frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 21 November 2022
DOI 10.3389/fenvs.2022.901962

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SPECIALTY SECTION
This article was submitted to Drylands, a section of the journal Frontiers in Environmental Science

RECEIVED 22 March 2022
ACCEPTED 01 November 2022
PUBLISHED 21 November 2022

CITATION
Ebrahimi M and Saberi M (2022), The relationship between succession and reclamation of desertified areas in artificial forests of *Calligonum* spp. in an arid desert of southeastern Iran.
Front. Environ. Sci. 10:901962.
doi: 10.3389/fenvs.2022.901962

The relationship between succession and reclamation of desertified areas in artificial forests of *Calligonum* spp. in an arid desert of southeastern Iran

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This research investigates the association between the succession and restoration of degraded land in the southeast of Iran with artificial *Calligonum* forests regarding vegetation changes, soil properties, carbon (C) and nitrogen (N) pools in vegetation and soil. Eight forestry sites were selected, aged 1, 4, 6, 9, 11, 16, 25, and 30 years. Observations indicated that vegetation percentage, density, frequency, richness, and diversity of species substantially increased ($p < 0.01$). The highest percentage of vegetation (80.30%), density (62.70 n ha^{-1}), richness (14.15), and diversity (0.90) was observed in the 30-year site. At the end of the succession phase under study (the 25- and 30-year sites), the variation trend of vegetation was steady. As the age of the forests increased, the soil nutrient values increased significantly during succession ($p < 0.01$), even though acidity and electrical conductivity (EC) did not change significantly over time ($p > 0.01$). In the early stages of succession, the soil's C and N pools (aerial biomass, root, and litter) did not increase significantly ($p > 0.01$). Over time, however, C and N pools of the soil and plants increased (the highest amounts were seen in the 30-year site). The results indicated a significant difference in the soil and vegetation properties in the forestry sites. In general, planting native species and the succession of vegetation can play an effective role in preserving the environment in degraded lands and increasing the C and N pools.

KEYWORDS

arid rangelands, vegetation succession, species richness, carbon pool, soil degradation

Introduction

The Iranian Plateau's arid and semi-arid regions' climatic characteristics have led to sensitive and fragile conditions. In these areas, soil erosion and desertification are among the processes directly or indirectly threatening water and soil resources strongly. The restoration of vegetation in degraded rangelands can have a considerable effect on reducing soil erosion and preventing further land degradation (Ebrahimi et al., 2019).

Accordingly, forestry plans have been conducted throughout Iran to revive desert rangelands and degraded lands (Rigi Pardad et al., 2021).

Forestry practices in Iran involve covering the soil surface using plant species adaptable to arid climatic conditions. For instance, several species, such as *Calligonum polygonoides*, L., *C. bungei* Boiss, and *C. comosum* (L`Her), have been widely cultured for forestry and desertification control (Amiraslani and Dragovich, 2011; Rigi Pardad et al., 2021). However, cultivating native, non-native, and adaptable species in arid lands to revive vegetation requires a great deal of analysis and assessment (Ebrahimi et al., 2019). These programs should study the effect of cultivated species on the soil and vegetation where they are planted. Selecting the appropriate species for forestry to revive vegetation and conserve soil and water resources are the main components of forestry (Hashemi Rad et al., 2018). Plants affect soil by altering its physical and chemical properties. The soil properties and food reserves strongly depend on the type of vegetation (Rigi Pardad et al., 2021).

Programs for restoring vegetation in arid areas have multiple objectives: creating secondary succession (Ebrahimi et al., 2019; Udayana et al., 2019), curbing wind and water erosion, improving soil quality and fertility, increasing carbon (C) and nitrogen (N) storage in aerial and below-ground plant biomass, cleaning the air, reducing greenhouse gases, and ultimately increasing the plant production. Therefore, restoring vegetation can play a substantial role in sustainable development and ecosystem health (Cao et al., 2011; An et al., 2019; Udayana et al., 2019; Hu et al., 2020). Given the insufficient precipitation in arid areas and the subsequent lack of plant biomass, increasing biomass volume by cultivating adaptable plants can boost the ecosystem's power to elevate C and N pools in the soil, reinforce vegetation and soil, and contribute to C and N sequestration (UNDP, 2000; Ritchie, 2020; Tessema et al., 2020).

CO_2 and NO are among the most well-known greenhouse gases, whose atmospheric concentration increases due to increased industrial activities, leading to abnormal global warming and depletion of the Earth's ozone layer (Conant et al., 2017; Hashemi Rad et al., 2018). The slightest change in the amount of C and N pools increases the amount of atmospheric C and N levels (Chapuis-Lardy et al., 2007; Hu et al., 2020; Tessema et al., 2020; Yang et al., 2020). Accordingly, the global community entered into the Kyoto Treaty in December 1997 in an extensive effort to reduce greenhouse gas emissions. One of the stressed ideas in this treaty is the attempt to reduce the atmospheric levels of greenhouse gases by preserving and creating vegetation and sequestration of C and N (Mehdipour et al., 2007; Rigi Pardad et al., 2021). C and N sequestration refers to a set of processes in which additional atmospheric concentrations of C and N are captured and stored in plant biomass and soil (Rigi Pardad, 2021). Semi-arid and arid rangelands are a great option for C and N sequestration. Moreover, increasing biomass in these areas has several advantages by reducing sequestration costs. With these advantages, international organizations such as the FAO and the UNDP have selected these areas as sites for implementing C sequestration programs (Veramesh et al., 2010). In preliminary studies in Iran, the UNDP reported that the C sequestration volume by forestry in arid and desert rangelands predominantly vegetated with *Haloxylon* spp equals 14 ton ha^{-1} after 20 years, reaching 21 ton ha^{-1} in 50 years by proper management (Abedi et al., 2008).

Arid rangelands have excellent potential for storing C and N (Conant et al., 2017; Tessema et al., 2020). Studies on the changes in C and N pools in arid rangelands cultivated with woody plants indicate that compared to other lands, arid rangelands display a significant increase in C and N pools due to biological reactions (Ritchie, 2020; Tessema et al., 2020). This increase can be attributed to the direct relationship between fluctuations in biomass generation with C and N pools in a region and the influential role of related management models (Tessema et al., 2020). Shams Abad is a desert region and one of the prominent locations known for wind erosion in Sistan and Baluchestan, Iran. Large parts of Shams Abad have been cultivated with perennial species, leading to considerable changes in the local ecosystem. Nonetheless, research on the effect of forestry in Iran's degraded and desert regions on conserving biodiversity, soil properties, and C and N pools is rare.

This study was carried out to find out how afforestation changed the vegetation cover and the C and N pools of plant-soil in the vegetation communities in the arid desert steppe of Iran. We aimed to evaluate the plant variety and richness of afforestation succession in the arid area of southeastern Sistan and Baluchestan, Iran, and to investigate the influence of afforestation on native plant species, *C. polygonoides* L., *C. bungei* Boiss and *C. comosum* L`Her., on plant-soil C and N reservoirs. Our hypothesis is that 1) *Calligonum* planting aids in the development of plant species and soil fertility, and 2) soil fertility in the initial phase does not change significantly compared to the middle phase.

Material and methods

Study area

The artificial forests in the Shams Abad Desert (between latitude 27°9′31″–27°29′10″N and between longitude 60°10′32″–60°37′19″E), Sistan and Baluchestan, Iran, were selected as the study site, with an area of 112,350.30 ha (Figure 1). With less than 80 mm of annual rainfall, the area has a hot and dry environment. There have been drastic variations in rainfall over the years. Extreme rainfall volatility leads to severe instabilities of annual fodder production. A large portion of rainfall occurs during December, January, and

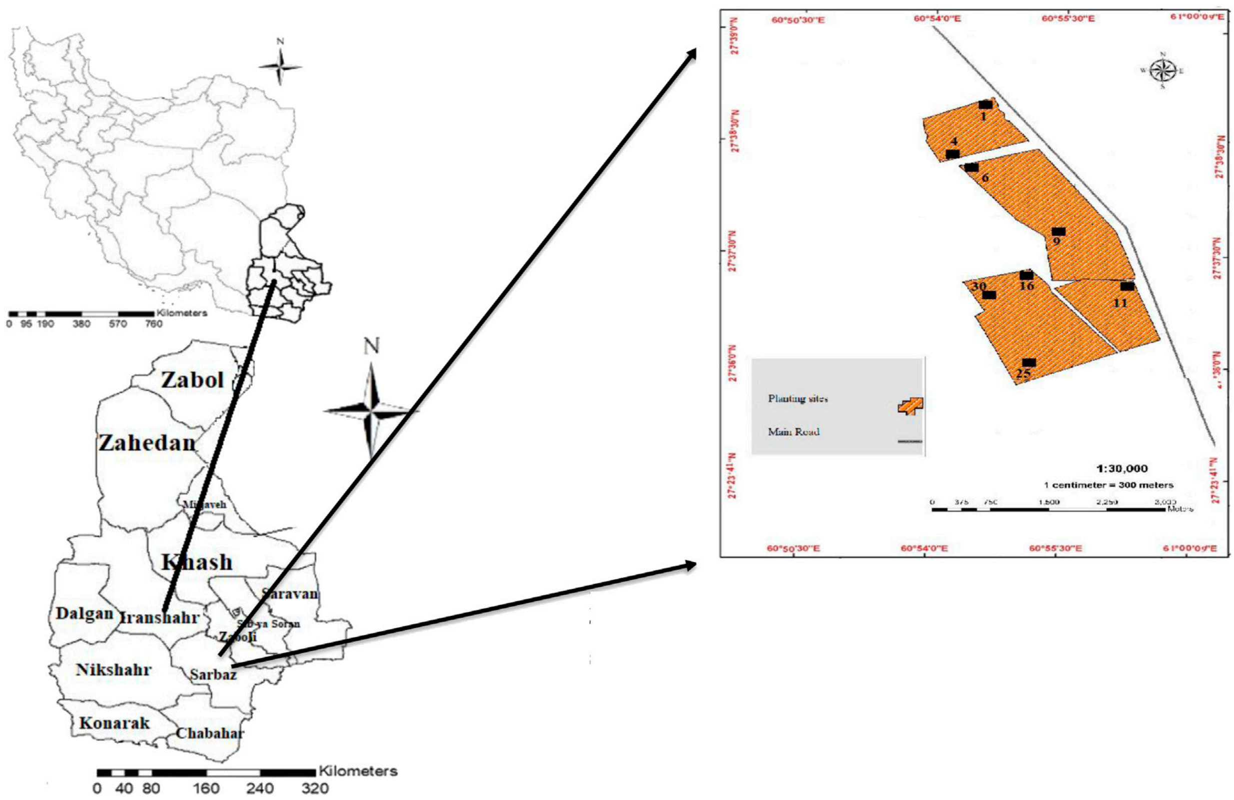

FIGURE 1
Sampling sites in the Shams Abad artificial forest, Iran. The black squares indicate the sampling sites, and the numbers below the squares indicate the ages of the sites.

February in the form of rainstorms, leading to torrents as water cannot penetrate the soil due to the region's light soil texture and lack of vegetation. In other months, especially during spring and summer, the region suffers absolute aridity, a condition where only deep-rooted plants with extensive roots capable of maintaining their relationship with in-depth soil moisture can survive. It is only natural that under such conditions, the seedlings of native plants, which experience significant growth following the generous winter rainfalls, stop growing as they are deprived of access to the moisture below the surface when the rainfalls stop and cause the soil to lose its surface moisture. The seedlings thus shrivel and perish in hot weather and summer aridity. Thus, it is challenging to replace native plants perishing due to various factors. The average temperature of the area is 30°C. The minimum and maximum temperature the region experiences is −8°C and 57°C, respectively, recorded in December and July. On most summer days, the temperature exceeds 50°C, hampering any form of vital plant activities for a relatively long period. In addition to rainfall and temperature, winds and storms are factors that can restrict vegetation (Report of Rangeland Improvement, 2018).

The assessment of forestry area

In this study, the selected forestry sites were cultivated with the following species: *C. polygonoides* L., *C. bungei* Boiss, and *C. comosum* (L`Her). The species were aged 1, 4, 6, 9, 11, 16, 25, and 30 years. The vegetation was thoroughly analyzed in a specific 1-ha area in each site. In March 2019, data were gathered using a randomized complete block design (RCBD). The plant species were identified and named in the Botany Laboratory of the University of Zabol. The identified plants and assigned nomenclatures were matched with those in the studies by Rechinger et al. (1984), Rechinger et al. (1988). The chorotype of plants was matched with that in the study by Zohary (1963). Low-age sites (1, 4, 6, and 9 years) were protected against livestock grazing. However, livestock grazing was permissible in sites aged 11, 16, 25, and 30 years (sheep and goats). A total of 40 sample stands with 100 m × 100 m dimensions were selected to determine the changes in plant populations (five stands were assigned to each site). Quadrats (2 m × 3 m, 5 m × 5 m, 5 m × 5 m, 6 m × 6 m, 8 m × 8 m, 10 m × 10 m, 15 m × 15 m, 20 m × 20 m for 1, 4, 6, 9, 11, 16, 25, and 30 ages, respectively) were used to measure vegetation characteristics in each stand along 100-m transect lines by the systematic random sampling method (75 quadrats per stand). In general, 120 transects were sampled. The distance between the transect lines was 10 m.

The visual estimation method was used to estimate the percentages of vegetation and bare soil. The number of species in a sampled area was used to calculate the density of species (Ebrahimi et al., 2016). The relative density factors (RD), relative cover factors (RC), and relative frequency factors (RF) were used to compute the importance values (IV) of species. The characteristics of a dominant plant species may be derived from these characteristics. The relative density of a plant species is the ratio of its density to the overall density. An area or sample of vegetation may be defined as having a relative cover of a certain species in proportion to the cover of total plant species. Species frequency as a percentage of total plant cover is known as the relative frequency (Khosravi et al., 2017). Species richness was estimated by quantifying species per quadrate.

The formula $H' = -\sum_{i=1}^{s} pi \cdot lnpi$ was used to determine the plant species' diversity. In this formula, pi is the percent of points in a line where plant species i was found (Khosravi et al., 2017). Pielou's J index ($H'/\ln S$) was used to measure evenness, where S is the number of species that were sampled in each quadrat.

Plant C and N pools measurement

In each age class, inside the quadrate, the aerial parts (stems and leaves) related to the growth of the current year's *Calligonum*, related species, and all the litters under the canopy cover were extracted. To ensure minimum degradation of vegetation, plant species were collected in three quadrats in each age class. At 45-cm soil depth in each quadrate, below-ground biomass was collected using the root auger (25 cm diameter). The samples were spread on a tray to remove the soil around the roots. In each age class, all aerial organs, roots, and litters were dried (70°C for 48 h) to determine dry mass. Total plant N was measured using the modified Kjeldahl method (Bremner, 1996), and organic plant C was measured using the method of Nelson and Sommers (1982).

Measuring soil properties

Soil samples at 45-cm depth were collected from under the shrubs' canopy cover. At the same time, biomass samples were collected from roots and the lines between the shrubs (10–15 m distance) inside the quadrates. In case the quadrats had no shrubs, the plants nearest to the quadrats were selected. In each age class, a total of 15 soil samples were collected at random. A 2-mm sieve plate was used to separate soil samples that had been air-dried.

The laser diffractometry method (LDM) was used to determine the soil texture (Wang et al., 2012). The saturated soil-paste method (Thomas, 1996) was used to determine the acidity (pH) using a pH meter. The EC was measured using an EC meter (Rhoades, 1996). Total nitrogen (N) was measured using the Kjeldahl method (Bremner, 1996). The available phosphorus (P) was determined using the Olsen method *via* a spectrophotometer (Bray and Kurtz, 1954). The available potassium (K) was measured using a flame photometry device (Knudsen et al., 1982). Soil organic matter (OM) was measured based on the method of Lo et al. (2011), and the bulk density (BD) of soil was measured using the volumetric ring method (Wu et al., 2010). The soil organic C pool was determined using the equation: $Cp = BD \times SOC \times D$ (Deng et al., 2013; Wang et al., 2014). In this equation, Cp is the soil organic C pool (kg m^{-2}), BD (g cm^{-3}) denotes the bulk density of the soil, SOC is an abbreviation for soil organic C content (g kg^{-1}), and D (cm) denotes the thickness of the soil layer tested. The soil N pool was calculated using the following equation: $Np = BD \times TN \times D$ (Deng et al., 2013; Wang et al., 2014). In this equation, Np (kg m^{-2}) is the soil N pool, BD (g cm^{-3}) is soil bulk density, and TN (g kg^{-1}) is the total soil N content.

Data analysis

After studying the outlier values, verifying normal distribution, and testing homogeneity of variance, data analysis was conducted with a randomized complete block design (RCBD) in SPSS (Ver. 20.0) to investigate any significant difference among the age groups. To compare mean pairs, Duncan's multiple range test (DMRT) was used. The values of indexes, including richness, evenness, and diversity, were calculated using the PAST data analyzer. The main trends in reclamation ages were described by fitting polynomial functions to vegetation indices using the curve fit feature in the SPSS (Ver. 20.0) software package.

Results

Vegetation changes

In the study sites, 15 plant species, including ten families and three genera, were listed (Table 1). The maximum number of plant species (15 species, Figure 2A), genera (13 genera, Figure 2B), and family (ten families, Figure 2C) was in the 25- and 30-year age classes. The lowest number of species (five species, Figure 2A), genus (three genera, Figure 2B), and family (three families, Figure 2C) was related to the age class of 1 year. The highest frequency was, respectively, seen in *Polygonaceae* (20%), *Amaranthaceae* (20%), and *Fabaceae*

TABLE 1 Plant species composition in the eight study areas (1, 4, 6, 9, 11, 16, 25, and 30 years after afforestation).

Species	Family	Growth form	Life history	Chorotype	1 year		4 years		6 years		9 years		11 years		16 years		25 years		30 years	
					Presence/ Absence	IV (%)	Presence/ Absence	IV (%)	Presence/ Absence	IV (%)	Presence/ Absence	IV (%)	Presence/ Absence	IV (%)	Presence/ Absence	IV (%)	Presence/ Absence	IV (%)	Presence/ Absence	IV (%)
Hammada salicornica (Moq.) Iljin	*Amaranthaceae*	Ph	P	IT-SA	1	31.57	1	12.31	1	33.18	1	37.39	1	27.48	1	29.31	1	30.49	1	44.48
C. polygonoides L.	*Polygonaceae*	Ph	P	IT-SS	1	32.40	1	40.00	1	60.10	1	65.59	1	69.10	1	72.13	1	75.10	1	77.10
Calligonum bungei Boiss.	*Polygonaceae*	Ph	P	IT-SS	1	34.14	1	39.11	1	51.19	1	66.59	1	76.10	1	79.12	1	80.19	1	82.24
Calligonum comosum L'Hér.	*Polygonaceae*	Ph	P	IT-SS	1	33.26	1	42.28	1	50.43	1	67.59	1	74.25	1	76.15	1	79.20	1	80.25
Prosopis cineraria (L.) Druce	*Fabaceae*	Ph	P	SS	1	27.34	1	30.07	1	1.23	1	35.07	1	33.34	1	35.12	1	35.30	1	40.21
Ziziphus spina-christii (L.) Willd.	*Rhamnaceae*	Ph	P	SS	0	0	1	3.32	1	4.27	1	3.32	1	3.32	1	4.77	1	5.30	1	12.67
Tamarix macrocarpa (Ehrenb.) Bge.	*Tamaricaceae*	Ph	P	IT-SS	0	0	0	0	0	0	1	23.44	1	1.83	1	5.10	1	5.75	1	10.83
Periploca aphylla Decne.	*Asclepiadaceae*	Ph	P	SS	0	0	0	0	0	0	1	2.19	1	2.19	1	3.42	1	14.89	1	20.21
Peganum harmala L. PEGHA.	*Nitrariaceae*	F	P	IT-M-SS	0	0	0	0	0	0	1	3.44	1	11.23	1	10.23	1	29.91	1	29.13
Alhagi camelorum Fisch. ex DC	*Fabaceae*	Sh	P	IT	0	0	0	0	0	0	1	6.12	1	12.33	1	9.21	1	19.78	1	20.33
Suaeda fruticosa (L.) Forssk.	*Amaranthaceae*	Sh	P	IT-SS-SA	0	0	0	0	0	0	0	0	0	0	1	2.78	1	16.76	1	18.11
Gymnocarpus decandrus Forssk.	*Caryophyllaceae*	Sh	P	SS	0	0	0	0	0	0	0	0	1	6.19	1	7.00	1	15.43	1	16.22
Rhazya stricta Decne.	*Apocynaceae*	Sh	P	IT-SS-M	0	0	0	0	0	0	0	0	0	0	1	3.21	1	13.18	1	14.22
Chenopodium album subsp. L.	*Amaranthaceae*	F	A	C	0	0	1	2.44	1	5.78	0	0	0	0	0	3.45	1	21.99	1	23.42
Tribulus terrestris L.	*Zygophyllaceae*	B	A	PR	0	0	1	4.76	1	5.23	1	5.44	0	0	0	6.12	1	13.10	1	15.67

P, perennial; A, annual; Ph, phanerophyte; F, forb; Sh, shrub; B, bush.

1 and 0 indicate the presence and absence of a plant species, respectively.

M, Mediterranean; SA, Saharo-Arabian; C, Cosmopolitan; IT, Irano-Turanian; SS, Sahara-Sindian; PR, poly regional (Pontic and Irano-Anatoli, Irano-Touranian, Europe-Siberian, and Mediterranean).

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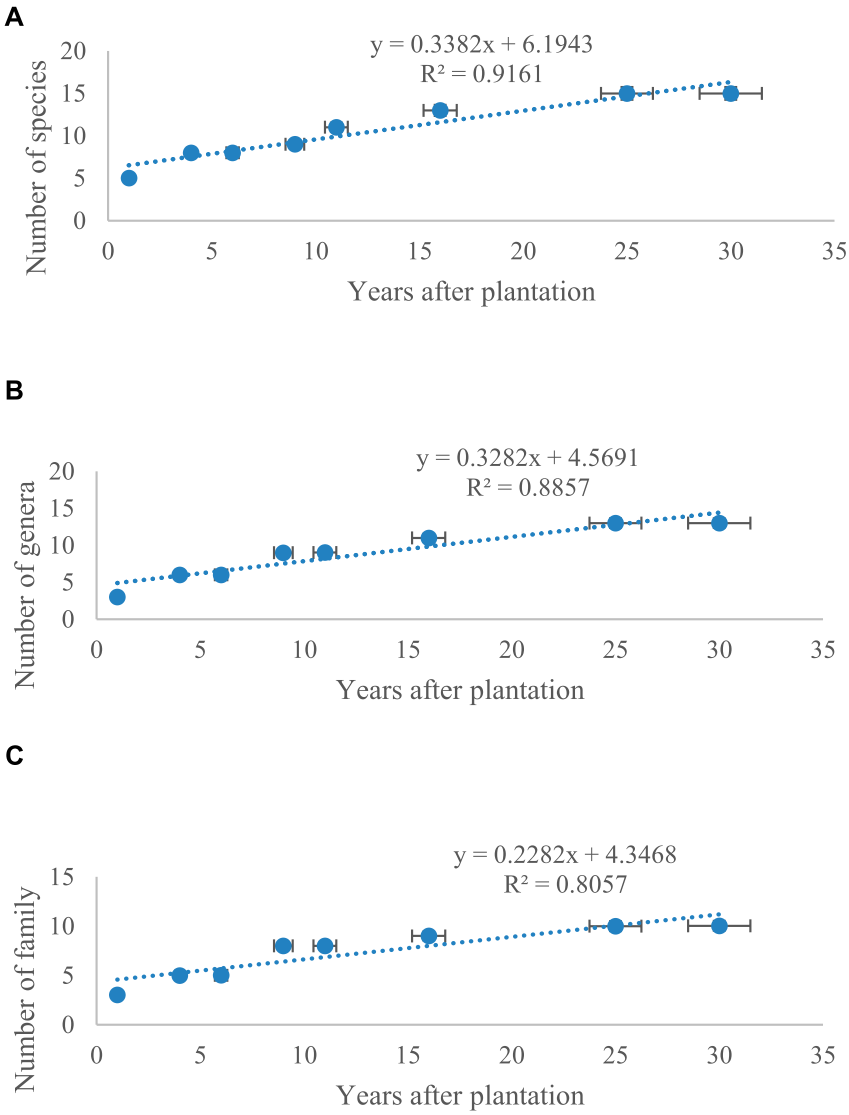

FIGURE 2
Variations of vegetation properties in the eight *Calligonum* planting sites. **(A)** Number of species, **(B)** genera, and **(C)** families. Vertical bars show standard errors.

(13%) families. Most species were perennials (86.66%). Annuals had an insignificant share (13.33%) in the forestry sites. A chorological study (Table 1) showed that the largest proportion of the flora belongs to the Sahara-Sindian elements (60%), followed by Irano-Turanian (20%) and Saharo-Arabian (15%).

According to importance value (IV), the following species were predominant in all sites: *C. polygonaides*, *C. Bungei*, and *C. comosum*, and with the increasing age from 1 year to 30 years, vegetation cover (Figure 3A) and density (Figure 3B) displayed an ascending trend.

The maximum and minimum percentage of vegetation cover was seen in the 30-year site (80.30%) and the 1-year site (30.90%), respectively (Figure 3A). Vegetation percentage had an almost constant trend from the 16-year site to 30-year site.

The density of species increased from 22.30 n ha^{-1} in the 1-year site to 62.70 n ha^{-1} in the 30-year site (Figure 3A). The density of species in the 25- and 30-year sites displayed a steady trend. In lands cultivated with *Calligonum*, the bare soil (Figure 3C) decreased significantly over time (p < 0.01). The highest amount of litter was seen in the 30-year age class. The results indicated that cultivating *Calligonum* significantly elevated the diversity (Figure 3D) and richness (Figure 3E) of species in the region (p < 0.01).

In contrast, evenness (Figure 3F) did not change significantly in the age classes in the study (p > 0.01). The 30-year age group

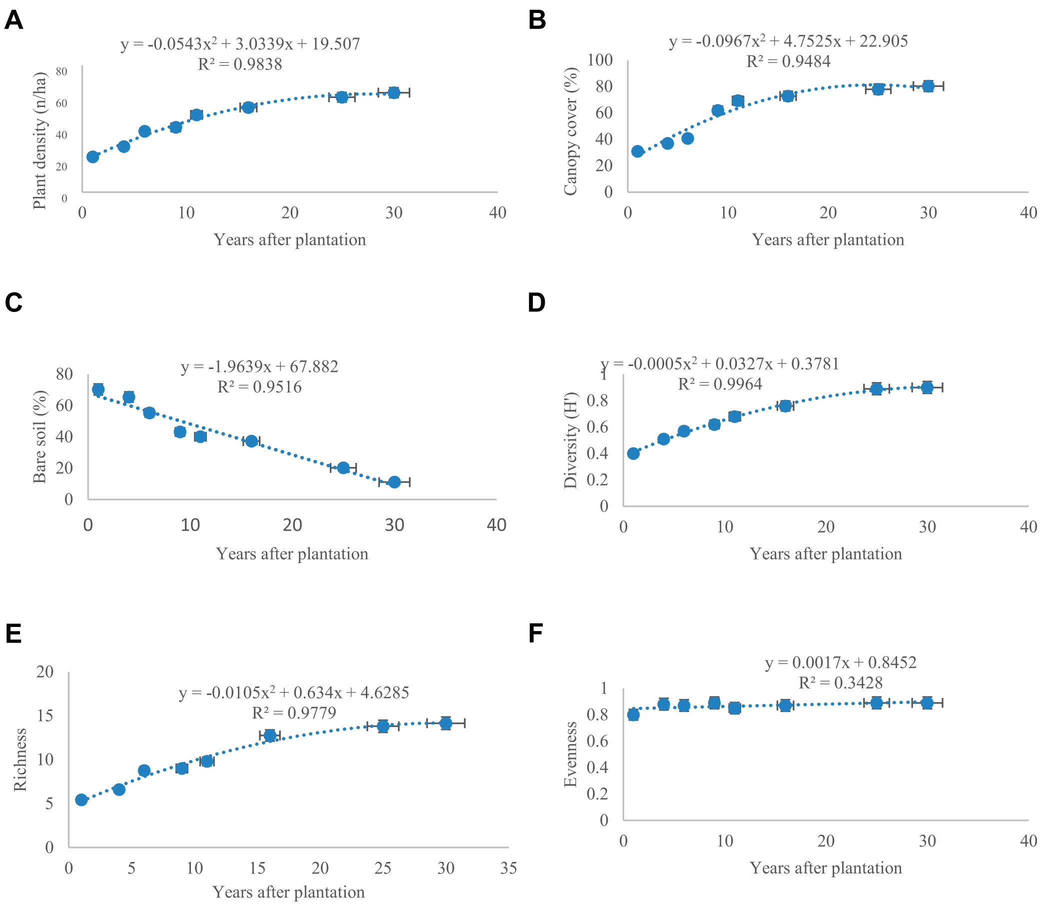

FIGURE 3
Vegetation characteristics in the eight *Calligonum* planting sites. **(A)** Plant density, **(B)** canopy cover, **(C)** bare soil, **(D)** diversity (H′), **(E)** richness, and **(F)** evenness. Vertical bars show standard error.

displayed the highest diversity (0.9) and richness (14.15). The 9- and 11-year age classes did not differ significantly ($p > 0.01$) in terms of richness and diversity, indicating that restoring vegetation in arid regions with harsh climatic conditions is time-consuming. Vegetation in disturbed land prone to wind erosion excellently responded to biological restoration with significant changes, thus confirming the primary hypothesis of the study.

Soil properties changes

Changes in soil properties and C and N pools in artificial forests re-vegetated with *Calligonum* in the period of 1–30 years have been shown in Table 2. Our findings showed that soil acidity changes were insignificant ($p > 0.01$). The results indicated that EC under and between the canopy cover did not change significantly over time ($p > 0.01$), despite the lower EC between the canopy cover of *Calligonum* plants compared to the inter-canopy cover of plants mass, indicating a significant difference ($p < 0.01$). Over time, as the re-vegetated forests aged, soil fertility factors including organic matter, N, P, and K increased significantly ($p < 0.01$). The lowest recorded amounts of organic matter, N, P, and K were observed at the initial phase (1-year) of restoration. The highest values of the parameters were recorded at the end of the period. The amount of soil organic matter in the 30-year site was approximately 3.09 times (under the canopy cover of *Calligonum*) greater than the beginning of the succession phase (1-year). At the end of the phase, the N, P, and K levels were 12, 6.44, and 6.84 times greater than those at the beginning of the succession phase. The level of the N pool followed the same pattern. N and C pool levels were the highest amounts underneath the *Calligonum* canopies in the area that underwent succession for 30 years than in the area that underwent treatment of 1-year. Moreover, the changes in the C and N pool levels were not significant among the 1- and 4-year

TABLE 2 Characteristics of soil under canopy (UC) and inter canopy (IC) in the eight *Calligonum* planting sites.

Planting age		OM (%)	N (g kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	ECe (dSm^{-1})	pH	CaCO3 (g kg^{-1})	C pool (ton ha^{-1})	N pool (ton ha^{-1})	Texture
1	UC	3.00 ± 0.01^{Aj}	0.10 ± 0.01^{Al}	2.22 ± 0.01^{Ak}	80.50 ± 9.98^{An}	5.00 ± 0.01^{Aa}	8.00 ± 0.50^{Aa}	383.50 ± 3.50^{Aa}	2.00 ± 0.01^{Ac}	0.80 ± 0.01^{Af}	Sandy
	IC	2.10 ± 0.01^{Bk}	0.10 ± 0.01^{Al}	2.00 ± 0.01^{Bk}	55.43 ± 9.98^{Bo}	4.00 ± 0.01^{Ab}	8.00 ± 0.53^{Aa}	386.00 ± 3.55^{Aa}	1.30 ± 0.01^{Bd}	0.30 ± 0.01^{Bj}	
4	UC	3.50 ± 0.01^{Aj}	0.25 ± 0.01^{Ak}	3.33 ± 0.01^{Aj}	110.00 ± 9.98^{Am}	5.00 ± 0.01^{Aa}	8.30 ± 0.52^{Aa}	384.50 ± 3.60^{Aa}	3.34 ± 0.01^{Ad}	1.20 ± 0.01^{Ae}	Sandy
	IC	2.20 ± 0.01^{Bk}	0.10 ± 0.01^{Bl}	2.78 ± 0.01^{Bk}	85.60 ± 9.98^{Bn}	4.00 ± 0.02^{Ab}	8.20 ± 0.50^{Aa}	395.00 ± 3.64^{Aa}	$1.75.30 \pm 0.01^{Bd}$	$0.46.30 \pm 0.01^{Bj}$	
6	UC	4.35 ± 0.01^{Af}	0.35 ± 0.01^{Aj}	4.35 ± 0.01^{Af}	150.32 ± 9.98^{Ak}	5.21 ± 0.01^{Aa}	8.53 ± 0.37^{Aa}	372.90 ± 3.43^{Aa}	4.44 ± 0.01^{Ad}	2.20 ± 0.01^{Ad}	Sandy
	IC	3.40 ± 0.01^{Bj}	0.20 ± 0.01^{Bk}	3.21 ± 0.01^{Bj}	100.30 ± 9.98^{Bm}	4.00 ± 0.01^{Ab}	8.30 ± 0.50^{Aa}	380.90 ± 3.45^{Aa}	2.50 ± 0.01^{Bd}	0.83 ± 0.01^{Bf}	
9	UC	5.62 ± 0.01^{Ae}	0.50 ± 0.01^{Ad}	5.62 ± 0.01^{Ae}	230.50 ± 9.98^{Ae}	5.29 ± 0.01^{Aa}	8.62 ± 0.40^{Aa}	377.70 ± 3.48^{Aa}	6.62 ± 0.01^{Ad}	2.78 ± 0.01^{Ad}	Sandy
	IC	4.10 ± 0.01^{Bf}	0.30 ± 0.01^{Bf}	4.30 ± 0.01^{Bf}	140.32 ± 9.98^{Bl}	4.00 ± 0.01^{Ab}	8.45 ± 0.52^{Aa}	383.60 ± 3.48^{Aa}	3.65 ± 0.01^{Bd}	1.34 ± 0.01^{Be}	
11	UC	6.30 ± 0.01^{Ad}	0.64 ± 0.01^{Ac}	6.30 ± 0.01^{Ad}	260.83 ± 9.98^{Ad}	5.00 ± 0.02^{Aa}	8.70 ± 0.30^{Aa}	361.20 ± 3.37^{Aa}	7.65 ± 0.01^{Ad}	2.90 ± 0.01^{Ad}	Loamy sand
	IC	4.50 ± 0.01^{Bf}	0.37 ± 0.01^{Bf}	5.00 ± 0.01^{Be}	170.30 ± 9.98^{Bj}	4.27 ± 0.01^{Ab}	8.45 ± 0.31^{Aa}	363.20 ± 3.36^{Aa}	4.30 ± 0.01^{Bd}	1.70 ± 0.01^{Be}	
16	UC	7.50 ± 0.01^{Ac}	0.75 ± 0.01^{Ac}	7.50 ± 0.01^{Ac}	300.40 ± 9.98^{Ac}	5.13 ± 0.01^{Aa}	8.76 ± 0.30^{Aa}	369.40 ± 3.40^{Aa}	9.50 ± 0.01^{Ad}	3.36 ± 0.01^{Ac}	Loamy sand
	IC	5.23 ± 0.01^{Be}	0.46 ± 0.01^{Be}	5.89 ± 0.01^{Be}	190.50 ± 9.98^{Bf}	4.32 ± 0.01^{Ab}	8.53 ± 0.25^{Aa}	369.40 ± 3.40^{Aa}	6.54 ± 0.01^{Bd}	2.00 ± 0.01^{Bd}	
25	UC	8.30 ± 0.01^{Ab}	0.80 ± 0.01^{Ab}	9.30 ± 0.01^{Ab}	400.30 ± 9.98^{Ab}	5.20 ± 0.04^{Aa}	8.86 ± 0.13^{Aa}	343.50 ± 3.33^{Aa}	19.30 ± 0.01^{Ad}	4.78 ± 0.01^{Ab}	Loamy sand
	IC	6.50 ± 0.01^{Bd}	0.52 ± 0.01^{Bd}	7.30 ± 0.01^{Bc}	250.50 ± 9.98^{Bd}	4.00 ± 0.01^{Ab}	8.60 ± 0.15^{Aa}	346.70 ± 3.34^{Aa}	13.21 ± 0.01^{Bd}	2.76 ± 0.01^{Bd}	
30	UC	9.27 ± 0.01^{Aa}	1.20 ± 0.01^{Aa}	14.30 ± 0.01^{Aa}	550.67 ± 9.98^{Aa}	5.23 ± 0.02^{Aa}	8.86 ± 0.23^{Aa}	347.90 ± 3.30^{Aa}	23.29 ± 0.01^{Ad}	6.64 ± 0.01^{Aa}	Loamy sand
	IC	7.42 ± 0.01^{Bc}	0.83 ± 0.01^{Bb}	9.54 ± 0.01^{Bb}	300.12 ± 9.98^{Bc}	4.00 ± 0.01^{Ab}	8.60 ± 0.25^{Aa}	351.60 ± 3.30^{Aa}	17.29 ± 0.01^{Bd}	4.32 ± 0.01^{Bb}	

[a]Each column has different capital case letters indicating significant changes between the under canopy and inter canopy of the same afforestation years (t-test). Each column has different lowercase letters indicating significant changes between the under canopy and inter canopy of the various afforestation years ($p < 0.05$, *post-hoc* Duncan test). Means ± SE.

sites. The soil surface layer in the 30 years' *Calligonum*-planted area exhibited higher silt and clay than the other areas (Table 2).

C and N pools variations

The amounts of C pool in aerial biomass, roots, and litter in artificial forests cultivated with *Calligonum* are shown in Table 3. The results showed that the C pool in aerial biomass, roots, and litters at the beginning of the phase was 1.30, 1.50, and 0.21 ton ha^{-1}, respectively, an insignificant difference with the 4-year class ($p > 0.01$). Over time, the C pool increased substantially ($p < 0.01$). The maximum C pool was observed in the 30-year class. Notably, the C pool showed an ascending trend at the end of the study period. In contrast, soil C storage showed a steady trend. Over time, the N pool in aerial biomass, roots, and litters increased significantly as the re-vegetated forests aged ($p < 0.01$) (Table 4). The lowest N pool was observed at the beginning of the study period. Like C pool results, the N pool at the initial phase (1-year) did not change significantly compared to the 4-year age class ($p > 0.01$). Over time, the N pool in aerial biomass, roots, and litters increased significantly as the re-vegetated forests aged ($p < 0.01$) (Table 4). Maximum C and N pools in all age classes were observed in roots, aerial biomass, and litters, respectively, showing a significant difference ($p < 0.01$).

Discussion

The changes in plant communities and ecological processes extend the ecological niche and increase the capturing of seeds

TABLE 3 Plant C pool (ton ha^{-1}) in the eight *Calligonum* planting sites.

Planting age		Above-ground biomass	Below-ground biomass	Litter
1	UC	1.30 ± 0.01^{Al-B}	1.50 ± 0.01^{Al-A}	0.21 ± 0.01^{Al-C}
	IC	0.50 ± 0.01^{Bn-B}	0.84 ± 0.01^{Bn-A}	0.10 ± 0.01^{Bm-C}
4	UC	1.50 ± 0.01^{Al-B}	1.90 ± 0.01^{Ak-A}	0.33 ± 0.01^{Al-C}
	IC	1.07 ± 0.01^{Bm-B}	1.10 ± 0.01^{Bm-A}	0.23 ± 0.01^{Bl-C}
6	UC	1.89 ± 0.01^{Ak-B}	2.70 ± 0.01^{Aj-A}	0.70 ± 0.01^{Ak-C}
	IC	1.20 ± 0.01^{Bl-B}	1.89 ± 0.01^{Bk-A}	0.60 ± 0.01^{Bk-C}
9	UC	3.62 ± 0.01^{Af-B}	3.50 ± 0.01^{Af-A}	0.87 ± 0.01^{Aj-C}
	IC	2.50 ± 0.01^{Bj-B}	2.65 ± 0.01^{Bj-A}	0.80 ± 0.01^{Aj-C}
11	UC	4.30 ± 0.01^{Ae-B}	5.64 ± 0.01^{Ae-A}	1.30 ± 0.01^{Ae-C}
	IC	3.32 ± 0.01^{Bf-B}	3.89 ± 0.01^{Bf-A}	1.00 ± 0.01^{Bf-C}
16	UC	6.82 ± 0.01^{Ad-B}	8.75 ± 0.01^{Ad-A}	1.90 ± 0.01^{Ad-C}
	IC	4.23 ± 0.01^{Be-B}	5.46 ± 0.01^{Be-A}	1.73 ± 0.01^{Ad-C}
25	UC	10.69 ± 0.01^{Ab-B}	13.80 ± 0.01^{Ab-A}	2.67 ± 0.01^{Ac-C}
	IC	6.45 ± 0.01^{Bc-B}	7.52 ± 0.01^{Bd-A}	2.30 ± 0.01^{Ac-C}
30	UC	14.27 ± 0.01^{Aa-B}	17.56 ± 0.01^{Aa-A}	4.30 ± 0.01^{Aa-C}
	IC	9.42 ± 0.01^{Bb-B}	10.83 ± 0.01^{Bc-A}	3.42 ± 0.01^{Bb-C}

[a]Each column has different capital case letters indicating significant changes between the under canopy and inter canopy of the same afforestation years (t-test). Each column has different lowercase letters indicating significant changes between the under canopy and inter canopy of the various afforestation years ($p < 0.05$, *post hoc* Duncan test). Each row has capital case letters after the space line indicating significant change among litter, above-ground, and below-ground. Means ± SE.

TABLE 4 Plant N pool (ton ha^{-1}) in the eight *Calligonum* planting sites.

Planting age		Above-ground biomass	Below-ground biomass	Litter
1	UC	6.33 ± 1.01^{Al-B}	7.52 ± 1.01^{Al-A}	5.21 ± 1.00^{Al-C}
	IC	4.53 ± 1.01^{Bn-B}	7.86 ± 1.01^{Bn-A}	5.10 ± 1.00^{Bm-C}
4	UC	6.53 ± 1.01^{Al-B}	7.92 ± 1.01^{Ak-A}	5.33 ± 1.00^{Al-C}
	IC	6.09 ± 1.01^{Bm-B}	7.12 ± 1.01^{Bm-A}	5.23 ± 1.00^{Bl-C}
6	UC	6.93 ± 1.01^{Ak-B}	8.72 ± 1.01^{Aj-A}	5.70 ± 1.00^{Ak-C}
	IC	6.20 ± 1.01^{Bl-B}	7.91 ± 1.01^{Bk-A}	5.60 ± 1.00^{Bk-C}
9	UC	8.65 ± 1.01^{Af-B}	9.52 ± 1.01^{Af-A}	5.87 ± 1.00^{Aj-C}
	IC	7.53 ± 2.01^{Bj-B}	8.67 ± 1.01^{Bj-A}	5.80 ± 1.00^{Aj-C}
11	UC	9.30 ± 2.01^{Ae-B}	11.66 ± 2.0^{Ae-A}	6.30 ± 2.00^{Ae-C}
	IC	8.35 ± 2.01^{Bf-B}	9.91 ± 2.01^{Bf-A}	6.00 ± 2.00^{Bf-C}
16	UC	11.85 ± 2.01^{Ad-B}	14.77 ± 2.01^{Ad-A}	6.90 ± 2.00^{Ad-C}
	IC	9.26 ± 2.01^{Be-B}	11.48 ± 3.01^{Be-A}	6.73 ± 2.00^{Ad-C}
25	UC	15.72 ± 3.01^{Ab-B}	19.82 ± 4.01^{Ab-A}	7.67 ± 2.00^{Ac-C}
	IC	11.48 ± 3.01^{Bc-B}	13.54 ± 4.01^{Bd-A}	7.30 ± 2.00^{Ac-C}
30	UC	19.30 ± 4.01^{Aa-B}	23.58 ± 5.01^{Aa-A}	9.30 ± 2.00^{Aa-C}
	IC	14.45 ± 4.01^{Bb-B}	16.85 ± 4.01^{Bc-A}	8.42 ± 2.00^{Bb-C}

[a]Each column has different capital case letters indicating significant changes between the under canopy and inter canopy of the same afforestation years (t-test). Each column has different lowercase letters indicating significant changes between the under canopy and inter canopy of the various afforestation years ($p < 0.05$, *post hoc* Duncan test). Each row has capital case letters after the space line indicating significant change among litter, above-ground, and below-ground. Means ± SE.

(Jules et al., 2008; Suganuma et al., 2014). These changes facilitate the distribution of new plant species and lead to the establishment of suitable species in later stages of succession (Liu et al., 2015). Forestry provides appropriate habitats where plants can grow in arid and desert regions (Amici et al., 2012). Established species can improve environmental conditions worldwide (Ebrahimi et al., 2019). The microclimate created in the understory of the cultivated species reduces the effect of extreme sunlight; the temperature under the canopy cover of these plants is low, thus reducing the evapotranspiration and, subsequently, water demand in these areas compared to vegetation-free areas (Ebrahimi et al., 2019; Moghbeli et al., 2021). In the study, shrub and forb cover are plant structures that increased due to the planting and establishment of *Calligonum* species in the afforested area. These species rapidly increase biomass and provide a diverse canopy and vertical structure. In addition, increasing the canopy helped to increase the substrate coverage (Moghbeli et al., 2021).

Furthermore, the established plant species in re-vegetated areas help extend plant species in arid and desert areas by capturing the seeds of plant species (Aghababaei et al., 2017). The bushes and shrubs function as seed distributors by conserving wind-scattered seeds, thus increasing the quantity and diversity of plants. The seedlings of other plants can be established under the shade of these bushes, allowing herbaceous species to create colonies and attain sustainability (Hamidi et al., 2020; Moghbeli et al., 2021). Improved conditions and reduced soil erosion due to developments in plant communities increase the soil fertility and permeability, creating a suitable context for seed germination, seedlings' growth, and enhanced efficiency of plants in nutrient- and water-poor environments (Su et al., 2002; Zehtabian et al., 2006; Khosravi et al., 2017).

The 30-year site had the lowest bare soil percentage. It can be attributed to the *C. comosum* mass growing in large communities, covering the soil surface. Therefore, the percentage of canopy increases as the forestry sites age. Multiple research studies have indicated that increasing the quantity and diversity of plant species is among the most positive effects of biological measures in combating desertification (Zehtabian et al., 2006). The cultivation of *Haloxlon* in Shandan, Sistan and Baluchestan, Iran, confirmed that the quantity and diversity of plant species in the region increased significantly as the age of the re-vegetated forests increased (Ebrahimi et al., 2019). Pouyafar and Asgari Moghadam (2006) studied the environmental effects of oil mulch. They concluded that cultivating *H. aphyllum* significantly increases vegetation, species composition, and below-ground biomass. Teymuri Majnabadi et al. (2020) studied the effect of succession on the performance of desert rangelands in Iran. This study confirmed that succession has significantly improved the conditions of microhabitats for the growth of herbaceous plants in degraded desert lands.

Species composition and diversity are some of the essential characteristics of ecosystems; thus, vegetation diversity should be considered in the re-vegetation period (Brancalion et al., 2010). Johnston (2011) discussed coastal ecosystems in Sacramento, California, USA. He reported that species that can foster favorable conditions for other plants through succession are more critical than cultivating various species not resistant to harsh conditions. Our findings indicated that forestry helped enrich vegetation and provided better growth conditions for the plants to produce seeds. Over time, as the forestry sites aged, the emergence of other plant species was observed, increasing richness and diversity substantially. Strauss (2000) examined artificial forests in Australia and reported that forestry with native species substantially enriches native species in the re-vegetated forests. Ebrahimi et al. (2019) evaluated species composition of artificial forests in Sistan and Baluchestan and demonstrated that the diversity reaches a maximum amid succession. Ruiz-Jaen and Aide (2005) examined plant structure and diversity in Sabana Seca, Puerto Rico, in mid-successional re-vegetated forests. They concluded that plant diversity increases significantly over time.

In this study, the perennial species in the 30-year site displayed the highest growth in population. Increased plant density and diversity can be helpful for ecosystem composition (Teymuri Majnabadi et al., 2020; Moghbeli et al., 2021). The planted shrubs and trees can capture and store mineral and water nutrients in the soil and increase soil fertility (Mofidi et al., 2013; Ebrahimi et al., 2019). These plants can also protect bush species under the canopy cover against extreme sunlight and temperatures in arid regions (Khosravi et al., 2017). The fertile soil and microclimate under the shrubs function as fertile resources for low-height herbaceous plants (Moghbeli et al., 2021). These resources are vital for reviving desert lands since they establish natural substitutes by facilitating the growth of other plants (Ebrahimi et al., 2019). Research studies have shown that biodiversity consistently increases as the succession continues due to the increase in ecosystem complexity (Ruiz-Jaen and Aide, 2005; Jafarian et al., 2014). Aghababaei et al. (2017) examined the process of diversifying plant species from the beginning of Iran's forest re-vegetation projects. They concluded that the introduction of additional species increases diversity after 25 years.

Livestock grazed on *C. comosum* sites aged 11, 16, 25, and 30 years. An average grazing rate increases the richness and diversity of species (Khosravi et al., 2017; Moghbeli et al., 2021). Omar (1991) discussed vegetation changes in Kuwait's arid rangelands. He showed that fully protected rangelands, that is, long-term protection programs (10 years), display signs of rangeland degradation. Diversity and richness at the beginning of the succession phase can be attributed to the high dynamics of a limited number of annuals. High dynamics is an essential structural feature at the beginning of the succession phase (Liu et al., 2015). Moreover, the low quantity of species, diversity, and richness at the beginning of the succession phase in younger sites compared to older sites can be attributed to preventing grazing (El-Keblawy and Ksiksi, 2005; Ebrahimi et al., 2019). Therefore, it can be concluded that well-managed grazing is one of many tools for modifying rangelands and forest understory in modified areas.

The results indicated that re-vegetating desert land with *Calligonum* improved soil fertility in the region. The establishment of plant species in arid lands with harsh conditions significantly increased the soil N, P, and K under the crown of plants. The results of the researchers showed that the *Calligonum* species improves the soil structure, and the establishment of plant species increases the nutrients in the soil such as N, P, and K, and with the development of plants, the organic matter of the soil also increases significantly (Biabani, 2016). Zehtabian et al. (2006) reported that planting *Calligonum* in Semnan strengthened soil structure and increased soil N, P, and K. The increased diversity and frequency of perennials can be partially attributed to greater soil fertility. The increase in soil nutrient levels under the canopy cover of plants indicates the accumulation of litter, roots, and further root-related activities (Jozefowska et al., 2017). Two factors can activate this mechanism: First, improved vegetation in the region, resulting in decreased wind erosion. Vegetation can capture nutrients and particles carried by the wind. Second, higher nutrient levels are considerably associated with soil roots and adding root mass to the soil (Jozefowska et al., 2017; Yuuan et al., 2018).

We found that soil nutrient value gradually increased during succession; the maximum soil nutrient value was calculated in the 30-year site. This result confirms the second hypothesis presented in the Introduction section. The higher soil fertility in sites with higher ages can be partly explained by increased litter accumulation resulting in increased organic matter and nutrients in the soil due to increased vegetation canopy (Jozefowska et al., 2017; Yuuan et al., 2018; Teymuri Majnabadi et al., 2020).

In sites with higher ages, more extensive canopy covers will allow livestock to access more nutrients. Trees and shrubs with long lifespan increase soil fertility more than the annuals. This increase can be due to the immediate elimination of nutrients stored under canopy cover by the wind in sites with lower age (Cheng et al., 2004).

It should be noted that the biological restoration in arid areas where extreme sunlight and temperatures (high evapotranspiration) limit plant growth can increase vegetation and reduce exposure to sunlight in the space under plant species, hence lowering soil temperature and water loss. Moreover, higher amounts of plant litter and organic matter further increase water storage in the soil. Thus, more litter in low-age areas will result in higher soil fertility (Frouz and Novakova, 2005; Frouz et al., 2008; Ebrahimi et al., 2019).

The results showed that soil EC increased with the age of forests. This increase, however, was insignificant. This increase in EC, especially under the canopy cover, can be due to soluble salts generated by litter accumulation (Jafarian et al., 2014; Lalozaei et al., 2016). Biabani (2016) stated that *Calligonum* has increased soil EC in Iranshahr deserts, Iran.

The results indicated that organic C and N pools in the soil under the canopy were higher than between the canopy, which can be attributed to the higher percentage of the canopy of plant species, litter, and the higher root mass under the canopy, increasing organic C and N pools in surface soil by causing aerial organs and litter to decompose. Consequently, plant textures become an important source of organic soil C. These plant textures can gradually be transferred to the soil and undergo chemical and biological changes. The maximum C and N pools in the soil and plants were observed in the 25- and 30-year sites. In areas with more vegetation, the amounts of plant textures transferred to the soil will be higher; thus, there will be greater organic matter and, subsequently, N and C pools (Shirzai et al., 2020). Most of the C and N pools in the soil were elevated to the under canopy of sites. The high amount of C and N pools under canopy of *Calligonum* may be due to the fact that most of the organic matter in the soil, related to the decomposition of dead roots and the conversion of microbial biomass to organic matter, which is located at the surface layer soil under canopy of plants (Dianati Tilaki et al., 2009). Dong et al. (2014) reported that large amounts of plant litter in the top soil increase the C stored in this layer of soil compared to deep soil. Woomer et al. (2004) showed that approximately 60% of organic carbon is stored at a soil depth of 20 cm under canopy of plants. Soil C pool is positively correlated to organic matter (Garten and Charles, 2002). This result shows the positive effect of vegetation development in the studied sites.

The results showed that the amounts of C and N pools in the below-ground biomass were higher than those in the above-ground biomass. The reason for this can be attributed to the high amount of woody tissue in the roots compared to the above-ground parts of the plants (Capuana, 2020; Rigi Pardad et al., 2021). In arid rangelands, below-ground biomass of the plants has the largest proportion of total biomass, while above-ground biomass has a small proportion of the total plant biomass (Joneidi Jafari et al., 2013). Plant organs with woody tissue have a greater ability to store C and N (Motamedi et al., 2020). In this regard, other studies have acknowledged that the woodier the tissues in the plant, the greater the plant's ability to uptake C and N (Motamedi et al., 2020; Tessema et al., 2020). Increasing the share of the root increases C and N entrance into the soil (Moghbeli et al., 2021). The type of plant species and even different organs of a plant have different potentials for C and N pools. In fact, the performance of plants to store carbon is a function of various factors such as morphological traits, including plant root height, canopy cover, plant density, plant distribution pattern, topographic characteristics, physical and chemical properties of the soil, and management factors (such as livestock grazing and rangeland exclusion) (Conti and Diaz, 2013; Mirlashkari, 2016). Expansion of vegetation cover will lead to reducing and modifying the amount of CO_2 in the atmosphere by increasing photosynthetic levels and eventually increasing the level of C uptake (Souri et al., 2020). Mirlashkari (2016), in the investigation of the impacts of exclusion on the soil C and N pool in the Jonabad rangeland of Zahedan, Iran, reported that C and N pools were higher in the site with higher plant biomass than the grazed area.

Yang et al. (2020) also emphasized the significance of litter and roots in the increasing soil C pool. They reported that a high soil C pool originates from mycorrhiza, root exudates, and surface litter. Hu et al. (2020) examined the impact of decomposed litter on the amount of soil C pool in the Chinese Plateau. They reported that adding plant litter and root exudates significantly increases the soil C pool. Shirzai et al. (2020) examined the effect of species on C and N pools in the desert lands of Leuchonassi, Sistan and Baluchestan, Iran. They reported that C and N sequestration highly correlates with plant litter and organic matter amounts in the soil. With increasing age, the succession of soil organic matter increased substantially. Therefore, increased C and N pools due to increasing the succession age can be associated with improved vegetation, higher frequency of species and leaf accumulation, and, subsequently, more organic matter in these sites. Furthermore, by increasing the succession age, the mass of below-ground organs in the soil increases. Motamedi et al. (2020) concluded that total C sequestration has a positive and significant relationship with the height and mass of the plant, total aerial biomass, total below-ground biomass, and the amount of litter and soil organic C. The highest C and N pools of plant tissues in all the study sites were observed in roots, aerial organs, and litter, respectively. As the re-vegetated forests aged, tissue C and N increased in plants. This increase can be attributed to the wooden root texture of *Calligonum* compared to the aerial organ (Capuana, 2020). In desert rangelands, below-ground plant biomass has the highest portion of the total biomass (Tessema et al., 2020). Over time and by aging, the plant's wooden textures thicken and increase their C and N sequestration ability. The roots' increased effect in C and N sequestration stores more C and N in the soil (Souri et al., 2020).

In conclusion, in this paper, the Shams Abad Desert, known for its wind erosion in southeastern Iran, was selected as the study area to study the influence of biological restoration in a desert ecosystem. Was the biological restoration program in this region successful? (Resources Center, Mohammdi et al., 2018)

-The changes in vegetation, soil fertility, and C and N pools over time indicate the success of this forestry project.
-A greater value should be assigned to the leading species density at the beginning of the project to increase the restoration rate so that increased vegetation and soil fertility can more easily solve the land degradation problem for the locals.
-Agroforestry is a helpful tool to increase vegetation and improve soil fertility. However, biological restoration requires suitable species and precise management plans since any incorrect action wastes financial resources and causes irreparable damage to the environment.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

ME proposed the concept for the research and designed the research plan. ME carried out the experiments, evaluated the findings, and wrote the first version of the manuscript. MS worked on developing methodologies and overseeing the project on a local level. All authors participated in the editing of the work, reviewed, and approved the submitted version.

Acknowledgments

This study was conducted with the assistance of the Iranshahr Department of Natural Resources. Soil and plant tests were conducted using the facilities of the Soil Laboratory of the Faculty of Soil and Water at the University of Zabol.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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