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Variation in soil carbon stock and nutrient content in sand dunes after afforestation by *Prosopis juliflora* in the Khuzestan province (Iran)

Mostafa Moradi (1), Fatemeh Imani (1), Hamid Reza Naji (2), Sareh Moradi Behbahani (1), Mohammad Taghi Ahmadi (1)

Prosopis juliflora **is one of the suitable tree species used as vegetation cover for sand dunes fixation. The objectives of this study were to determine the effect of** ***P. juliflora*** **afforestation and its canopy coverage classes on soil carbon (C) stock and nutrient status in sand dunes after 22 years since afforestation. We hypothesized that increasing the canopy coverage would result in higher soil C stocks and nutrient content. We selected two 10-ha afforested sand dunes with 25-50% and more than 75% canopy coverage, respectively, and a 10-ha non-afforested dune (control). At each site, 15 soil samples were taken at two depths (0-5 cm and 5-50 cm). The results indicated a strong increase in the topsoil C stock (from 0.54 to 4.49 tC ha^{-1} in control and afforested sites, respectively), while a lower change in subsoil C stock was detected (3.0 and 4.6 tC ha^{-1} in control and afforested sites, respectively). Although, different canopy classes resulted in no significant differences in soil C stock, significant differences were observed for all the soil physico-chemical properties that were studied.**

Keywords: Canopy Coverage, Carbon Stock, Soil Physico-chemical, C/N Ratio

Introduction

Around 80 million hectares of Iran are occupied by arid and semi-arid lands, with five million hectares as active sand dunes (Amiraslani & Dragovich 2011). Therefore, large de-desertification programmes have become necessary. One method to fix sand dunes consists in afforestation (Li et al. 2010). This action not only increased plant coverage and soil nitrogen (N), but also may sequester atmospheric carbon (C) dioxide (Hu et al. 2015, Li et al. 2013). Moreover, vegetation cover of sand dunes has been reported to increase soil moisture (Li et al. 2007) and soil nutrients (Niu et al. 2015) and to restore plant diversity (Bremer & Farley 2010).

Despite the fact that sand dunes afforestation could result in high ecosystem C stock (Garcia-Franco et al. 2014), not all plant species can survive in such a harsh environment (Lal 2004). In fact, water shortage creates a serious limitation for successful plantations (Jackson et al. 2005) even though other factors may also play an important role, *e.g.*, plant species (Zhang et al. 2013), stand age (Sariyildiz et al. 2015), and management (Jones & Donnelly 2004). *Prosopis juliflora* is known as a species with good performance in arid and semi-arid areas for afforestation (Shackleton et al. 2014) and this species has been planted in several parts of Iran. However, the effects of sand dunes afforestation with *P. juliflora* on soil C and nutrients remain still poorly understood, though some preliminary information about the impacts on soil physico-chemical properties have been previously reported (Kahi et al. 2009).

The objectives of this study were to determine the effect of *P. juliflora* sand dunes afforestation on soil C stocks and the nutrient status of afforested sand dunes. In addition, we determined the variation of soil C stock and soil physico-chemical properties under different canopy coverage classes. We hypothesized that increasing the canopy coverage could result in higher soil C stock and nutrient status of sand dunes.

Material and methods

Study site

The study site was located towards the south of Susa and north of Ahvaz at latitude 48° 17′ 16″ N and longitude 31° 37′ 60″ E in Khuzestan province of Iran. This site suffers from active sand dunes mostly covered by *Cyperus rotundus, Pennisetum orientallis, Echinops kermanshahanicus* and *Artemisia vulgaris*. The mean annual temperature and mean precipitation at the site are 23 °C and 251 mm, respectively (Fig. 1); soil can be classified as an Entisol; slopes are between 0 and 2% and altitude between 25 and 49 m a.s.l. The site studied was covered by petroleum mulch in 1991 and an afforestation program with *Prosopis juliflora* started in 1993.

Soil sampling, analysis and carbon stock

We selected two afforested sand dunes (10 ha each) with two levels of canopy cover (25-50% and >75%) and a nearby non-afforested sand dune (10 ha) as control. Canopy coverage was estimated using a dot grid on aerial photography (Carreiras et al. 2006). At each site fifty 20 × 20 m quadrat plots were randomly selected (Baldeck et al. 2013) and five soil samples from four corners and the centre of each plot were taken in April 2015 using a manual auger. The five soil sub-samples were pooled by depth (0-5 and 5-50 cm) and

(1) Department of forestry, Faculty of Natural Resources and Environment, Behbahan Khatam Al-Anbia University of Technology (Iran); (2) Department of Forest Sciences, University of Ilam, Ilam (Iran)

@ Mostafa Moradi (moradi4@gmail.com)

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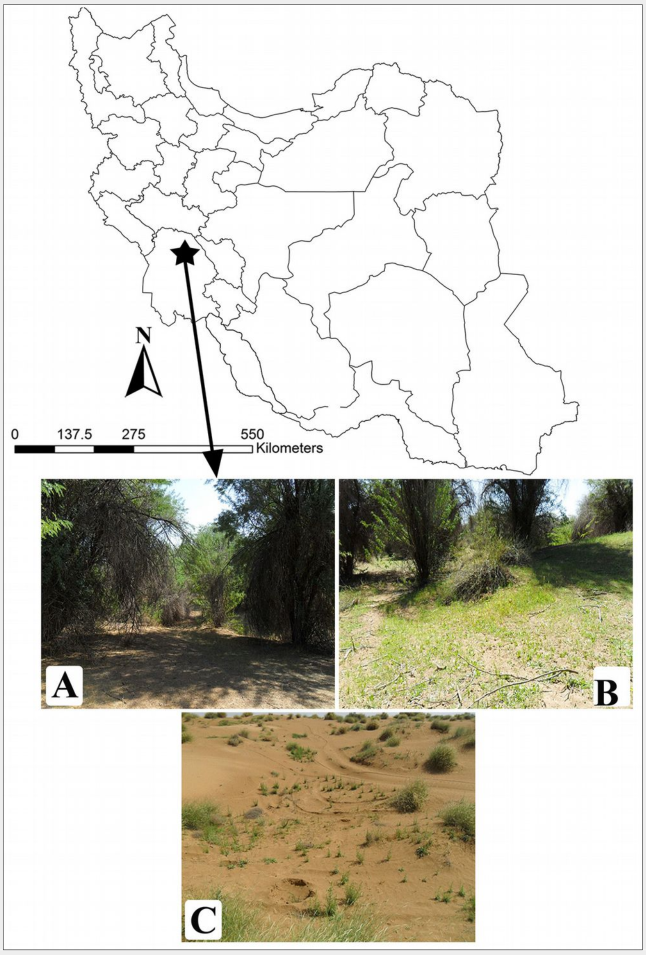

Fig. 1 - Location of the study site and different canopy coverage classes (A: canopy coverage of 25-50%; B: More than 75% canopy coverage; C: control dunes).

plot, and then transferred to the laboratory for the further analyses. The soil C stock (Cs, tC ha^{-1}) was computed using the following equation (Stringer et al. 2015 – eqn. 1):

$$Cs = Bd \cdot d \cdot C$$

where *Bd* is the soil bulk density (g cm^{-3}), *d* is the depth of sampling (cm) and *C* is the soil organic C content (%).

Soil organic C and total N were respectively determined by the methods of Walkley & Black (1934) and Bremner & Mulvaney (1982). Soil potassium (K) and available phosphorus (P) were extracted using ammonium acetate (Morwin & Peach 1951) and Olsen et al. (1954) method. The soil texture was defined using the hydrometric method (Houba et al. 1995). Soil pH and electrical conductivity (EC) in deionized water were measured using the method proposed by McLean (1982).

Statistical analysis

The data were checked for normality and homogeneity of variance using the Kolmogorov-Smirnov test and the Levene's test, respectively. Differences in soil C stock and soil physico-chemical properties between afforested sites and control were tested using a two-way ANOVA followed by LSD test. In addition, Pearson's correlation analysis was used to detect relationships between soil C stock and physico-chemical properties. All analysis were performed using the software SPSS® ver. 15 (IBM, Armonk, NY, USA) for Windows®.

Results

Soil physico-chemical properties

Our result indicated that the interactions between soil depth and canopy classes are significant for soil C stock and physico-chemical properties. The soil texture at a depth of 0-5 cm in the afforestation and control site were respectively sandy-loam and sandy. The soil texture at 5-50 cm was sandy in both the afforestation and control sites. A significant increase of 44 % was observed in topsoil (0-5 cm) silt percentage in afforestation compared to control sites. No significant differences in silt percentage were observed between sites at 5-50 cm depth (Tab. 1). Soil EC was significantly affected by both canopy cover classes and soil depth. The lowest EC value belonged to control dunes, followed by 25-50 % canopy coverage and next 75 % canopy coverage (Tab. 1). Soil pH was significantly decreased in afforestation sites compared to the control dune (Tab. 1). In the afforestation sites, soil P was significantly

Tab. 1 - The ANOVA for soil physico-chemical properties in studied afforestation, control dunes and soil depth. Values followed by the same letters were not significantly different (p>0.05) within rows after LSD test. Values are means ± SE.

Canopy Cover	25-50%		>75%		Control		F-value	P-value
Soil depth	0-5 cm	5-50 cm	0-5 cm	5-50 cm	0-5 cm	5-50 cm		
Silt (%)	10.00 ± 0.65 a	6.00 ± 0.30 bc	10.13 ± 0.66 a	5.07 ± 0.20 c	6.53 ± 0.29 b	5.73 ± 0.12 bc	27.25	0.001
Sand (%)	90.00 ± 0.65 c	94.00 ± 0.30 ab	89.87 ± 0.66 c	94.93 ± 0.20 a	93.47 ± 0.29 b	94.27 ± 0.12 ab	27.25	0.001
EC (d s m^{-1})	1.15 ± 0.07 a	0.81 ± 0.07 b	1.01 ± 0.06 a	0.66 ± 0.02 c	0.40 ± 0.01 d	0.25 ± 0.01 e	47.31	0.001
pH	7.39 ± 0.05 d	7.89 ± 0.09 b	7.63 ± 0.09 c	7.99 ± 0.10 ab	8.11 ± 0.08 ab	8.17 ± 0.04 a	12.34	0.001
P (ppm)	14.07 ± 2.20 a	2.79 ± 0.020 b	10.28 ± 1.70 c	3.82 ± 0.21 c	1.87 ± 0.04 c	1.37 ± 0.06 c	20.91	0.001
K (ppm)	216.33 ± 18.90 a	200.07 ± 10.48 ab	170.00 ± 14.44 b	130.67 ± 4.58 c	109.00 ± 6.46 c	124.60 ± 5.46 c	14.88	0.001
N %	0.04 ± 0.00 b	0.04 ± 0.01 b	0.06 ± 0.00 a	0.04 ± 0.01 b	0.02 ± 0.00 c	0.03 ± 0.00 bc	4.42	0.001

Tab. 2 - The ANOVA for carbon stock and C/N in afforestation, control sand dunes and soil depth. Values followed by the same letters were not significantly different (p>0.05) within rows after LSD test. Values are means ± SE.

Canopy Cover	25-50%		>75%		Control		F-value	P-value
Soil depth	0-5 cm	5-50 cm	0-5 cm	5-50 cm	0-5 cm	5-50 cm		
SOC (tC ha^{-1})	4.15 ± 0.39 a	4.91 ± 0.30 a	4.50 ± 0.29 a	4.64 ± 0.31a	0.54 ± 0.04 c	3.03 ± 0.17 b	36.69	0.001
C/N	12.93 ± 0.65 a	2.48 ± 0.28 cd	10.66 ± 1.03 b	2.30 ± 0.39 cd	3.56 ± 0.45 c	1.42 ± 0.11 d	74.34	0.001

higher at both soil depths compared to the control dune. The lowest soil K was observed in the control dunes for both depths as afforestation resulted in a significant increase in soil K (Tab. 1). Although the soil N values in studied sites were low, afforestation led to significant soil N increase in topsoil (0-5 cm) compared to the control dunes, with >75% canopy coverage sites having the highest N levels in topsoil. In deeper soil depth, no significant difference was observed between afforestation and control dunes (Tab. 1).

Soil C stock in afforested and control dunes

Topsoil C stock (SOC) showed an increasing trend from 0.54 to 4.50 tC ha^{-1} in control to afforestation dunes (Tab. 2). Despite the significantly higher carbon stock in afforested areas, no significant differences were observed between the two canopy classes (Tab. 2). The same SOC patterns related to afforestation were observed at the deeper soil depth and no significant difference was observed between the soil depths studied in afforested dunes (Tab. 2).

The lowest C/N ratio belonged to the subsoil (5-50 cm) in control dunes, and the highest value belonged to topsoil in the 25-50 % canopy class (Tab. 2). Furthermore, the C/N ratio decreased with soil depth in both afforestation and control sites (Tab. 2).

The soil pH and sand content in topsoil showed significant negative correlations with C stock, while positive correlations between soil C stock and all other studied parameters were observed. (Tab. 3).

Considering the significant correlations between soil silt and the rest of soil parameters, C/N and silt were important in determining soil physico-chemical properties of sand dunes in topsoil (Tab. 3).

Unlike the topsoil, soil C stock in subsoil significantly correlated with only soil P, EC and C/N ratio. Additionally, C/N ratio was positively and significantly correlated with soil EC and silt and negatively with soil N and sand (Tab. 4).

Tab. 4 - Correlations between soil carbon stock, C/N and soil physico-chemical properties at 5-50 cm soil depth. (*): p<0.05 (2-tailed); (**): p<0.01 (2-tailed).

Soil property	SOC	C/N	Silt	Sand	EC	pH	P	K	N
SOC (tC ha^{-1})	1	-	-	-	-	-	-	-	-
C/N	0.35*	1	-	-	-	-	-	-	-
Silt (%)	0.03	0.31*	1	-	-	-	-	-	-
Sand (%)	-0.03	-0.31*	-1.00**	1	-	-	-	-	-
EC (d s m^{-1})	0.38*	0.40**	-0.30*	0.30*	1	-	-	-	-
pH	-0.27	-0.17	0.17	-0.17	-0.26	1	-	-	-
P (ppm)	0.38**	0.09	-0.54**	0.54**	0.72**	-0.16	1	-	-
K (ppm)	0.25	0.03	-0.03	0.03	0.24	-0.01	0.27	1	-
N (%)	0.24	-0.56**	-0.37*	0.37*	0.01	-0.01	0.33*	0.30*	1

Tab. 3 - Correlations between soil carbon stock, C/N and soil physico-chemical properties at 0-5 cm soil depth. (SOC): soil carbon stock (tC ha^{-1}); (EC): electrical conductivity; (P): phosphorus; (K): potassium; (N): nitrogen; (**) p<0.01 (2-tailed).

Soil property	SOC	C/N	Silt	Sand	EC	pH	P	K	N
SOC (tC ha^{-1})	1	-	-	-	-	-	-	-	-
C/N	0.80**	1	-	-	-	-	-	-	-
Silt (%)	0.71**	0.54**	1	-	-	-	-	-	-
Sand (%)	-0.71**	-0.54**	-1.00**	1	-	-	-	-	-
EC (d s m^{-1})	0.77**	0.71**	0.59**	-0.59**	1	-	-	-	-
pH	-0.72**	-0.57**	-0.54**	0.54**	-0.65**	1	-	-	-
P (ppm)	0.70**	0.58**	0.52**	-0.52**	0.73**	-0.57**	1	-	-
K (ppm)	0.69**	0.53**	0.45**	-0.49**	0.70**	-0.53**	0.74**	1	-
N (%)	0.73**	0.25	0.54**	-0.54**	0.54**	-0.52**	0.49**	0.53**	1

Discussion

Afforestation with *P. juliflora* increased soil C content to a depth 50 cm compared to control dunes. This is consistent with predictions for nitrogen fixing trees like *P. juliflora* (Resh et al. 2002), and with the results of Hu et al. (2015).

Although canopy coverage class did not have any significant effect on soil C stock, our results showed a slight increase in soil C stock with higher canopy coverage. This pattern is consistent with Schulp et al. (2008) who stated the importance of overstory on soil carbon input. Overstory can change light penetration and moisture content (Buck & St Clair 2012), which can in turn affect soil C stock (Dorfer et al. 2013). Additionally, tree spacing and canopy closure influence temperature, moisture, litter, and consequently change decomposition rate and soil C stock (Paul et al. 2002).

As in Garcia-Franco et al. (2014), afforestation in the current study resulted in a higher soil C/N ratio. Changes in soil N with change in land use from sand dunes to afforested area was also seen by Li et al. (2016a). Increased soil N in the sand dunes after afforestation is likely responsible for increasing soil carbon sequestration (Grunzweig et al. 2007). Higher C/N ratio and also C stock at the topsoil in sand dunes indicated the importance of this thin soil layer in C sequestration of arid lands (Nadal-Romero et al. 2016).

Canopy coverage is known as an important factor influencing topsoil nutrients (Johnson et al. 2016). Significant effects of canopy coverage and litter input on soil N and C have been previously observed in topsoil (Conti et al. 2016). This may be due to the higher litter fall in higher canopy coverage class (Arriaga & Maya 2007). Similar results were observed in EC and pH, indicating the significance of canopy coverage and afforestation on the parameters stated, which is consistent with the study of Naseri et al. (2012). Likewise, decrease in EC with soil depth was seen by Li et al. (2010).

Soil K and P were previously shown to be significantly affected by afforestation, with an increasing trend from bare to afforested dunes (Li et al. 2016b). This might be related to the soil pH reduction providing better conditions for these two nutrients availability in soil (Moradi et al. 2015). Soil texture has been reported among the factors strongly affecting the soil carbon dynamic (Paul et al. 2002). In our study, the soil silt and sand respectively had positive and negative correlations with soil C stock, which could be due to longer residence time of soil organic carbon in silt (Dobarco & Van Miegroet 2014). Improvement of soil physico-chemical properties and soil C stock after two decades of afforestation demonstrates the remarkable importance of *P. juliflora* in the parameters studied and long term fixation of sand dunes.

Soil fertility and organic carbon were important factors on C stock in arid lands, as soil C stock and physico-chemical properties highly correlated (Garcia-Franco et al. 2014). However, afforestation resulted into soil pH decreasing from alkaline toward neutral. Soil pH negatively affected on the C stock. Considering these two, we could conclude that soil pH declines after afforestation and prevents carbon loss to the atmosphere (Shi et al. 2012).

Conclusion

P. juliflora afforestation in sand dunes resulted in higher soil C stock. Higher C stock in topsoil and high level of correlation between soil C stock and almost all soil physico-chemical properties studied, especially in topsoil, indicated the importance of soil features in soil C stock of arid lands. Furthermore, canopy coverage is considered a factor affecting soil N, which consequently resulted in higher soil C stocks in sand dunes of Iran.

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