a
Q. macranthera	0.76 ± 0.06 a	0.63 ± 0.06 a	0.56 ± 0.05 a	0.45 ± 0.05 a	0.39 ± 0.04 a	0.20 ± 0.04 a
C. orientalis	0.72 ± 0.06 a	0.60 ± 0.05 a	0.53 ± 0.05 a	0.44 ± 0.05 a	0.36 ± 0.04 a	0.19 ± 0.04 a

Significant differences among tree species are indicated with lowercase letters (a,b) by Duncan's test at $\alpha = 0.05$.

All calculated allometric equations had a good coefficient of determination (R^2). In particular, only one R^2 value (i.e., the trunk component of *C. orientalis*) is below 0.7; all the other R^2 values are above 0.7 (Table 4). All R^2 values were significant at $\alpha = 0.01$.

Table 4. Allometric equations for different tree species and components. D is the *DBH* in cm, H is the tree height in m, B is the biomass of the tree component in kg tree^{-1}, and SEE is the standard error of the estimate.

Tree Component	Allometric Equations	R^2	SEE	*F*-Value
P. nigra				
Leaf	$B = 0.417(D^2H)^{0.257}$	0.8021	0.07	64.86 **
Branch	$B = 0.766(D^2H)^{0.501}$	0.8124	0.09	60.62 **
Trunk	$B = 8.469(D^2H)^{0.231}$	0.8188	0.06	76.82 **
Root	$B = 3.257(D^2H)^{0.134}$	0.8958	0.02	146.16 **
Whole tree	$B = 16.265(D^2H)^{0.234}$	0.8762	0.05	113.25 **
P. abies				
Leaf	$B = 0.508(D^2H)^{0.230}$	0.8190	0.04	72.37 **
Branch	$B = 7.808(D^2H)^{0.236}$	0.8523	0.04	92.34 **
Trunk	$B = 5.087(D^2H)^{0.296}$	0.8201	0.04	68.39 **
Root	$B = 0.819(D^2H)^{0.318}$	0.8342	0.05	70.44 **
Whole tree	$B = 12.018(D^2H)^{0.288}$	0.8173	0.04	71.58 **
Q. macranthera				
Leaf	$B = 0.076(D^2H)^{0.483}$	0.8326	0.06	84.57 **
Branch	$B = 4.072(D^2H)^{0.203}$	0.7751	0.03	51.71 **
Trunk	$B = 8.778(D^2H)^{0.156}$	0.7298	0.03	43.21 **
Root	$B = 1.184(D^2H)^{0.187}$	0.7456	0.04	41.02 **
Whole tree	$B = 12.059(D^2H)^{0.201}$	0.8262	0.03	80.84 **
C. orientalis				
Leaf	$B = 0.039(D^2H)^{0.574}$	0.7472	0.05	74.39 **
Branch	$B = 2.946(D^2H)^{0.246}$	0.7356	0.04	52.50 **
Trunk	$B = 10.608(D^2H)^{0.126}$	0.6116	0.03	51.93 **
Root	$B = 0.849(D^2H)^{0.226}$	0.7959	0.03	44.67 **
Whole tree	$B = 12.100(D^2H)^{0.197}$	0.7740	0.03	76.50 **

** indicates significance at $\alpha = 0.01$.

The individual tree biomass of *P. nigra* and *P. abies* was significantly higher than that of *Q. macranthera* and *C. orientalis*, and the individual tree biomass of *Q. macranthera* was significantly higher than that of *C. orientalis*, while the difference in the individual tree biomass means between *P. nigra* and *P. abies* was not significant (Table 5). The leaf, branch, trunk, and root biomass followed the order *P. nigra* followed by *P. abies* followed by *Q. macranthera* followed by *C. orientalis*. The biomass of the tree component followed the order trunk followed by branch followed by root followed by leaf in all tree species. It is worth noting that the amount of branch biomass accounted for about 32% to 39% of the total tree biomass in the whole species. Only about 3.1% to 5.5% of the trees' biomass was leaf biomass.

Table 5. Biomass (mean ± SD, kg tree^{-1}) of tree components. Values in brackets are the percentage of the tree component biomass to the whole tree biomass.

Tree Component	*Pinus nigra*	*Picea abies*	*Quercus macranthera*	*Carpinus orientalis*
Leaf	3.00 ± 0.35 (3.1) a	2.80 ± 0.27 (3.1) a	2.02 ± 0.25 (5.2) b	1.80 ± 0.20 (5.5) b
Branch	37.50 ± 2.38 (38.8) a	36.04 ± 2.10 (39.4) a	12.40 ± 1.45 (32.2) b	11.75 ± 1.22 (35.7) b
Trunk	40.09 ± 2.50 (41.4) a	37.18 ± 2.71 (40.7) a	17.65 ± 2.01 (45.9) b	13.90 ± 2.17 (42.2) c
Root	16.12 ± 0.85 (16.7) a	15.40 ± 0.82 (16.8) a	6.41 ± 0.42 (16.7) b	5.49 ± 0.40 (16.7) b
Whole tree	96.71 ± 9.20 a	91.42 ± 9.07 a	38.48 ± 4.10 b	32.94 ± 3.75 c

Significant differences among tree species are indicated with lowercase letters (a–c) by Duncan's test at $\alpha = 0.05$.

The results indicate that the total biomass in the *P. nigra* plantation was significantly higher than that in the *P. abies* plantation, and the total biomass in the *P. abies* plantation was significantly higher than that in the control area (Table 6). The biomass of trees, litter, and DW in the plantations was significantly higher than in the control, while the biomass of shrub and herb layers in the control was significantly higher than in the plantations.

Table 6. Biomass (mean ± SD, Mg ha^{-1}) of trees, shrubs, herbs, litter, and deadwood (DW) by the allometric method.

Biomass Type	*Pinus nigra* Plantation	*Picea abies* Plantation	Control
Tree component			
Leaf	0.92 ± 0.08 a	0.65 ± 0.07 b	0.13 ± 0.02 c
Branch	14.59 ± 1.05 a	10.98 ± 1.02 b	1.02 ± 0.10 c
Trunk	15.38 ± 1.10 a	11.02 ± 1.60 b	1.60 ± 0.09 c
Root	2.80 ± 0.11 a	2.08 ± 0.16 b	0.26 ± 0.04 c
Shrub component			
Leaf	0.23 ± 0.04 b	0.24 ± 0.07 b	0.41 ± 0.05 a
Branch	1.10 ± 0.07 b	1.15 ± 0.10 b	2.60 ± 0.10 a
Root	0.44 ± 0.05 b	0.47 ± 0.06 b	0.98 ± 0.08 a
Herb component			
Above-ground	0.36 ± 0.05 b	0.37 ± 0.05 b	0.49 ± 0.05 a
Below-ground	0.40 ± 0.05 b	0.44 ± 0.06 b	0.56 ± 0.05 a
Litter	1.48 ± 0.10 a	1.15 ± 0.13 b	0.72 ± 0.06 c
DW	0.96 ± 0.09 a	0.57 ± 0.06 b	0.30 ± 0.04 c
Total Biomass	38.66 ± 2.17 a	29.12 ± 2.36 b	9.07 ± 0.96 c

Significant differences among sites are indicated with lowercase letters (a–c) by Duncan's test at $\alpha = 0.05$.

The AGB value of trees, estimated by the FAO model, was the highest in the *P. nigra* plantation, followed by the *P. abies* plantation, followed by the control area (Table 7).

Table 7. The above-ground biomass (AGB) of trees (mean ± SD) estimated by the FAO model in the study sites.

Parameter	*Pinus nigra* Plantation	*Picea abies* Plantation	Control
(A) AGB by the oven-dry biomass of the tree (kg tree^{-1})	80.59 ± 2.55 a	76.02 ± 2.74 a	29.76 ± 2.20 b
(B) AGB by the oven-dry biomass of the inventoried volume (kg tree^{-1})	40.09 ± 2.50 a	37.18 ± 2.71 a	15.77 ± 2.16 b
Biomass Expansion Factor (BEF)	2.01 ± 0.13 a	2.04 ± 0.15 a	1.89 ± 0.19 a
VOB (m^3 ha^{-1})	27.05 ± 2.31 a	19.45 ± 2.07 b	2.10 ± 0.29 c
WD (g cm^{-3})	0.55 ± 0.04 b	0.51 ± 0.03 b	0.74 ± 0.06 a
AGB (Mg ha^{-1})	29.90 ± 2.54 a	20.23 ± 2.14 b	2.94 ± 0.48 c

(A) AGB of Trunk + Branch + Leaves. (B) AGB of Trunk. Note: Significant differences among the means at different sites are indicated with lowercase letters (a–c) by Duncan's test at $\alpha = 0.05$.

The amount of C storage was the highest in the trunks of trees, followed by branches, roots, and leaves at all studied sites (Figure 1). The amount of C storage in all components of the trees was at the highest level in the *P. nigra* plantation, followed by *P. abies* plantation, followed by the control area. The amount of C storage in the shrub components was at the highest level in the control area, followed by the *P. abies* plantation, followed by the *P. nigra* plantation (Figure 2). The highest amount of C storage was detected in the branches of shrubs, followed by roots and then by leaves.

The amount of C storage observed in the herbal layer was similar to that in the shrub layer. Both the above-ground biomass (AGB) and the below-ground biomass (BGB) were the highest in the control area followed by the *P. abies* plantation and then the *P. nigra* plantation (Figure 3).

The amount of C storage in litter and deadwood was at the highest level in the *P. nigra* plantation followed by the *P. abies* plantation and the control area (Figure 4). The amount of C storage in the litter was higher than that in the deadwood at all sites.

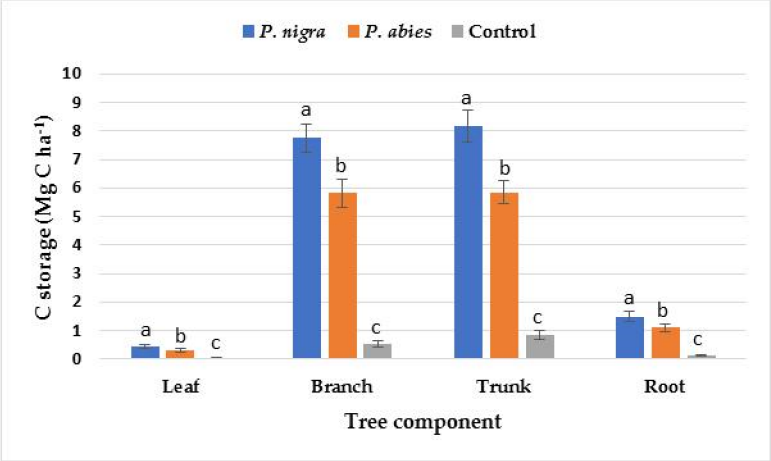

Figure 1. C storage in tree components at the study sites (significant differences among the means at different sites are indicated with lowercase letters by Duncan's test at $\alpha = 0.05$; the bars indicate the standard error of the estimate).

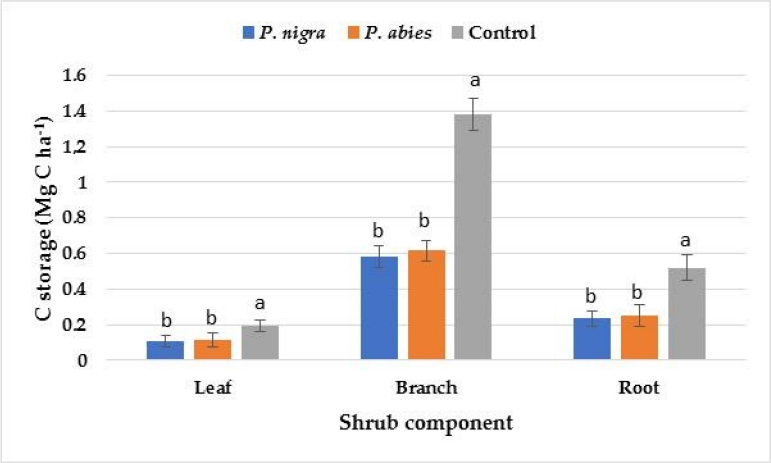

Figure 2. C storage in shrub components at the study sites. Significant differences among the means at different sites are indicated with lowercase letters by Duncan's test at $\alpha = 0.05$; the bars indicate the standard error of the estimate.

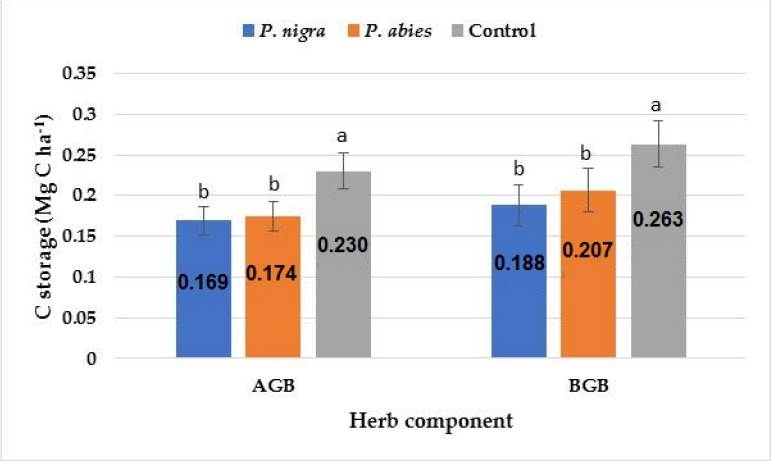

Figure 3. C storage in herb components at the study sites. Significant differences among the means at different sites are indicated with lowercase letters by Duncan's test at $\alpha = 0.05$; the bars indicate the standard error of the estimate.

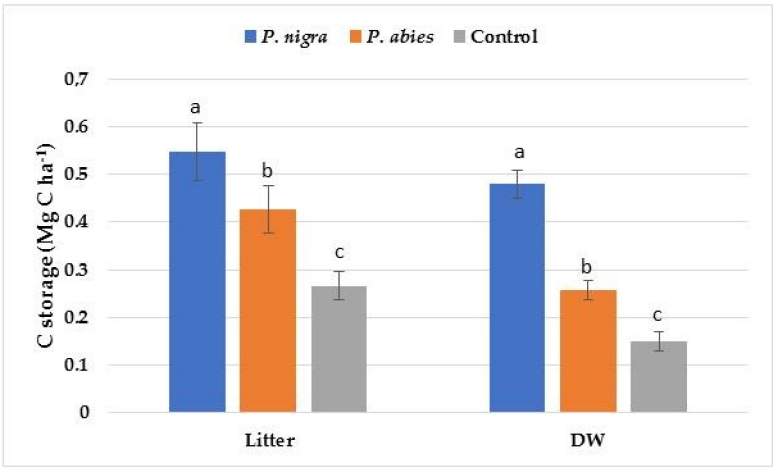

Figure 4. C storage in litter and deadwood (DW) at the study sites. Significant differences among the means at different sites are indicated with lowercase letters by Duncan's test at $\alpha = 0.05$; the bars indicate the standard error of the estimate.

The volume of deadwood in the *P. nigra* plantation was higher than that in the *P. abies* plantation in all decay classes except DC1 (Table 8). The biomass and C storage of deadwood in the *P. nigra* plantation were higher than those in the *P. abies* plantation in all decay classes. The lowest values of the volume, biomass, and C storage of deadwood were observed in the control area in all decay classes.

Table 8. Volume, biomass, and C storage of deadwood (DW) at the study sites.

Decay Class	Volume (m^3 ha^{-1})			Biomass (Mg ha^{-1})			C storage (Mg ha^{-1})		
	P. nigra	*P. abies*	Control	*P. nigra*	*P. abies*	Control	*P. nigra*	*P. abies*	Control
DC1	0.68 ± 0.10 a	0.57 ± 0.10 a	0.11 ± 0.03 b	0.33 ± 0.09 a	0.23 ± 0.06 b	0.10 ± 0.02 c	0.16 ± 0.04 a	0.11 ± 0.03 b	0.05 ± 0.01 c
DC2	0.54 ± 0.10 a	0.39 ± 0.08 b	0.07 ± 0.02 c	0.24 ± 0.05 a	0.15 ± 0.03 b	0.07 ± 0.02 c	0.12 ± 0.03 a	0.07 ± 0.02 b	0.04 ± 0.01 c
DC3	0.39 ± 0.05 a	0.24 ± 0.05 b	0.04 ± 0.01 c	0.17 ± 0.03 a	0.09 ± 0.03 b	0.06 ± 0.01 b	0.08 ± 0.02 a	0.04 ± 0.01 b	0.03 ± 0.01 c
DC4	0.32 ± 0.05 a	0.15 ± 0.03 b	0.04 ± 0.01 c	0.13 ± 0.03 a	0.06 ± 0.01 b	0.04 ± 0.01 b	0.07 ± 0.02 a	0.03 ± 0.01 b	0.02 ± 0.01 c
DC5	0.25 ± 0.05 a	0.11 ± 0.03 b	0.03 ± 0.01 c	0.09 ± 0.02 a	0.04 ± 0.01 b	0.03 ± 0.01 b	0.05 ± 0.01 a	0.02 ± 0.01 b	0.01 ± 0.00 c

Significant differences among the means at different sites are indicated with lowercase letters (a–c) by Duncan's test at $\alpha = 0.05$.

The bulk density (BD) at the upper soil layer (0–10 cm) in the control area was significantly higher than that in the plantations, while at the lower soil layer (10–20 cm) the BD was not significantly different between the plantations and the control (Table 9). The highest organic C (OC) value at both soil depths was detected in the *P. nigra* plantation followed by the *P. abies* plantation and the control area. The soil C storage (SCS) value in the *P. nigra* plantation was significantly higher than that in the *P. abies* plantation, and the SCS value in the *P. abies* plantation was significantly higher than that in the control area. The soil carbon sequestration rate (SCS_R) at the depths of 0–10 cm and 10–20 cm in the *P. nigra* plantation was about three and two times higher than in the *P. abies* plantation, respectively (Table 9).

Considering the total carbon storage, for above-ground biomass, both in the plant components and in the deadwood, and below-ground biomass down to the 20 cm soil depth, the highest value was found in the *P. nigra* plantation followed by the *P. abies* plantation and then the control area (Figure 5).

Table 9. Soil C storage (SCS) and soil carbon sequestration rate (SCS_R) (mean ± SD) in different soil depth classes at the study sites. BD, soil bulk density; OC, soil organic C.

Soil Characteristics	Soil Depth (cm)	*Pinus nigra* Plantation	*Picea abies* Plantation	Control
BD (g cm^{-3})	0–10	0.69 ± 0.03 b	0.71 ± 0.05 b	0.82 ± 0.05 a
	10–20	0.80 ± 0.04 a	0.82 ± 0.06 a	0.89 ± 0.06 a
OC (%)	0–10	5.85 ± 0.22 a	4.57 ± 0.24 b	3.51 ± 0.20 c
	10–20	3.76 ± 0.15 a	3.03 ± 0.17 b	2.15 ± 0.11 c
SCS (Mg C ha^{-1})	0–10	40.36 ± 1.16 a	32.45 ± 1.10 b	28.78 ± 1.07 c
	10–20	30.08 ± 1.03 a	24.85 ± 1.11 b	19.13 ± 0.98 c
SCS_R (Mg C ha^{-1} yr^{-1})	0–10	0.46 ± 0.02 a	0.15 ± 0.02 b	
	10–20	0.44 ± 0.03 a	0.23 ± 0.03 b	

Significant differences among sites are indicated with lowercase letters (a—c) by Duncan's test at $\alpha = 0.05$.

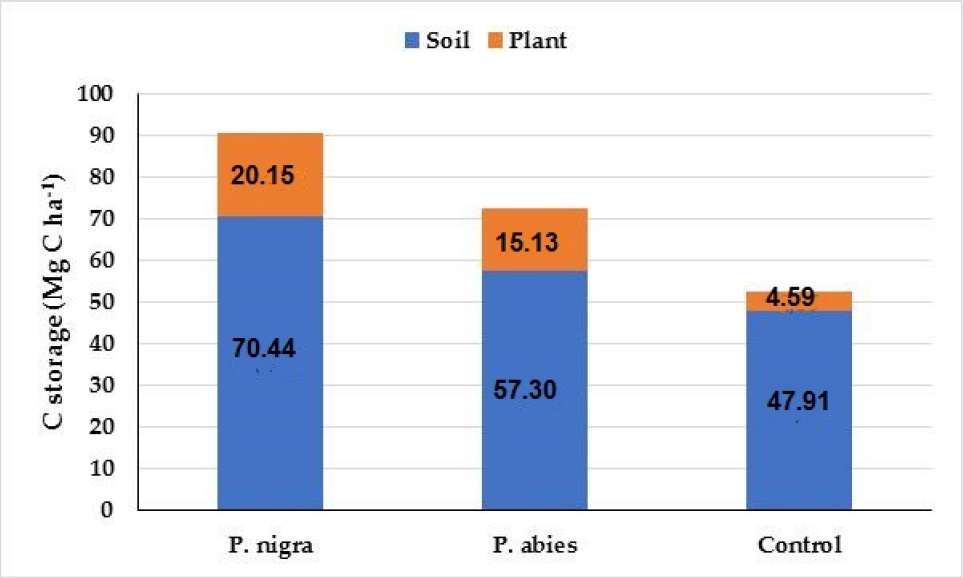

Figure 5. C storage in plants (trees + shrubs + herb + litter + DW) and soil (depth: 0–20 cm) at the study sites.

4. Discussion

The plantations set up in the last century were not made for the purpose of compensating for climate change and carbon sequestration [36–38], but the results of the current study show that the plantations with the *P. nigra* and *P. abies* tree species increased the carbon storage of the biomass and soil as compared with the control area.

The AGB of trees was estimated by both the allometric method and the FAO method. The AGB estimated by the FAO method was 3.2% lower in the *P. nigra* plantation (30.89 Mg ha^{-1} by the allometric method and 29.90 Mg ha^{-1} by the FAO method) and 10.7% lower in the *P. abies* plantation (22.65 Mg ha^{-1} by the allometric method and 20.23 by the FAO method) than the allometric estimate, while the AGB estimated by the FAO method in the control area was 6.9% higher (2.75 Mg ha^{-1} by the allometric method and 2.94 Mg ha^{-1} by the FAO method) than the value that was estimated by the allometric method.

Our results indicate that the volume of deadwood in the plantations was greater than the volume in the control area. The deadwood accounted for 7.46% of the standing volume and 2.67% of the stand's carbon storage in the *P. nigra* plantation, and 6.98% of the standing volume and 1.93% of the stand's carbon storage in the *P. abies* plantation. These results are in line with the results of previous research showing that the volume of deadwood in forests is directly related to the forest standing volume [29]. Lo Monaco et al. [29] also stated that the volume and dynamics of deadwood are related to forest vegetation, and that

deadwood plays an important role in storing atmospheric carbon in oak and pine forests. Therefore, it is predicted that with the aging of these plantations, the standing volume and consequently the volume of deadwood and the amount of carbon stored in them will increase in the coming years.

Our results and those of others provide insights into how the species of trees used in plantations influence carbon stores. Previous studies have demonstrated that plantations with different coniferous tree species increase the carbon storage within the ecosystem [14,31]. The amount of carbon stored in both the biomass and soil of the *P. nigra* plantation was higher than in the *P. abies* plantation. Furthermore, Gao et al. [31] studied the carbon storage in biomass, litter, and soil of different plantations in a semiarid temperate region of northwest China and reported the ecosystem C storage to be as follows: *Picea crassifolia* (469 C Mg ha^{-1}) followed by *Larix gmelinii* (375 C Mg ha^{-1}), *Populus simonii* (330 C Mg ha^{-1}), and *Pinus tabuliformis* (281 C Mg ha^{-1}), 59.5–91.1% of which was in the soil, and the highest soil C was stored in the *Picea crassifolia* plantation (411 C Mg ha^{-1}). Yen et al. [14] observed that the C sequestration in plantations was differentiated by species. In fact, in four different coniferous species, they found that the mean C sequestration in Japanese cedar (*Cryptomeria japonica*) (4.03 Mg ha^{-1} yr^{-1}) and Taiwania (*Taiwania cryptomerioides*) (3.52 Mg ha^{-1} yr^{-1}) was higher than in Chinese fir (1.79 Mg ha^{-1} yr^{-1}) and Taiwanese red cypress (2.36 Mg ha^{-1} yr^{-1}).

In forests, terrestrial C is stored in different pools, but trees and soil are the main pools as they store more C than the others. Our results reveal that the share of soil in the carbon storage was higher than the share of biomass. About 78% to 79% of the ecosystem's carbon was stored in the soil of plantations and 21% to 22% was stored in the biomass of the plantations, while in non-plantation areas (the control area) the soil share of the ecosystem's carbon storage was 91.3%. The results show that the amount of carbon storage in the upper soil layer (0–10 cm) was higher than that in the lower soil layer (10–20 cm) in both plantations and the control area. Usually, the largest amount of carbon accumulates in the surface layer of the soil and the amount of carbon decreases with increasing soil depth, similar to this study's findings, as reported by Paul and Clark [39]. Accordingly, soil carbon storage is an important part of the carbon storage in terrestrial ecosystems, which has a large impact on the CO_2 in the atmosphere (about 75% of the atmospheric carbon is stored in the soil) [39,40].

The role of the forest in C sequestration has ecological, environmental, social, and economic value and is related to other ecosystem services [37], such as educational, aesthetic, and cultural heritage value, recreation, and tourism. Plantation is considered to be an effective strategy to prevent soil erosion and degradation and to promote the restoration of degraded ecosystems. Forest plantation renaturalization should be considered to promote the forest ecosystem's evolution towards a natural forest system in order to protect biodiversity and improve wildlife habitat [41]. On the other hand, the process of naturalization of degraded forests may not have much influence on the C stores for a considerable amount of time. Guedes et al. [42] demonstrated that the total ecosystem C stocks in the Miombo woodlands (116 Mg ha^{-1}) were significantly lower than in plantation stands with *P. taeda* (363 Mg ha^{-1}) and *Eucalyptus grandis* (407 Mg ha^{-1}). Nevertheless, Chen et al. [43], who studied the carbon stock density in planted as compared to natural *Pinus massoniana* forests in sub-tropical China, found that carbon stock densities ranged from 78 to 210 Mg ha^{-1} and from 97 to 177 Mg ha^{-1}, respectively. The fixation of large amounts of carbon is regarded as an important environmental contribution of forests, and this characteristic has global implications [8–11,41–45]. Soto-Cervantes et al. [45] reported that the average carbon sequestration per year is 0.30 kg for each tree in a mixed *Pinus durangensis* and *Pinus cooperi* plantation. In accordance with the results of this study, Justine et al. [39] studied the biomass stock and carbon sequestration in a chronosequence of *Pinus massoniana* plantations and reported that the total ecosystem carbon storage varied with stand age, ranging from 169.90 C Mg ha^{-1} in the five-year plantation to 326.46 C Mg ha^{-1} in the 42-year plantation, of which 80.29% came from the mineral soil carbon and 19.71% came

from the vegetation. Likewise, Sharma et al. [44] estimated a carbon stock of 108 Mg ha^{-1} in the Chir Pine (*Pinus roxburghii* Sarg.) plantation in central Nepal.

As found in another study [46], close-to-nature plantation management could mitigate climate change by improving the plantation's carbon sequestration capacity. In addition to the benefits that forest ecosystems generally provide for society, forest plantations can capture significant amounts of GHGs and CO_2. Large-scale afforestation could significantly change the ground cover, the soil quality, and the water conservation function, which all constitute fundamental issues in semi-arid mountain ecosystems [47–49].

One of the most important issues that should be considered is the time dependence of the forest carbon store. In the current study, the age of forest stands was limited, and the current results pertain to the limited range of forest ages. Therefore, further research is needed to elucidate the carbon storage in forest stands that are older in age.

5. Conclusions

Afforestation (forest plantation) is an excellent alternative to barren lands to mitigate high atmospheric concentrations of CO_2 and, at the same time, reduce global warming. The results of this study show that 25-year-old plantation ecosystems (vegetation and soils) with *P. nigra* and *P. abies* species stored 1.73 and 1.38 times more carbon as compared with adjacent non-planted (control) areas, respectively. Soil conservation and an increase in the biodiversity of plant and animal species are other positive consequences of these plantations. Plantations with tree species that are resistant to harsh mountain climates with non-timber production purposes constitute a suitable and sustainable solution to reducing atmospheric carbon and global warming. According to the results, we conclude that the restoration of landscapes by tree plantation has a substantial and favorable impact on the acceleration of carbon sequestration. Forest plantation, even with atypical species, can in fact be considered a strategy that promotes the evolution to more stable natural forest systems that provide multiple ecosystem services.

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