# THE ROLE OF *HALOXYLON* PLANTATIONS IN IMPROVING CARBON SEQUESTRATION POTENTIAL OF SAND DUNES OF IRAN

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**Abstract.** Rehabilitation of desertified land in semi-arid and arid regions through *Haloxylon* plantations has a great potential to increase carbon sequestration. In this study, carbon distribution and sequestration were examined in different parts of *Haloxylon spp.* and depths of soil surface. Afterward, the economic value of carbon sequestration in the *Haloxylon* plantation was estimated. In order to investigate vegetation variables, a systematic random method with 10 nested plots was applied. Plant properties including diameter at breast height, tree height, height to crown, and the small and large diameters of the crown were measured. Tree and soil sampling was conducted in 10 × 10 $m^2$ and 5 × 5 $m^2$ plots, respectively. Soil was sampled at 0-15 and 15-30 cm depths of *Haloxylon* plantation and control area. Litter were harvested at1 × 1 $m^2$ plots. Algometric equations and Walkley-Black method were used to determine plant biomass and soil organic carbon sequestration. The results showed that planting *Haloxylon* increased carbon sequestration by up to 24.46 ton/ha compared to the control area. Economic value of carbon sequestration in the *Haloxylon* plantation was estimated at $3.74 million. Carbon was mostly sequestrated in the branches and roots. Carbon sequestration in different parts of the plant was calculated as 16.6 ton/ha (54% of total sequestration). Soil organic carbon sequestration was computed as 13.9 ton/ha (46% of total sequestration). *Haloxylon* species has a high potential for carbon sequestration. Nevertheless, the species used in rehabilitation of desertified lands need to be capable of maintaining other resources, especially water resources.

**Keywords:** *carbon sequestration, economic value, Haloxylon plantation, drylands, sand dunes, Ala region*

## Introduction

Throughout the history of the Earth, the planet’s surface has transformed dramatically due to various organic and inorganic phenomena (Mahdavi et al., 2011). Climate change and global warming are among the serious challenges to sustainable development and pose negative impacts on aquatic and terrestrial ecosystems (UNDP, 2000). A number of scientists have identified increased atmospheric concentrations of greenhouse gases (GHGs) to be responsible for climate change and global warming

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(Brooks, 1998). GHGs may have natural and human-caused sources. On the other hand, their levels can be reduced through chemical changes in the atmosphere or absorption of the gases by sinks. Each GHG has a particular lifetime and percentage contribution to the greenhouse effect.

Carbon dioxide ($CO_2$) has the greatest global warming potential (GWP) among all GHGs and is thus generally considered as the main determinant of the effects of GHGs on global warming (Hashemi and Karvani, 2010). Atmospheric GHGs, particularly $CO_2$, methane ($CH_4$), and nitrous oxide ($N_2O$), emitted from both natural and human-caused sources, absorb infrared radiation, generate heat, and consequently increase the temperature of the troposphere (the lowest portion of the Earth’s atmosphere). While $CO_2$, accounting for 81% of GHG emissions, is produced during the combustion of petroleum products, natural gas, coal, and all other fossil fuels, $CH_4$ (making 10% of emissions) comes from landfills, coal mines, oil and natural gas operations, and agriculture. On the other hand, $N_2O$ (responsible for 5% of emissions) is the result of using nitrogen fertilizers, burning fossil fuels, and industrial and waste management processes (Shuman, 2011). Two types of strategies, i.e. emission reduction and GHG capture, have been proposed to counter the greenhouse effect. Typical examples of emission reduction are improving energy saving technology and renewable energy development. GHG capture methods mainly involve carbon capture and storage and afforestation.

Numerous researchers have suggested afforestation and forest management as effective countermeasures against global warming (Srivastava et al., 1993; Silver et al., 2000; Kumar et al., 2001; Niles et al., 2002). According to the United Nations Framework Convention on Climate Change (UNFCCC, 2006), afforestation is effective for carbon mitigation. The emission reductions that are attributable to an afforestation or reforestation project activity (called “net anthropogenic greenhouse gas removals by sinks”) can be calculated as the “actual net GHG removals by sinks” minus the “baseline net GHG removals by sinks” minus “leakage” in five carbon pools (aboveground and below-ground biomass, litter, dead wood, and soil organic carbon pools). Of these five carbon pools, the aboveground and belowground biomass will change rapidly after afforestation. Based on the Clean Development Mechanism and Joint Implementation (CDM/JI) guidelines set by the UNFCCC, Suganuma et al. (2012) evaluated the sequestered carbon amount (as carbon credit) following the afforestation of a 45 × 50 $km^2$ arid area. They found that carbon mitigation amount by the applied arid land afforestation was equivalent to 0.88% of $CO_2$ emission in Japan in 2008 (Suganuma et al., 2012).

Carbon sequestration is the process through which atmospheric carbon dioxide is absorbed, stored, and deposited as carbohydrates in plant tissues (Abdi et al., 2008). In addition to synthesis of carbon compounds by plants, the viability and stability of carbon in plant tissues are also critical. In fact, as the decomposition rate of carbon compounds decreases, carbon sequestration in the ecosystem increases. Therefore, since the lowest rate of decomposition is observed in arid areas where there is too little moisture, such areas are important in terms of carbon sequestration (Gao et al., 2007; Ardo and Olsson, 2003). Drylands, many of which may have degraded soils, cover about 40% of the global land area (FAO, 2000). Although dryland soils are commonly low in carbon content, the above-mentioned facts may suggest their high potential for carbon sequestration (Scurlock and Hall, 1998; Rosenberg et al., 1999).

Desertification is defined as land degradation in arid, semi-arid, and dry sub-humid areas due to various reasons such as climate change and human activities (UNEP, 1990). Land desertification can damage soil structure and reduce soil aggregates. This will affect the global carbon cycle through reducing the total soil carbon pools and increasing the emission of $CO_2$ from the soil and vegetation into the atmosphere (Lal, 2001; Jabro et al., 2008; Yu et al., 2007). Su et al. (2010) compared soil carbon sequestration at 0-30 cm depths of rehabilitated desert lands and a control area in northwest China. They reported that the values reached 1.8-9.4 and 7.5-17.3 Mg/ha over 7- and 32-year rehabilitation periods, respectively. They hence concluded that desertification control could be beneficial to soil carbon sequestration and soil quality improvement (Su et al., 2010).

Amani and Maddah Arefi (2003) estimated the amount of carbon sequestrated in aerial biomass of $1.5 \times 10^6$ ha of Iran's desert lands planted with *Haloxylon* at about 5.7 million tons. They believed that considering equal amount of carbon sequestration in the underground organs and soil, total carbon sequestration would reach about 15 million tons.

Research has indicated significantly higher carbon concentration in samples from natural forests than in those from plantations (Elias and Potvin, 2003). Haghdoost et al. (2012) compared destroyed natural *Quercus castaneifolia* forests with *Acer velutinum* and *Alnus subcordata* plantations in Chamestan region (Mazandaran Province, Iran). They found soil carbon sequestration to have increased by up to 33.61 ton/ha in *Acer velutinum* plantations and to have decreased by up to 20.55 ton/ha in *Alnus subcordata* plantations. All previous measurements have confirmed the difference in carbon concentrations among various species, organs, treatment types, drying temperatures, provenances (natural/plantation), and climates. In addition, studies have assessed carbon concentrations of tree components by age not only in China (Zhang et al., 2009) but also in other parts of the world. Fu et al. (2013) ranked carbon concentration of aboveground tree organs as living branch > bark > foliage > dead branch > stem. In the ranking of belowground tree organs, large and small roots had the highest and lowest carbon concentrations, respectively (large roots > stumps > thick roots > medium roots > small roots). They concluded that despite the significant differences in carbon concentrations of various tree organs, trees of unalike ages were not significantly different in this regard. Forozeh et al. (2008) compared carbon sequestration potential of three shrub species, namely *Helianthemum Fire Dragon*, *Dendrostellera lessertii*, and *Artemisia sieberi* in the arid rangelands of Iran. According to their findings, *Artemisia sieberi* had the greatest carbon sequestration potential. Moreover, among the four tree parts (leaves, branches, stems, and roots), stems and leaves had the highest and lowest potential, respectively.

The rate of carbon sequestration is much lower in young areas than in old areas. Moreover, organic carbon concentrations in sand dunes elevate as the age of *Haloxylon* plantations increases. For instance, high carbon sequestration (15 ton/ha) was observed in a 41-year-old *Haloxylon* plantation (Sarparast et al., 2013). On the other hand, conifers have greater carbon sequestration potential compared to broad-leaved plants (Abbas Nejad and Khajodin, 2012).

Biomass is the basis for estimating the cost of carbon sequestration (McDicken, 1997). Masses of *Acacia* and *Fraxinus excelsior* (covering 207 and 90 ha in Cheetgar Park of Tehran, Iran) increased carbon sequestration by 99877.5 and 12600 ton, respectively. Since the average cost of these masses is $200 per ton, the economic value of carbon sequestration is about 20 and 2.5 million dollars in these pilot areas, respectively (Varamesh et al., 2011).

The present study aimed to investigate carbon sequestration potential of different parts of *Haloxylon spp*. and various soil depths of *Haloxylon* plantations. It also sought to estimate the cost of carbon sequestration through rehabilitation of sandy desertified lands in Ala region of Semnan Province, Iran.

## Methods

### *Introduction to Haloxylon species (saxaul)*

*Haloxylon ammodendron* (saxaul) belongs to the Amaranthaceae (Salsoloideae subfamily) family placed in the Caryophyllales order. The genus exists in shrub or small tree forms with very small leaves that join in the base. It resembles conifers due to its needle-like leaf appearance. Two major species of *Haloxylon* are *Haloxylon aphyllum* (black saxaul) and *Haloxylon persicum* (yellow or white saxaul). Studies on natural and artificial saxaul lands have shown that the plant can live only as long as 15-25 years depending on species and germination conditions. In fact, older saxaul plantations require more germination (Jafari et al., 2009). *H. aphyllum* and *H. persicum* are dominant plants in the deserts of the Irano-Turanian region (Pyankov et al., 1999). Stabilization of Iran’s sand dunes with vegetation was initiated in October 1959. *Haloxylon* plantations are currently covering an area of about 2 million ha (Baghestani Meybodi et al., 2006). In Ala region of Semnan Province, planting *Haloxylon* and rehabilitation of sandy desertified land started in 1974 and germination was performed in 1990 (*Fig. 1*).

***Figure 1.*** *Haloxylon plantation, gaps, and underground water level changes (increase and decrease)*

### *Site description*

The study area (35°32′0″N 53°30′5″E/35°33′50″N 53°30′49″E) covered 766 ha of Semnan Plain. It was located on a playa and had a geomorphological structure containing clay plains and sand ripples (*Fig. 2*). The mean temperature and mean absolute minimum and maximum temperatures during 1965-2005 were 18.4°C, -0.4°C (in January), and 37.7°C (in July), respectively. The mean precipitation was 140.8 mm in the same period.

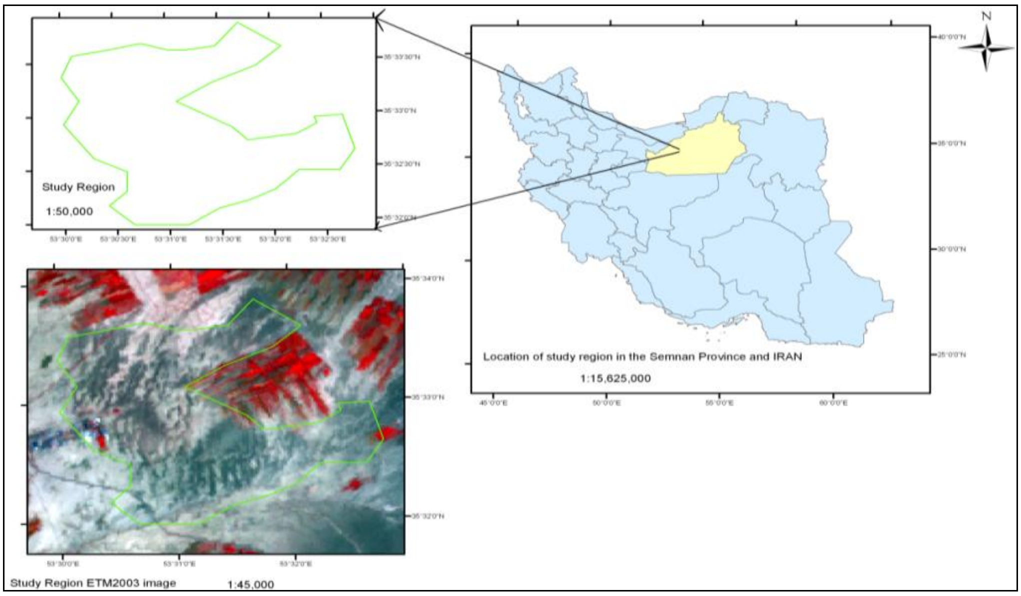

***Figure 2.*** *Map of the study area and its location in Semnan Province, Iran*

De Martonne's index (De Martonne, 1926) was used for climate classification based on mean annual precipitation and temperature through the following *Equation 1:*

$$I = P/T + 10 \qquad \text{(Eq. 1)}$$

where I, P, and T are de Martonne's aridity index, annual precipitation (in mm), and annual temperature (in °C), respectively. Using the previously mentioned values, I was calculated as 4.9 for the study area, i.e. the area had an arid climate during the study period.

### *Sampling method*

In this study, vegetation variables were examined through a systematic random method with 10 nested plots. Six plots were used for each mass. The plot sizes were 10 × 10 $m^2$, 5 × 5 $m^2$, and 1 × 1 $m^2$ for tree, soil, and litter sampling, respectively (*Fig. 3*). Moreover, in order to reduce edge effects, a few rows around each mass were not sampled and the samples were mostly collected from the center of the masses. Both *Haloxylon* plantation and the adjacent lands (control area) were sampled. Five parallel transects with two square nested plots on each were placed on the study area. The first transect was established randomly and the subsequent transects were placed with a specific distance based on the area of the region. In the 10 × 10 $m^2$ plots, *Haloxylon* characteristics including diameter at breast height (DBH), tree height (H), height to crown (Hc), and the small and large diameters of the crown ($D_s$ and $D_l$, respectively) were measured. Soil was sampled from 0-15 and 15-30 cm depths of the four corners of the 5 × 5 $m^2$ plots. The obtained samples were then mixed to form a single sample for each plot (Gao et al., 2007). Moreover, all the litter over the 1 × 1 $m^2$ plots of each mass was collected and weighed. Afterward, 20-g samples were packed in plastic bags and transported to the laboratory to determine moisture and carbon percentage (McDicken, 1997). Due to the absence of vegetation on the control area, only soil was sampled.

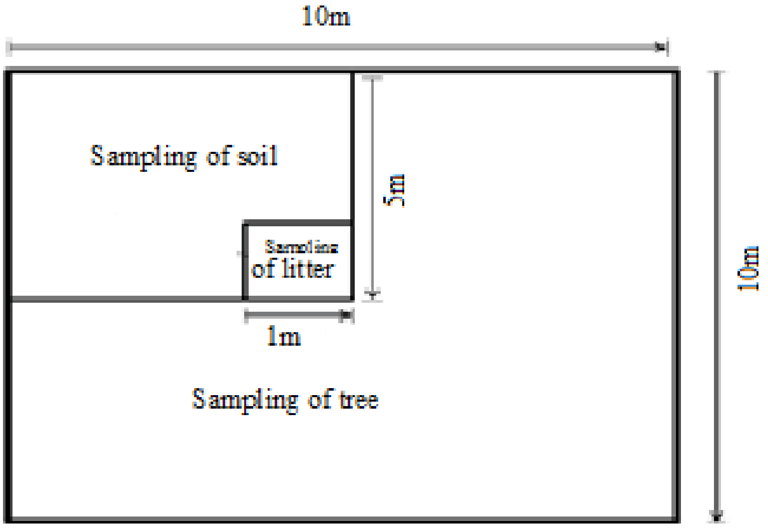

***Figure 3.*** *The size of plots used to measure each of the plant variables*

### *Biomass calculation*

Trunk volume, canopy structure and volume, and aerial and underground biomass of *Haloxylon* were calculated based on the method proposed by Hernandaz et al. (2004). First, *Equations 2, 3,* and *4* were used to obtain tree basal area, volume, and biomass (per kg), respectively:

$$A_b = \pi \times r^2 \quad \text{(Eq. 2)}$$

$$V = A_b \times H \times K_c \quad \text{(Eq. 3)}$$

$$Biomass = V \times WD \times 1000 \quad \text{(Eq. 4)}$$

where π = 3.14, r = radius of the tree (m), and $K_c$ = 0.54. $A_b$, V, Kc, H, and WD are basal area of the tree ($m^2$), tree volume ($m^3$), tree height, and density ($g/cm^3$), respectively.

In order to save time and costs and to avoid destructive sampling methods for estimating root biomass of *Haloxylon spp*, root biomass of *H. aphyllum* and *H. persicum* species were calculated using *Equation 5* and considering 83% and 93% of aerial biomass as root biomass, respectively:

$$BGB = AGB \times K \quad \text{(Eq. 5)}$$

where AGB and BGB are aerial and underground biomass, respectively. K is percentage of aerial biomass.

Canopy volume of *Haloxylon spp*. was calculated using *Equation 6:*

$$V\left(m^3\right) = \left(\pi \times D_b^{\,2} \times H_c\right)/12 \tag{6}$$

where $D_b$ is $(D_l + D_s)/2$.

### *Laboratory methods*

In the laboratory, samples of trunks, branches, roots, and litter were dried in the oven at 105°C for 24 h and their moisture content was determined. The samples were then thoroughly ground. Afterward, three 2-g quantities of each sample were combusted in an electric furnace (500-600°C) for three-four hours. The burnt samples were dried in a desiccator and their ash weight was recorded. As the initial and ash weights were both available, the organic carbon percentages of tree organs and litter were separately computed based on the ratio of organic carbon to organic materials in *Equation 7:*

$$OM = 1/2OC \tag{Eq. 7}$$

where OM and OC are organic material and organic carbon, respectively.

Organic carbon percentage was determined by Walkley-Black method (1934). Organic carbon was oxidized using potassium dichromate ($K_2Cr_2O$) in an acidic environment full of $H_2SO_4$. The remaining potassium dichromate was then titrated by 0.1 normal sodium thiosulfate ($Na_2S_2O_3$) in the presence of potassium iodide reagent (KI).

The experiments were performed in both the presence and absence of soil samples. Therefore, 0.5-2 g dried soil (depending upon the amount of organic matter in the sample) along with 16 cc concentrated $H_2SO_4$ and 10 cc potassium dichromate 1 normal were poured into 100-cc Florence flasks and heated for 90 min at 120°C. The remaining amount of potassium dichromate was determined using iodometry, i.e. 25 cc of the flask contents (diluted with distilled water to reach a volume of 100 cc) along with 2 g potassium iodide was poured into 250-cc Erlenmeyer flasks. After adding 2 g potassium iodide, the obtained mixture was titrated with 0.1 normal sodium thiosulfate. The amounts of thiosulfate used for samples and controls were recorded at each stage of the experiment. Organic carbon percentage was then calculated using *Equation 8:*

$$OC\% = 4\left(A-B\right) \times 100 \times 3/S \times 1000 = 0.12\left(A-B\right)/S \tag{Eq. 8}$$

where OC, A, B, and S are organic carbon, amount of sodium thiosulfate applied to controls (cc), amount of sodium thiosulfate applied to samples (cc), and sample weight (g), respectively. In this equation, multiplying A-B by four reflects the fact that the real samples (25 cc) constituted one-fourth of the tested samples as they were diluted with distilled water to reach a volume of 100 cc. The value 3 in the equation represents carbon equivalent.

Finally, soil organic carbon content (kg/ha) was computed using *Equation 9:*

$$OC = 1000 \times OC\% \times B_d \times E \tag{Eq. 9}$$

where OC, OC%, $B_d$, and E are organic carbon (kg/ha), organic carbon percentage, soil bulk density (g/cm$^3$), and sampling depth (cm), respectively.

The economic cost of carbon capture and storage was estimated by considering $200 per ton of carbon as previously suggested by Varamesh (2009). All required diagrams were drawn in Microsoft Excel 2007.

## Results

### *Soil carbon sequestration*

According to our findings, planting *Haloxylon* in Ala region of Semnan Plain (during 1974-2012) significantly increased soil carbon sequestration. The total sequestered carbon in the study and control areas were 13.9 and 5.9 ton/ha, respectively. Thus, planting *Haloxylon* in this region increased carbon sequestration by up to 8 ton/ha compared to the control area (*Fig. 4*).

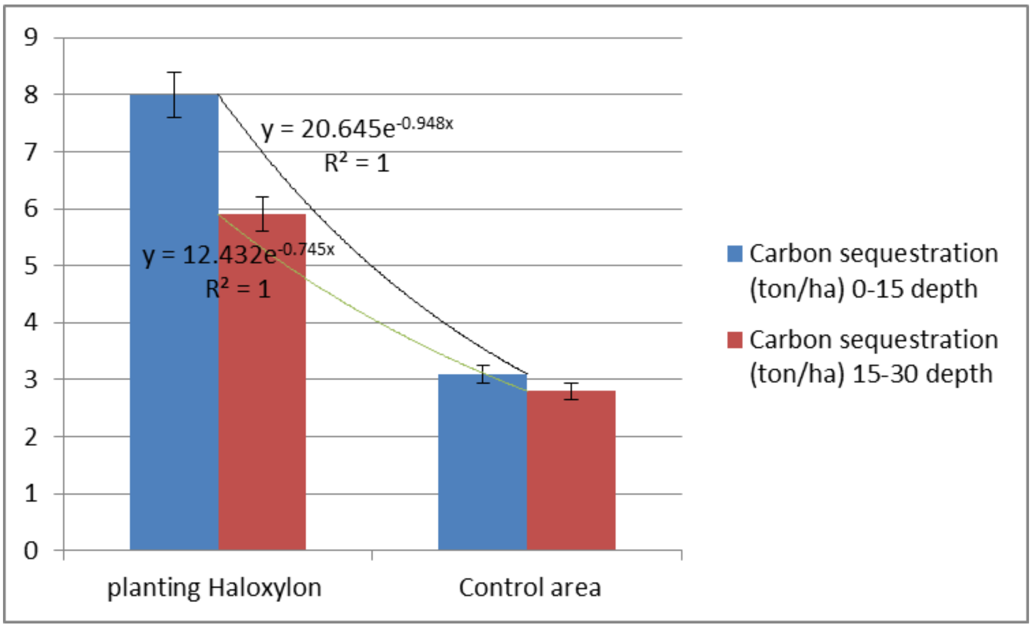

***Figure 4.*** *Carbon sequestration at 0-15 and 15-30 cm depths in Haloxylon plantation and control area (statistical significance at the 0.05 level)*

Comparison of mean values obtained from 0-15 and 15-30 depths of soil showed the greatest amount of soil carbon sequestration at 0-15 cm depth of the *Haloxylon* plantation. Moreover, in both areas, carbon sequestration was higher at 0-15 cm depth than at 15-30 cm depth. However, the difference was not significant in either area (*Fig. 4*).

### *Carbon sequestration in plant biomass*

Due to lack of vegetation in the control area, only plant biomass data related to the *Haloxylon* plantation is presented in *Table 1*. As it is seen, the highest and lowest amounts of plant biomass were detected in canopy and trunk, respectively. In addition, carbon sequestration in aerial biomass (total biomass of trunk and canopy) and litter was 7.1 and 3.5 ton/ha, respectively.

***Table 1.*** *Measurements of plant biomass (ton/ha) in the Haloxylon plantation (all values were equal to zero in the control area)*

| **Attribute** | **Value (ton/ha)** |
|---|---|
| Trunk biomass | 1.51 |
| Canopy biomass | 12.65 |
| Root biomass | 11.72 |
| Total biomass | 26.7 |
| Litter biomass | 8.1 |
| Carbon sequestration in aerial biomass | 7.1 |
| Carbon sequestration in underground biomass | 6.0 |
| Carbon sequestration in litter biomass | 3.5 |
| Total carbon sequestration in plant biomass | 16.6 |

## *Total carbon sequestration*

Total carbon sequestration per unit area in the *Haloxylon* plantation and the control area (wasteland) was 30.36 and 5.9 ton/ha, respectively ($P > 0.05$) (*Table 2*). Therefore, the planted *Haloxylon* species increased carbon sequestration by up to 24.46 ton/ha.

Furthermore, the highest and lowest carbon sequestration levels were related to branches and trunks, respectively. In general, carbon sequestration in various plant parts summed to 16.6 (54%). On the other hand, soil carbon sequestration reached a total of 13.9 ton/ha (46%) in the first and second depths (0-15 and 15-30 cm) of the whole *Haloxylon* plantation. Hence, maximum and minimum carbon sequestration occurred in soil and litter, respectively (*Table 2*).

Considering insufficient vegetation in the control area, no atmospheric carbon sequestration had occurred in this area. Therefore, only 5.83 ton/ha carbon was sequestrated by soil. In each hectare of the control area (wasteland), 3.1 ton (53%) and 2.8 ton (47%) organic carbon were sequestrated at 0-15 and 15-30 cm depths of soil, respectively (*Table 2*).

***Table 2.*** *The rate of carbon sequestration in different parts of the Haloxylon plantation and control area*

|  | **Parameter** |  | **Carbon sequestration (ton/ha)** | **Carbon sequestration percentage** |
|---|---|---|---|---|
| *Haloxylon* plantation | Plant part | Trunk | 0.74 | 3 |
|  |  | Branch | 6.16 | 21 |
|  |  | Root | 5.83 | 19 |
|  |  | Litter | 3.73 | 12 |
|  | Soil depth (cm) | 0-15 | 8.00 | 26 |
|  |  | 15-30 | 5.90 | 19 |
|  | Total |  | 30.36 | 100 |
| Control area | Soil depth (cm) | 0-15 | 3.1 | 52.5 |
|  |  | 15-30 | 2.8 | 47.5 |
|  | Total |  | 5.9 | 100 |

## Discussion

*Haloxylon* species are halophytic, psammophytic, and xerophytic plants. They are in fact considered as the most compatible species among desert and semi-desert plants and are hence widely used in sand dune stabilization (Safarnezhad, 2005). The present study revealed that planting sand dunes of the Ala desert area with *Haloxylon* led to high potential for carbon sequestration and could increase soil carbon sequestration by 8 ton/ha compared to the control area. Likewise, Amani and Maddah Arefi (2003), Sarparast et al. (2013), and Su et al. (2010) confirmed that soil carbon sequestration increased in *Haloxylon* plantations.

In the current study, comparison of carbon sequestration in various plant parts and soil depths indicated that soil and underground plant parts were responsible for more than 70% of carbon sequestration in the *Haloxylon* plantation. In contrast, Amani and Maddah Arefi (2003) found no significant differences between underground and aerial plant parts in this regard.

Trees remove carbon dioxide from the atmosphere through the natural process of photosynthesis. They store carbon in their leaves, branches, stems, bark, and roots. Carbon comprises about half of the trees' biomass dry weight. Since one ton of carbon equals 3.67 ton of carbon dioxide (Johnson and Coburn, 2010), the total amount of carbon sequestration in aerial, underground, and litter biomass per unit area of *Haloxylon* plantation in the present study was 16.6 ton/ha (*Table 2*). With the total area being 766 ha, carbon sequestrated by *Haloxylon spp.* equaled 12715.6 ton which means 46666.25 ton of $CO_2$ gas had been absorbed.

The significant amount of carbon sequestration in the soils of the studied *Haloxylon* plantation (45%) highlights the importance of soil as a natural resource to control GHG emissions. Besides, we found 0-15 cm depth of soil to have maximum carbon sequestration potential. Similarly, Abbas Nejad and Khajodin (2012) reported larger levels of carbon sequestration in soil surface layers. They also found carbon sequestration to decrease with increasing depth. Sheidai Karkaj et al. (2013) introduced high carbon stock in higher depths of microsites to cause greater expansion of *Atriplex* roots compared to *Agropyron* roots. However, due to the presence of litter and thus storage of more carbon in the higher depths (0-15 cm) of soil, this part was more important for carbon sequestration. In other words, carbon content had an inverse relationship with depth.

The high level of carbon sequestration in soil implies that soil erosion will undoubtedly lead to carbon waste. Therefore, any sort of biological or mechanical operation to prevent soil regression and promote vegetation is certainly beneficial to carbon sequestration management (Izaurralde et al., 2007; Abdi, 2005). In such conditions, carbon sequestration adds to other values and uses of forest ecosystems and can be used as an indicator for assessing the sustainability of natural resources (Varamesh et al., 2011). Furthermore, atmospheric carbon filtration using synthetic methods will impose heavy costs, e.g. about $100-300 in the U.S. (Cannell, 2003). Carbon sequestration in the studied *Haloxylon* plantation was about 24.46 ton/ha higher than the control area. As the plantation covered an area of 766 ha, the total increase in carbon sequestration was 18,736.36 ton. By considering the minimum value per ton of carbon sequestration as $200 (Varamesh, 2009), the economic value of carbon sequestration in the *Haloxylon* plantation was approximately $3.74 million.

Carbon sequestration potential varies depending on plant species, location, and management methods (Mortenson and Schuman, 2002). Forozeh et al. (2008), Haghdoost et al. (2012), Abbas Nejad and Khajodin (2012), and Sheidai Karkaj (2013) showed that various plant species lead to different levels of carbon sequestration. Alizadeh et al. (2010) indicated grazing management to be able to alter carbon sequestration levels. Terakunpisut (2007) suggested differences in carbon sequestration in various regions of a forest.

This investigation confirmed the carbon sequestration potential of *H. aphyllum* and *H. persicum*. Moreover, gaps in the area (*Fig. 1*) indicated sharp drop in groundwater and the necessity of sand control with other species in the studied region.

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