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Growth and carbon storage of black saxaul in afforested areas of the Aralkum Desert

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Abstract: This study aimed to determine the growth and carbon storage of planted *Haloxylon aphyllum* in the Aralkum Desert in Kazakhstan. Six sites afforested in 2000, 2005, 2009, 2010, 2013, and 2017 were selected. The root collar diameter (cm) and height (m) were measured for all *H. aphyllum* in 30 m × 44 m plots. Biomass accumulation (g m^{-2}) and carbon storage (C g m^{-2}) were calculated using allometric equations and the carbon concentration data of *Haloxylon* species. The diameters varied from 2.5 cm to 4.3 cm and the height varied from 106.2 cm to 223.7 cm. The growth of *H. aphyllum* was not linearly related to the afforestation year or soil properties. Tree growth might have been influenced by variations in the microclimate, such as temperature, precipitation, and dust storms. The mean total biomass accumulation was 20.57 g m^{-2} and ranged from 2.42 g m^{-2} to 64.53 g m^{-2}. The mean carbon storage was 9.70 C g m^{-2} and ranged from 1.12 C g m^{-2} to 30.61 C g m^{-2}. These biomass and carbon storage estimates were smaller than those reported for other Central Asian deserts, but afforestation enabled the generation of vegetative cover and consequently, carbon sequestration in the manmade Aralkum Desert.

Keywords: afforestation, allometry, Aral Sea, *Haloxylon aphyllum*

INTRODUCTION

Aral Sea has been desiccated by water abstractions from the contributing rivers to supply water for the irrigated cotton and rice cultivation since 1960 (Breckle *et al.* 2001). Furthermore, the dried sea floor has transformed to the desert Aralkum since the 1980s (Breckle *et al.* 2001). The soil in Aralkum is often high in salinity and low water content, organic matter, and nutrients (Breckle *et al.* 2001). The microclimate in Aralkum had changed by desiccation of Aral Sea, resulting in increasing salt and dust storm and deteriorating soil physical and chemical properties (Qadir *et al.* 2009). Afforestation has been used to rehabilitate the degraded area by reducing the wind erosion and improving soil quality (Khamzina 2006), since longer time is otherwise required for the natural vegetation introduction (Ravindran *et al.* 2007).

The choice of candidate species for afforestation in the Aralkum desert is limited by dryness, salinity, and large annual and seasonal variations in air temperature. *Haloxylon* species are introduced naturally under such conditions and are thus used for the afforestation on arid and saline soil (Orlovsky and Birnbaum 2002). These species have high tolerance to salinity, dryness, and low nutrients in the soil (Huang *et al.* 2003). They can accumulate high concentration Na^+ and K^+ ions in photosynthetic tissues, and can uptake the amount of water necessary for photosynthesis (Wang *et al.* 2004). Black saxaul (*Haloxylon aphyllum*) is a dominant woody species in the Central Asian deserts due to its xerophytic and halophytic characteristics. Afforestation with *Haloxylon aphyllum* may stimulate the introduction of other species, resulting in the expansion of vegetation cover (Novitskiy 2012). However, severe drought stress could decrease the photosynthetic activity, resulting in the reduction of *Haloxylon* species growth (Su *et al.* 2007).

Physical and chemical soil properties such as salinity, sodium absorption ratio, and sand ratio can determine the growth and mortality of *H. aphyllum* in the Aralkum (Matsui *et al.* 2019). Furthermore, climatic factors such as the amount of precipitation, seasonal temperature, and spring frosts could affect the growth and survival of *Haloxylon* species in arid desert regions (Kuzmina and Treshkin 2012). High wind speed stimulates the desiccation of vegetation, and sand accumulation by dust storms can induce the mortality of seedlings and small shrubs (Okin *et al.* 2001).

The carbon storage in arid land is estimated at 36% of the global carbon storage, and Kazakhstan has one of the world's largest dryland areas (Trumper *et al.* 2008). However, the carbon storage and sequestration in Central Asia and their contributions to the global carbon cycle have not been specified in spite of its large area and contribution to the global carbon cycle (Li *et al.* 2015). In particular, land areas naturally dominated or afforested by *H. aphyllum* may contain a considerable carbon stock (Thevs *et al.* 2013), but current estimates are uncertain because of the scarcity of field-based data (Yohe *et al.* 2006).

The aim of this research was to investigate the growth and carbon storage of *H. aphyllum* in afforested areas on the dry Aral Sea bed, Kazakhstan. We investigated (i) the growth dynamics of *H. aphyllum* through examining the chronosequence of afforestation sites, (ii) assessed the relationship of the plant growth with afforestation year and soil properties, and (iii) estimated the biomass and carbon storage in the *H. aphyllum* afforestation areas.

MATERIALS AND METHODS

Six sites of the afforested area were selected near Kazalinsk, southern part of the North Aralkum (Table 1; Fig. 1). The annual mean temperature and total precipitation measured 8.9°C and 123 mm by Kazalinsk meteorological station (Breckle and Wucherer 2012). Afforestation with *H. aphyllum* was conducted in 2000, 2005, 2009, 2010, 2013 and 2017 (Table 1). In August 2018, three 30 m × 44 m sized plots were randomly selected in each site for plant measurements. The plot size reflected the typical planting distance in Aralkum afforestation sites.

Table 1. Afforestation year and coordinates of each study site in the afforested area

Site	Afforestation year	Coordinate
S_{2000}	2000	N45°32.612′ E60°52.788′
S_{2005}	2005	N45°31.338′ E60°52.309′
S_{2009}	2009	N45°30.078′ E60°51.191′
S_{2010}	2010	N45°25.543′ E60°46.380′
S_{2013}	2013	N45°11.865′ E60°59.988′
S_{2017}	2017	N45°12.334′ E60°56.998′

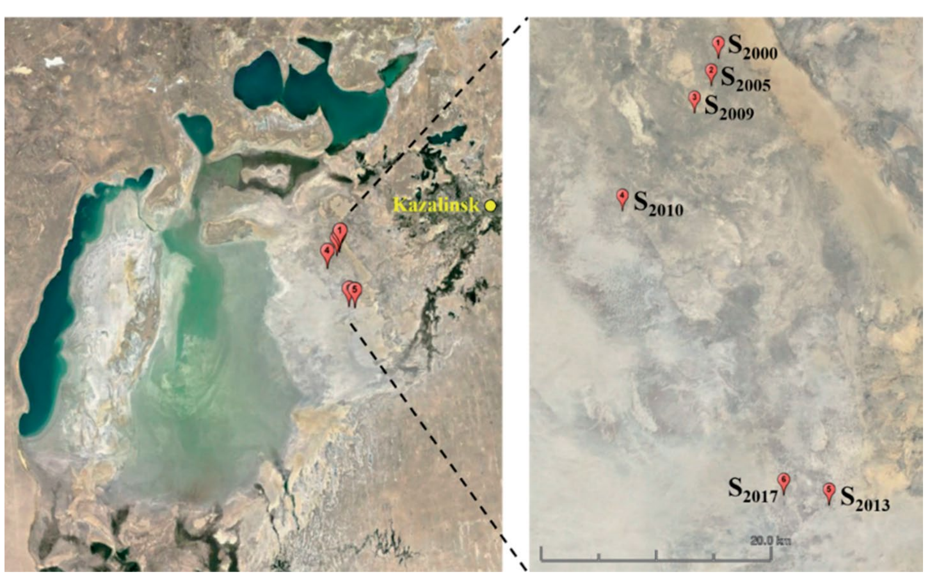

Fig. 1. Location of sites in Aralkum near Kazalinsk, Kazakhstan. The name of each site is shown in Table 1.

Root collar diameter (RCD, cm) was measured at 10 cm above ground using a digital caliper, and height (cm) was measured from ground to top of tree using a ruler for all *H. aphyllum* plants in each plot. The number of *H. aphyllum* plants was also counted and density of *H. aphyllum* plants (shrub ha^{-1}) was calculated in each plot.

Above-ground biomass (AGB), below-ground biomass (BGB), and total biomass (TB) of individual *H. aphyllum* were estimated using measured height (H) data in allometric equations (1), (2), and (3) (Xu *et al.* 2017):

$$\ln(AGB) = 3.381 \ln(H) - 10.408 \quad (1)$$

$$\ln(BGB) = 3.393 \ln(H) - 10.523 \quad (2)$$

$$\ln(TB) = 3.345 \ln(H) - 9.540 \quad (3)$$

Biomass accumulation ($g\ m^{-2}$) was calculated by dividing the sum of total biomass of all *H. aphyllum* by the plot area, and carbon storage ($C\ g\ m^{-2}$) was calculated by multiplying the biomass of each component by mean carbon content of *Haloxylon* species (above-ground component: 48.05% and below-ground component: 47.05%; Buras *et al.* 2012).

The differences in RCD, height, and number of *H. aphyllum*, as well as biomass accumulation and carbon storage in *H. aphyllum* among study sites were analyzed using ANOVA and Tukey post-hoc test. The relationship of diameter and height of *H. aphyllum* with afforestation year and soil properties in the depth of 0–10 cm (unpublished data, Appendix 1) were determined using correlation analysis with SAS 9.4.

RESULTS AND DISCUSSION

RCD (cm) was 2.9±0.1 in S_{2000}, 3.6±0.4 in S_{2005}, 3.9±0.2 in S_{2009}, 4.0±0.4 in S_{2010}, 4.3±0.4 in S_{2013}, and 2.5±0.1 in S_{2017}, respectively (Fig. 2). Height (cm) was 106.2±14.0 in S_{2000}, 112.7±10.6 in S_{2005}, 149.8±14.5 in S_{2009}, 189.8±2.3 in S_{2010}, 223.7±8.9 in S_{2013}, and 121.2±3.5 in S_{2017}, respectively (Fig. 2). There was a significant difference only between RCD in S_{2013} and that in S_{2000} or S_{2017}. Height was significantly higher in S_{2013} than in the other sites except for S_{2010}, and height in S_{2010} was significantly higher than that in the oldest (S_{2000}, S_{2005}) and in the youngest (S_{2017}) sites.

The height of *H. aphyllum* in the current study was within the range of results previously reported for *Haloxylon* species; 170 cm height of *H. aphyllum* in the Gurbantonggut Desert of China (Xu *et al.* 2011) and 15–160 cm of *H. aphyllum* in the Aral region of Kazakhstan (Matsui *et al.* 2019). Breckle (2013) reported that the height of psammophytic vegetation was 100–200 cm, and that of halophytic vegetation was below 100 cm in the Aralkum.

According to Zhu and Jia (2011), the height of *H. aphyllum* increased with the period after plantation in the afforested area in China (2 years to 30 years). Besides, the growth of *Haloxylon* species was related to soil properties such as salinity and nutrient content, and the properties of deeper soil layer had particularly high correlations with the growth of *Haloxylon* species (Matsui *et al.* 2019). However, in the current study, the growth of *H. aphyllum* showed a different tendency from afforestation year and soil properties. The correlation coefficients of RCD and height were not significant with afforestation year (0.05 and 0.46, respectively) and soil properties (−0.68 to −0.18 and −0.29 to 0.31, re-

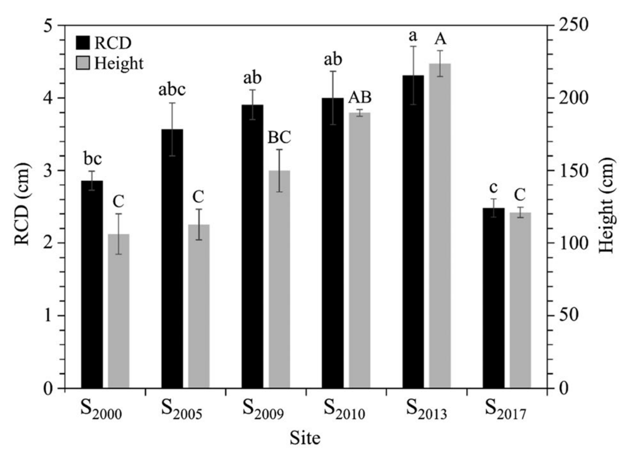

Fig. 2. The root collar diameter (RCD) and height of *Haloxylon aphyllum* in each afforested site. Error bars are the standard errors of the means, and different small and capital letters indicate significant differences in RCD and height, respectively ($p<0.05$).

Table 2. Correlation coefficient (r) of the root collar diameter (RCD) and height of *Haloxylon aphyllum* with afforestation year and soil properties

	Afforestation year	Soil property							
		pH	EC	Ca^{2+} content	K^+ content	Mg^{2+} content	Na^+ content	CEC	Available P
RCD	0.05	−0.18	−0.68	−0.25	−0.42	−0.62	−0.63	−0.32	−0.60
Height	0.46	−0.18	−0.14	0.31	0.06	−0.12	−0.17	0.24	−0.29

EC: electrical conductivity, CEC: cation exchange capacity, Available P: available phosphorus spectively) ($p < 0.05$; Table 2).

Thus, the growth of *H. aphyllum* might be influenced by microclimate variability of the sites such as temperature and precipitation rather than age and soil properties in this region. It was reported that spatial variations in microclimate and soil moisture conditions could influence the growth of *Haloxylon* species (Breckle 2013). Vegetation in some regions is under the influence of severe hot summer, cold winter and low precipitation. Moreover, the study areas are located in northern Aralkum, the region largely affected by dust storms that limit the plant growth (Breckle 2013). The intensity and frequency of dust storms vary spatially and temporally (Spivak *et al.* 2012). Therefore, it seems that there was a great variation in the growth of *H. aphyllum* among sites. Further study is needed to investigate the effect of microclimate on the growth of vegetation in Aralkum.

Density of *H. aphyllum* was 58.1 ± 16.6 in S_{2000}, 164.1 ± 24.1 in S_{2005}, 65.7 ± 6.7 in S_{2009}, 80.8 ± 11.0 in S_{2010}, 116.2 ± 11.0 in S_{2013}, and 108.6 ± 11.0 in S_{2017}, respectively (Fig. 3). The number of *H. aphyllum* in S_{2005} was highest, and was significantly higher than that in S_{2000}, S_{2009}, and S_{2010} in contrast

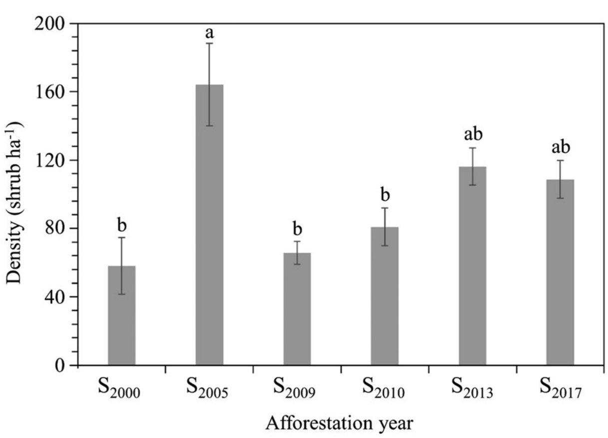

Fig. 3. The density of *Haloxylon aphyllum* in each afforested site. Error bars are the standard errors of the means and different letters indicate significant differences ($p < 0.05$).

to the growth pattern. The number of saxaul may vary among sites due to mortality of originally planted *H. aphyllum* as well as their self-propagation. Mean total biomass accumulation in afforested areas was 20.57 g m^{-2} (AGB: 10.45 g m^{-2} and BGB: 9.93 g m^{-2}), ranging from 2.42 g m^{-2} to 64.53 g m^{-2} (AGB: 1.21−32.98 g m^{-2} and BGB: 1.15−31.38 g m^{-2}) (Table 3). Mean carbon storage in afforested areas was 9.70 C g m^{-2} (AGB: 5.02 C g m^{-2} and BGB: 4.67 C g m^{-2}), ranging from 1.12 C g m^{-2} to 30.61 C g m^{-2} (AGB: 0.58−15.84 C g m^{-2} and BGB: 0.54−14.77 C g m^{-2}) (Table 3). Among the study sites, biomass accumulation and carbon storage were both highest in S_{2013}, and lowest in S_{2000}. Biomass accumulation and carbon storage had a tendency similar to that of height of *H. aphyllum*, despite the exceptionally large density *H. aphyllum* plants at S_{2005} site.

Biomass accumulation and carbon storage estimates for *H. aphyllum* in the current study were smaller than those in other regions in Kazakhstan and in Mongolia. Eisfelder (2017) reported that AGB of shrublands varied from 10 to 300 g m^{-2} in Kazakhstan. Zhaglovskaya (2017) reported that TB was 1,663 g m^{-2} in natural saxaul stand in the Ili River delta area, Kazakhstan. Batsaikhan (2018) reported that biomass of *H. aphyllum* was 35.8 to 290.8 g m^{-2} for AGB and 46.3 to 252.3 g m^{-2} for BGB in southern desert region, Mongolia. Relatively low biomass and carbon storage were akso related to extreme conditions in Aralkum as mentioned above. However, despite lower carbon storage compared to the other regions, Aralkum afforestation increased the vegetation cover and biomass carbon storage of otherwise sparsely vegetated land. Moreover, it was reported that afforested vegetation could increase soil carbon content and storage in saline and dry soil (Hbirkou *et al.* 2011). Thus, total carbon storage in Aralkum might be expected to increase in the long-term.

In the previous studies, various allometric equations for *Haloxylon* species were reported to estimate biomass and carbon storage (Buras *et al.* 2012; Xu *et al.* 2017). However,

Table 3. Biomass accumulation and carbon storage per unit of land area of *Haloxylon aphyllum* afforestation sites

Site	Biomass accumulation (g m^{-2})			Carbon storage (C g m^{-2})		
	AGB	BGB	TB	AGB	BGB	TB
S_{2000}	1.44 (0.40)c	1.36 (0.38)c	2.89 (0.79)c	0.69 (0.19)c	0.64 (0.18)c	1.33 (0.37)c
S_{2005}	5.11 (1.09)bc	4.83 (1.04)bc	10.21 (2.13)bc	2.46 (0.52)bc	2.27 (0.49)bc	4.73 (1.01)bc
S_{2009}	6.07 (0.79)bc	5.76 (0.75)bc	11.97 (1.54)bc	2.91 (0.38)bc	2.71 (0.35)bc	5.62 (0.73)bc
S_{2010}	13.43 (2.14)b	12.76 (2.03)b	26.44 (4.20)b	6.46 (1.03)b	6.00 (0.96)b	12.46 (1.98)b
S_{2013}	32.98 (3.45)a	31.38 (3.29)a	64.53 (6.70)a	15.84 (1.66)a	14.77 (1.55)a	30.61 (3.20)a
S_{2017}	3.92 (0.28)c	3.70 (0.26)c	7.84 (0.55)c	1.88 (0.13)c	1.74 (0.12)c	3.63 (0.25)c

Different letters indicate significant differences (*$p < 0.05$). AGB: above-ground biomass, BGB: below-ground biomass, TB: total biomass the growth of *H. aphyllum* in the current study was different from the other regions by the unique environment of the Aralkum. Thus, to estimate more accurate carbon storage, the site-specific allometric equations should be developed for *Haloxylon* species in the Aralkum.

CONCLUSION

This study investigated the growth and carbon storage of *H. aphyllum* in afforested areas in the Aralkum Desert, Kazakhstan. The growth of *H. aphyllum* varied among afforested sites, and might have been affected by the site microclimate and the strength or frequency of strong wind. Carbon storage estimates of 9.70 C g m^{-2} in total biomass of *H. aphyllum* in afforested areas imply the carbon sequestration through increasing vegetation cover of the desiccated Aral Sea bed. Longer-term monitoring on the Aralkum vegetation growth and further studies on the relationship between *Haloxylon* species and environmental variations are needed.

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Appendix 1. Soil properties in the study sites (An *et al.* unpublished data)

Site	pH	EC (ds m^{-1})	Exchangeable cation content (cmol$_c$ kg^{-1})				CEC (cmol$_c$ kg^{-1})	Available P (mg g^{-1})
			Ca^{2+}	K^+	Mg^{2+}	Na^+		
S_{2000}	8.46	12.89	3.05	0.00	0.16	0.04	3.25	2.21
S_{2005}	8.80	8.75	2.88	0.00	0.11	0.04	3.03	1.99
S_{2009}	8.69	9.76	2.85	0.00	0.12	0.03	3.00	2.19
S_{2010}	8.63	12.59	3.04	0.00	0.11	0.04	3.20	1.62
S_{2013}	8.62	12.23	3.66	0.01	0.15	0.06	3.88	2.27
S_{2017}	8.85	21.09	3.78	0.01	0.18	0.17	4.13	2.67

EC: electrical conductivity, CEC: cation exchange capacity, Available P: available phosphorus

