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Soil OC and N Stocks in the Saline Soil of Tunisian Gataaya Oasis Eight Years after Application of Manure and Compost

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Abstract: Soil organic matter plays an important role in improving soil properties, crop productivity and is a key constituent and driver of the global carbon cycle. Nevertheless, relatively limited quantitative information is available on the organic carbon (OC) stocks and the actual potentials for OC and total nitrogen (N) sequestration under arid cropping systems. In this study, we evaluated the immediate and long-term (after eight years) effects of compost or manure additions, at a rate of 100 t ha^{-1}, on the soil OC and N stocks in the Gataaya oasis in Southern Tunisia. The oasis had been abandoned and no additions had taken place in the 10 years prior to experiment. Soil samples were taken systematically every 10 cm up to a depth of 50 cm. After adding compost (CMP) and manure (MAN) in 2013, the bulk density (BD) decreased in the surface layers, especially at the 0–10 cm soil layer where it declined from 1.53 g cm^{-3} to 1.38 g cm^{-3} under compost and 1.41 g cm^{-3} under manure. Soil OC and N stocks, however, increased after adding compost and manure. Manure contributed more to OC stock increase than compost, with +337 and +241%, respectively. Correspondingly, the N stock increased by + 47 and +12%, respectively, due to manure and compost. After four years, compared to 2013 stocks, the decrease in OC stock was almost identical with −43 (CMP) and −41% (MAN). However, N stock seemed more stable under compost compared to manure, with −2 and −19%, respectively. After eight years, the N stock remained higher in the deepest layer 30–50 cm compared to other layers. This suggested that high gypsum application can inhibit N mineralization. The initial enhanced OC stock after the organic amendment, both for compost and for manure, was very quickly lost and after eight years had virtually returned to the initial OC state by the end of the eight years. Therefore, these oasis ecosystems require a near annual supply of exogenous organic material to maintain OC at an enhanced level. After eight years, manure amendment was found to be better than compost for increasing soil OC (3.16 against 1.86 t/ha, respectively) and for increasing N (0.35 against 0.18 t/ha, respectively). However, the cost and availability make the amendment with compost more interesting in oasis (400 Tunisian dinars/t for compost against 1016 Tunisian dinars/t for manure).

Keywords: drylands; Anthroposols; palm date compost; OC and N stocks; continental oasis

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1. Introduction

Creating oases around fresh water sources in a desert environment is a very old practice. This technique consists of creating a surface horizon (≈50 cm), a so-called 'anthropic horizon' [1]. This horizon can be relatively rich in organic matter (>1%), especially in comparison with the original soils (generally Lithosols), characterized by a poorly developed, saline surface and gypsum accumulation at depth. These oasis soils are a result of "soil engineering", i.e., humans acting to improve a soil. They are therefore classified as anthroposols [2], such soil 'modifications' can affect part or all the profile. The modifications improve soil fertility, allowing for larger food production to feed livestock and the local population. For oasis systems, they are in the majority of cases essentially the addition of exogenous organic matter, most often in the form of manure. This ancestral land management technique must be carried out on a (multi-) annual basis in order to preserve the arable anthropic horizon of the soils, thus preserving the oasis environment [3–5].

The irrigated date palms cultivation occupies a strategic key position in the development and support of life in arid and desert regions [6], and is especially relevant for the Tunisian context as its drylands cover about half of its total land area. Most of the new oases established since 2000 are now irrigated by unsustainable deep drilling practices. They are concentrated on the cultivation of the *Deglet Nour* date variety mostly in south-western Tunisia. However, it is currently still the best mode of valorization of land in these areas [7] due to the high profitability of this date variety. The Tunisian *Deglet Nour* date exports represent only 20% of total agriculture production. Overall, these exported Tunisian dates represent only 8% of world exports in quantity, but is internationally first placed in terms of its exports value (213 million TD, roughly the equivalent of 76 million US dollars) [6,8].

The present study area of Chott Djerid is in southwest Tunisia. This region is the main growing area of *Deglet Nour* date palm. Beside the growing of dates in the oasis systems, the land is used mainly for extensive livestock grazing by goats and camels. The oasis ecosystem located in such desert areas requires copious irrigation and continuous human management intervention (pollination, fertilization) to maintain production levels [3,9–11]. Oasis ecosystem management requires organic amendments, such as manure or alternatively compost (from date palm waste) to be made to the soil [3–5,12]. This is a sustainable production solution, but for these relatively poor farmers, however, an expensive one. Traditionally, the manure is therefore only applied under the trunks of date palms and amounts to 10 t/ha. The cost of one ton of manure is equivalent to 1016 Tunisian Dinar (TD), almost 10% of the basic cost in relation to the expected income. However, for compost it is much cheaper, at 400 TD/t. The oasis date palm cropping also requires further vital management expenses, including irrigation water, phytosanitary products, labor for tillage, replacement of dead tree dead trees, date harvesting, and pruning and pollination [13]. The oasis soils are known to be very poor in organic matter because of climate conditions, and require a near continuous addition of manure and compost for optimal fertility [3–5]. Therefore, it is still necessary to understand the temporal evolution of the organic stock (OC and N) in oasis soil. The aim of this study is to measure OC and N in a highly saline oasis soil. Indeed, the productivity of oasis soils is an integral function of the abundance of these two nutrients [14,15]. In this study, we follow the evolution of soil OC stocks and soil N stocks in two adjacent plots, one traditionally amended with manure and the other with compost made from waste date palm pruning.

2. Materials and Methods

2.1. Site Description, Experimental and Sampling Design

The continental oases of Kebili cover an area of 7000 ha. They are the largest palm groves in southern Tunisia and represent a model situation of land development in Saharan Tunisia. The Gataaya oasis (33°40′45′′N and 8°52′28′′E) is administratively attached to the Kebili North and is located about 8 km southwest of the city of Kebili (Figure 1). The Gataaya North oasis, with a total net area of 57 ha, is the oldest and a typical example of other oases in the region, it was created in 1933 and Gataaya village is in it. The oasis is limited to the southwest by the Chott Djerid and southeast by the Takodit oasis. The study area is characterized by a desert climate, average precipitation is 102.4 mm yr^{-1}, its potential evapotranspiration is 2750.5 mm yr^{-1}, average temperature 21.4 °C, and the maximum summer temperature can exceed 50 °C. The soils are saline gypsum soils. In

2012, the three study plots prior to the start of the experiment similar soil profiles are shown (Scheme 1). The oasis soil is relatively deep, with a saltwater table being present at a 120 cm. This saltwater is related to the Chott Djerid, which is a salty depression. The soil color is almost the same throughout the profile. It is yellowish brown (10 YR 6/4), the structure is grainy and there is a sandy–loamy texture. There is an abundant presence of the roots of date palms throughout the profile and the porosity is generally good. Gypsum crystals are more abundant in the deeper soil horizons. The gypsum increases with depth as it approaches the water table. Beyond two meters, we have a hard accumulation of reddish-yellow gypsum (7.5 YR 6/8).

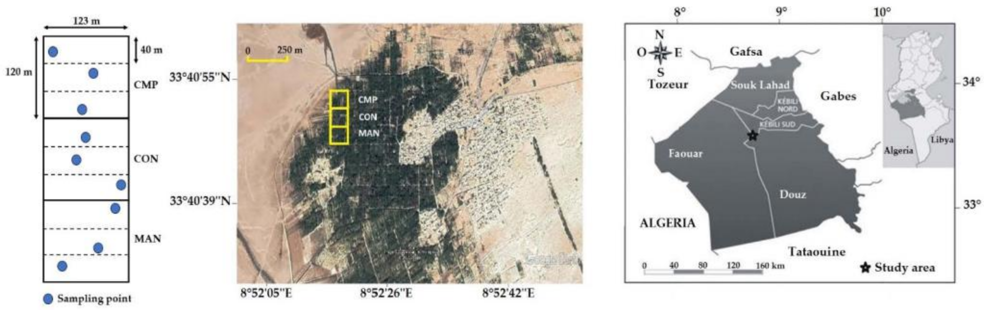
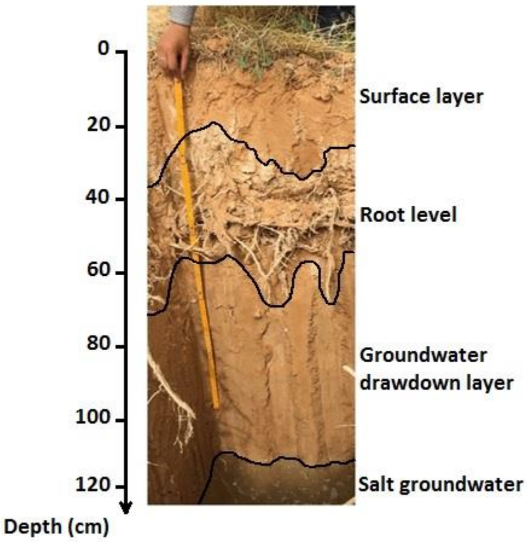


Figure 1. Geographic location maps of the study region and the experimental plots plan. CON: unamended control soil; CMP: soil with compost; MAN: soil with manure.



Scheme 1. Typical soil profile at the study site.

Historically, the oasis was abandoned for economic reasons, due to its aging trees and low yields of dates, and no additions had been added in the 10 years prior to the formal start of the experiment in 2012. Subsequently, since January 2012, an experiment was carried out by the GDA Gataaya (i.e., the local agricultural development group of Gataaya village) to examine the optimal restoration strategies for degraded or abandoned oases.

The experimental area consisted of three adjacent treatment plots of ~1.5 ha each, which are: (i) compost amended soil (CMP); (ii) manure amended soil (MAN); and (iii) unamended control without any additions (CON). Compost and manure were both applied at an equivalent rate of 100 t/ha all over the whole soil area, but only once from 22–24 January 2013 for manure and from 30 January to 1 February 2013 for compost.

The manure (excretal waste of sheep and goats) comes from the herds of the local farmers living in the oases. The manure characteristics were: pH value 6.2, OC content 46.8%, N content 6.2%, and P content 6.3%. For compost, essentially the waste of date palms when pruning, was processed by small association of agricultural development association in the oasis. The compost characteristics were: pH value 7.9, OC 37.2%, N 5.8%, and P 4.6%.

For the analysis, three individual samples were taken and analyzed from the whole manure and compost pile. For the sampling, each treatment plot of ~1.5 ha was split into three subsections (0.5 ha each). Each plot was subdivided into three sub-plots, each of which had an area of almost 0.5 ha (Figure 1). The choice of locations for the sampling points was determined using a metal ring thrown at random in each of the subplots. Thus, from each plot $3 \times 3 = 9$ soil samples were taken for each sampling layer. The samples for soil analysis were taken in the halfway between two date palms and for 0–10, 10–20, 20–30, and 30–50 cm depths. The first sampling took place in January 2013 (immediate after), the second in December 2016 (ca. 46–47 months after organic residue additions), and the third in December 2020 (ca. 94–95 months after initial residue additions).

2.2. Chemical Analysis, Soil OC Stocks and Soil N Stocks

The bulk density (BD) was determined by the cylindrical core method (BD = dry soil weight/cylinder volume). Soil OC content was measured by oxidation method of Walkey and Black by the mixture of $K_2Cr_2O_7$–H_2SO_4 [16]. Soil N was measured by the Kjeldahl method [17]. The particle size distribution (i.e., coarse sand, fine sand, coarse silt, fine silt, and clay) reflected that of the whole soil [18]. The soil pH was determined in (1:2.5) in water suspension. Gypsum percentage was determined using the ammonium carbonate treatment and precipitation by barium chloride [19]. Carbonates were analyzed according to the Scheibler method [20]. The electrical conductivity (EC) was analyzed in a saturated soil paste [21]. Sodium adsorption ratio (SAR) is an important parameter to analyze the effective removal of sodium when dealing with water irrigation, for its elements Ca^{2+}, Mg^{2+}, and Na^{+} are measured using a high-performance liquid ion chromatograph, model 881 (Compact IC). To estimate soil OC stocks in the upper 50 cm, we summed soil OC stocks of the individual layer. The soil OC and N stocks were calculated for each individual layer using the following equations [22,23]:

$$\text{Soil OC stock} = \text{OC} \times \text{BD} \times \text{D} \tag{1}$$

with OC in %, the BD in g cm^{-3}, and sample depth (D) in cm. Soil OC stocks expressed in t C ha^{-1}, then soil OC stock converted into g C m^{-2}. The N stock (g N m^{-2}) was also calculated in a similar manner.

2.3. Statistical Analysis

Data were analyzed using the statistical analysis software (IBM SPSS Statistics Version 20). The ANOVA test and the descriptive statistics for the different variables were conducted to test the significance of treatments, soil depth, year, their interaction regarding soil OC and total N stocks, and differences of $p < 0.05$ were considered statistically significant.

3. Results

3.1. Pre-Experiment Soil Characteristics

Table 1 shows that the sand (CS+FS) and silt fractions (CSi+FSi) together making up 90% of the particle size fractions in the soil texture determination. The soils were of this sandy to sandy–loamy texture throughout the profile. The soil pH values were generally alkaline (7.5–7.8). The EC was always lowest in the surface (5.1 mS/cm), with highest EC value being observed in the deeper 30–50 cm layer (25.7 mS/cm). Gypsum contents were higher at greater depth in the profile, i.e., ranging from 1.2% at 0–10 cm to 24.3% at 30–50 cm depth. The SAR range in our soils ranged from 1.1 to 6.1, and with the electrical conductivity (EC) was also greater than 5 mS/cm. Soil calcium carbonate ($CaCO_3$) ranged from 8.0% at the surface layer (0–10 cm) to 16.0% in the 20–30 cm layer, but it decreased towards the deeper layers where the gypsum ($CaSO_4.2H_2O$) becomes more dominant.

Table 1. Soil properties in 2012 (Mean ± Standard Error; *n* = 3).

Depth	Particle Size (%)					pH	Gypsum	$CaCO_3$	EC	SAR
(cm)	CS	FS	CSi	FSi	C		(%)	(%)	(mS/cm)	
0–10	33.1 ± 0.2	17.5 ± 0.4	18.1 ± 0.1	29.10 ± 0.2	3.0 ± 0.1	7.51 ± 0.01	1.2 ± 0.2	8.0 ± 0.2	5.1 ± 0.1	1.1 ± 0.1
10–20	33.1 ± 0.1	12.8 ± 0.1	8.2 ± 0.0	36.0 ± 0.2	9.0 ± 0.1	7.61 ± 0.01	2.0 ± 0.1	15.7 ± 0.2	17.7 ± 0.1	3.1 ± 0.1
20–30	30.1 ± 0.1	18.0 ± 0.1	5.0 ± 0.2	37.8 ± 0.1	9.0 ± 0.1	7.74 ± 0.09	12.1 ± 0.1	16.0 ± 0.4	15.5 ± 0.2	6.0 ± 0.2
30–50	31.2 ± 0.2	18.9 ± 0.1	6.0 ± 0.2	35.0 ± 0.1	5.1 ± 0.1	7.76 ± 0.01	24.3 ± 0.4	9.4 ± 0.4	25.7 ± 0.4	6.1 ± 0.0

CS: Coarse Sand (200–2000 µm); FS: Fine Sand (50–200 µm); CSi: Coarse Silt (20–50 µm); FSi: Fine Silt (2–20 µm); C: Clay (<2 µm); EC: Electrical Conductivity; SAR: Sodium adsorption ratio.

3.2. Soil Property Changes in the Field Experimental Plots

The OC after the organic residue amendment was different between CON, CMP, and MAN. The addition of the compost increased the OC contents in the different layers, but the effect was larger for manure than the compost (Table 2). In three plots, soil OC was higher in the upper part of the soil (0–10 cm) when compared to the lower parts of the soil (30–50 cm) (Table 2). No difference in soil OC for the CON treatment occurred between 2013 and 2016 for all soil depths. In 2013, the soil OC increased under CMP and MAN in comparison with CON. In all soils, OC was higher in the upper part (0–10 cm) compared to lower down in soil profile (30–50 cm) (Table 2). The higher soil OC content of MAN led to the manure bringing in more soil OC than the CMP, noticeable in all layers, but especially in the surface layer (i.e., 16.42 g C kg^{-1} under MAN against 13.05 g C kg^{-1} soil OC under CMP). However, in 2016, a reduction in soil OC contents is clear, regardless of the type of amendment made. For the surface layer 0–10 cm, the observed decrease under CMP is 44% from 13.05 to 7.34 g C kg^{-1}; for MAN, the decrease is 42% from 16.42 to 9.46 g C kg^{-1} (Table 2). In 2020, this decrease was very pronounced in all layers and under the two MAN or CMP modes, for example, the soil OC content of the soil under MAN went from 16.42 g C kg^{-1} in 2013 to 6.58 g C kg^{-1} in 2020.

Table 2. Soil properties in the three plots under the three treatments between 2013 and 2020.

		Depth		OC (g C kg^{-1})	N (g N kg^{-1})	C/N	BD (g cm^{-3})	pH
2013	CON	0–10	Mean	4.12	0.29	14.01	1.54	7.50
			St. Dev.	0.38	0.00	1.05	0.01	0.01
		10–20	Mean	3.35	0.38	8.96	1.54	7.47
			St. Dev.	1.29	0.01	3.54	0.01	0.07
		20–30	Mean	1.80	0.86	2.07	1.62	7.43
			St. Dev.	0.43	0.04	0.41	0.01	0.02
		30–50	Mean	1.00	0.63	1.61	1.70	7.44
			St. Dev.	0.06	0.06	0.26	0.01	0.01
	CMP	0–10	Mean	13.05	0.87	15.07	1.48	7.47
			St. Dev.	0.37	0.01	0.37	0.04	0.02
		10–20	Mean	9.66	0.75	12.96	1.53	7.50
			St. Dev.	2.11	0.00	2.89	0.02	0.07
		20–30	Mean	7.38	0.75	9.87	1.65	7.57
			St. Dev.	0.95	0.00	1.23	0.03	0.09
		30–50	Mean	4.20	0.42	9.90	1.74	7.62
			St. Dev.	0.41	0.00	1.02	0.03	0.05
	MAN	0–10	Mean	16.42	1.03	16.02	1.43	7.64
			St. Dev.	0.53	0.00	0.52	0.04	0.04
		10–20	Mean	11.54	0.88	13.10	1.51	7.68
			St. Dev.	0.18	0.00	0.17	0.05	0.02
		20–30	Mean	9.47	0.96	9.96	1.58	7.64
			St. Dev.	0.42	0.08	1.19	0.08	0.04
		30–50	Mean	6.36	0.69	9.14	1.73	7.67
			St. Dev.	1.45	0.03	1.82	0.03	0.05

Table 2. *Cont.*

		Depth		OC (g C kg^{-1})	N (g N kg^{-1})	C/N	BD (g cm^{-3})	pH
2016	CON	0–10	Mean	3.06	0.24	12.86	1.53	7.51
			St. Dev.	0.10	0.00	0.45	0.01	0.03
		10–20	Mean	4.59	0.85	5.48	1.49	7.48
			St. Dev.	2.30	0.05	2.97	0.02	0.04
		20–30	Mean	1.57	0.76	2.08	1.61	7.50
			St. Dev.	0.80	0.05	1.11	0.01	0.04
		30–50	Mean	1.06	0.58	1.88	1.70	7.52
			St. Dev.	0.33	0.07	0.75	0.01	0.06
	CMP	0–10	Mean	7.34	0.49	15.10	1.38	7.44
			St. Dev.	0.35	0.00	0.80	0.02	0.01
		10–20	Mean	6.41	0.58	11.02	1.45	7.46
			St. Dev.	0.79	0.00	1.36	0.04	0.03
		20–30	Mean	4.59	0.74	6.28	1.64	7.50
			St. Dev.	0.55	0.08	1.27	0.04	0.05
		30–50	Mean	2.16	0.67	3.24	1.71	7.59
			St. Dev.	0.14	0.04	0.38	0.03	0.03
	MAN	0–10	Mean	9.46	0.63	14.94	1.41	7.60
			St. Dev.	0.37	0.00	0.54	0.04	0.01
		10–20	Mean	6.68	0.68	9.88	1.50	7.59
			St. Dev.	0.42	0.00	0.67	0.05	0.03
		20–30	Mean	5.85	0.78	7.53	1.55	7.59
			St. Dev.	0.28	0.03	0.38	0.01	0.04
		30–50	Mean	3.88	0.67	5.80	1.73	7.64
			St. Dev.	0.45	0.05	0.83	0.03	0.04
2020	CON	0–10	Mean	2.60	0.21	13.23	1.55	7.59
			St. Dev.	0.20	0.07	4.96	0.02	0.08
		10–20	Mean	2.68	0.22	12.31	1.54	7.52
			St. Dev.	0.47	0.05	0.86	0.04	0.01
		20–30	Mean	1.40	0.22	6.69	1.64	7.55
			St. Dev.	0.17	0.05	2.06	0.02	0.07
		30–50	Mean	0.90	0.32	2.82	1.72	7.56
			St. Dev.	0.07	0.05	0.28	0.03	0.05
	CMP	0–10	Mean	3.32	0.20	17.02	1.53	7.58
			St. Dev.	0.34	0.04	5.38	0.02	0.07
		10–20	Mean	2.98	0.20	14.78	1.55	7.57
			St. Dev.	0.14	0.03	1.58	0.02	0.07
		20–30	Mean	2.24	0.24	9.87	1.65	7.60
			St. Dev.	0.08	0.05	2.70	0.01	0.06
		30–50	Mean	1.49	0.22	6.60	1.74	7.61
			St. Dev.	0.55	0.02	1.95	0.02	0.05
	MAN	0–10	Mean	6.58	0.46	14.27	1.49	7.58
			St. Dev.	0.23	0.05	1.12	0.01	0.04
		10–20	Mean	5.41	0.46	11.74	1.49	7.60
			St. Dev.	0.54	0.01	0.91	0.01	0.06
		20–30	Mean	4.41	0.44	10.19	1.58	7.61
			St. Dev.	0.34	0.05	1.25	0.06	0.04
		30–50	Mean	2.02	0.42	4.91	1.68	7.62
			St. Dev.	0.31	0.12	0.60	0.05	0.06

CON: unamended control soil; CMP: treatment with compost; MAN: treatment with manure.

The N in the experiment was also different between CON, CMP, and MAN, and it increased between treatments in that order. The variation in the means of the soil N contents between both plots was significantly different at all soil depths. In general, the contents of N among soil depths followed the soil OC contents. The concentration was higher in the upper soil layers and decreased gradually with soil depth (Table 2). The N contents under two treatments were different; both plots recorded a sharp increase in N at the upper layer, where the value reached 1.03 g N kg^{-1} under MAN and 0.87 g N kg^{-1} under CMP. The highest N value (1.03 g N kg^{-1}) in MAN was obtained at 0–10 cm depth, whereas the lowest value of 0.42 g N kg^{-1} was obtained in 30–50 cm at CMP treatment. We noted a 44% decrease in the 0–10 cm layer content for the CMP treatment from 0.87 g N kg^{-1} in 2013 to 0.49 g N kg^{-1} in 2016. However, an increase in the deep layer of 60%, from 0.42 g N kg^{-1} in 2013 to 0.67 g N kg^{-1} in 2016, which could be explained by the deep downward transport of

N with percolating irrigation water. For the MAN treatment, the decrease in the N content concerned all the layers, and there was a 39% decrease in the 0–10 cm surface layer, from 1.03 g N kg^{-1} in 2013 to 0.63 g N kg^{-1} in 2016 and a slight decrease of 3% in the 30–50 cm layer from 0.69 g N kg^{-1} in 2013 to 0.67 g N kg^{-1} in 2016. In 2020, the N contents for CON and CMP are almost similar on the order of 0.2 g N kg^{-1} in all layers. However, under MAN, the TN contents are almost double with 0.4 g N kg^{-1}.

The soil pH values throughout profiles in the three treatments (MAN, CMP, and CON) were alkaline in three, ranging from 7.43 to 7.68 (2013), 7.44 to 7.64 (2016), and from 7.52 to 7.62 (2020) (Table 2). Overall, the pH values in the upper 10 cm were generally slightly lower than below 10 cm depth for all three measurement periods. In the three plots, without treatment or with the addition of manure and compost, in general, the values of BD increase with depth, the surface layers have the lowest values. Compaction of soil, especially at higher depths, and inadequate organic matter amendment along with more sandy texture might have caused the relatively higher BD values. The BD values of the 30–50 cm layer were independent of the treatment type and always of the order of 1.7 g cm^{-3}. In 2013, we noted a small improvement in the CMP and MAN compared to the control plot CON. This improvement is more noticeable in 2016. Comparing the BD values in the 0–10 cm surface layer, we noted at the CMP level a transition from 1.48 g cm^{-3} in 2013 to 1.38 g cm^{-3} in 2016. In the MAN plot, we also noted a small improvement from 1.43 g cm^{-3} in 2013 to 1.41 g cm^{-3} in 2016 (Table 2). The improvement is clear in 2020 only at the level of the MAN treatment where the values of the apparent density are between 1.48 g cm^{-3} at the surface and 1.68 g cm^{-3} at 50 cm depth.

For the C/N ratio under the three treatments and regardless of the years of measurements, it is always high at the surface and low under the surface (Table 2).

3.3. Soil OC and N Stocks in Three Experimental Treatments in 2013, 2016 and 2020

The results demonstrate that soil OC stocks track soil OC levels in each layer and that the stock decreases with depth (Figure 2). Comparing the stocks in 2013 at the 0–50 cm depth between the three plots, we noted a significant increase of the stock under CMP (6.08 kg C m^{-2}) and MAN (7.79 kg C m^{-2}) in comparison with CON (1.78 kg C m^{-2}) (Table 3).

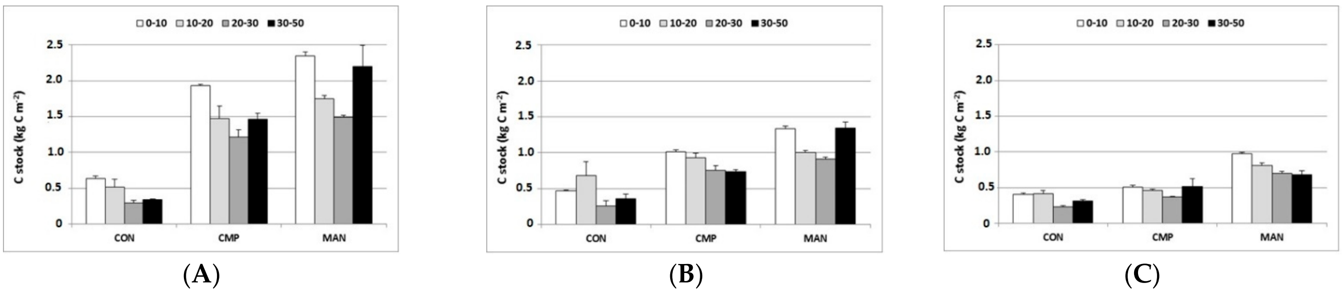


Figure 2. Change in soil OC stocks over 8 years under the different treatments for the four sampled profile depths. ((**A**–**C**) are respectively soil OC stocks in 2013, 2016, and 2020).

Table 3. Soil OC stocks and soil N stocks for 2013, 2016, and 2020 years.

	N Stock (kg N m^{-2})					
Depth cm	**2013**		**2016**		**2020**	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**	**Mean**	**St. Dev.**
CON						
0–10	0.05	0.00	0.04	0.00	0.03	0.01
10–20	0.06	0.00	0.13	0.01	0.03	0.01
20–30	0.14	0.01	0.12	0.01	0.04	0.01
30–50	0.21	0.02	0.20	0.02	0.11	0.02
0–50	0.46	0.03	0.48	0.04	0.21	0.04
CMP						
0–10	0.13	0.00	0.07	0.00	0.03	0.01
10–20	0.11	0.00	0.08	0.00	0.03	0.00
20–30	0.12	0.00	0.12	0.01	0.04	0.01
30–50	0.15	0.00	0.23	0.02	0.08	0.00
0–50	0.51	0.01	0.50	0.03	0.18	0.02
MAN						
0–10	0.15	0.00	0.09	0.00	0.07	0.01
10–20	0.13	0.00	0.10	0.00	0.07	0.00
20–30	0.15	0.02	0.12	0.01	0.07	0.01
30–50	0.24	0.01	0.23	0.02	0.14	0.04
0–50	0.67	0.04	0.54	0.03	0.35	0.05
	OC Stock (kg C m^{-2})					
CON						
0–10	0.63	0.06	0.47	0.01	0.40	0.03
10–20	0.52	0.20	0.68	0.34	0.41	0.08
20–30	0.29	0.07	0.25	0.13	0.23	0.03
30–50	0.34	0.02	0.36	0.11	0.31	0.03
0–50	1.78	0.35	1.77	0.59	1.36	0.16
CMP						
0–10	1.93	0.03	1.01	0.04	0.51	0.05
10–20	1.47	0.30	0.93	0.11	0.46	0.03
20–30	1.22	0.17	0.76	0.11	0.37	0.01
30–50	1.46	0.15	0.74	0.04	0.52	0.18
0–50	6.08	0.65	3.44	0.30	1.86	0.27
MAN						
0–10	2.35	0.10	1.33	0.07	0.98	0.03
10–20	1.75	0.08	1.00	0.06	0.81	0.07
20–30	1.49	0.05	0.91	0.05	0.70	0.05
30–50	2.20	0.51	1.35	0.14	0.68	0.10
0–50	7.79	0.73	4.59	0.31	3.16	0.26

CON: unamended control soil; CMP: treatment with compost; MAN: treatment with manure.

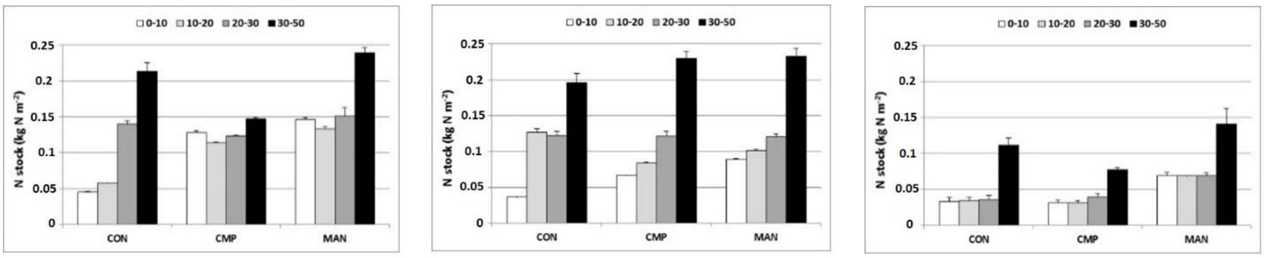
We found that taking the CON plot as a base value, the compost added in CMP plot 4.30 kg C m^{-2} and stock increased by 241%. For the MAN plot, manure added 6.00 kg C m^{-2} and its stock increased by 337 % (Table 4). In 2016, we noted that the soil OC stock remained stable under the CON plot. While under CMP and MAN, a clear decrease occurred in 2016. In fact, under CMP the total stock of the whole profile (0–50 cm) had to decrease to 3.44 kg C m^{-2} (a reduction of 57%). Whereas, under MAN the stock (0–50 cm) fell to 4.59 kg C m^{-2} (a relative loss of 59%) (Table 3).

Table 4. Evolution of soil OC and N stocks between 2013 and 2016.

Depth (0–50 cm)	OC Stock (kg C m^{-2})			N Stock (kg N m^{-2})		
Year	2013	2016	2020	2013	2016	2020
CON	1.78 ± 0.20	1.76 ± 0.34	1.36 ± 0.09	0.46 ± 0.02	0.48 ± 0.02	0.22 ± 0.03
CMP	6.08 ± 0.38	3.44 ± 0.17	1.86 ± 0.16	0.51 ± 0.01	0.50 ± 0.02	0.18 ± 0.01
MAN	7.79 ± 0.42	4.59 ± 0.18	3.16 ± 0.15	0.67 ± 0.02	0.55 ± 0.02	0.35± 0.03
CMP 2013-CON2013		4.30 (+241%)			0.06 (+12%)	
MAN 2013-CON2013		6.00 (+337%)			0.21 (+47%)	
CMP 2016-CON2016		1.67 (+95%)			0.02 (+4%)	
MAN 2016-CON2016		2.83 (+ 160%)			0.06 (+ 13%)	
CMP 2020-CON2020		0.50 (+37%)			−0.04 (−18%)	
MAN2020-CON2020		1.80 (+133%)			0.13 (+62%)	
CMP 2016-CMP2013		−2.65 (−43%)			−0.01 (−2%)	
MAN 2016-MAN2013		−3.20 (−41%)			−0.13 (−19%)	
CMP 2020-CMP2013		−4.23 (−69%)			−0.33 (−65%)	
MAN 2020-MAN2013		−4.62 (−59%)			−0.32 (−48%)	

In 2020, the soil OC stock has decreased significantly under CMP and MAN. Indeed, on 0–50 cm of depth, the stock for MAN decreased from 7.79 kg C m^{-2} in 2013 to 3.16 kg C m^{-2} in 2020; for the CMP, the same result is observed, the stock also decreased by 6.08 kg C m^{-2} at 1.86 kg C m^{-2} in 2020. The MAN remains a little advantageous in comparison with CMP.

For the N stock, we found roughly the same findings as the soil OC stock. On the depth of 50 cm, for the CON plot, 2013 and 2016 stocks are similar 0.46 and 0.48 kg N m^{-2}, respectively. This means, referring to the initial CON stock, compost brought 0.04 kg N m^{-2} in CMP and manure 0.21 kg N m^{-2} in MAN. Therefore, overall, more N was found in MAN than CMP, 0.67 and 0.51 kg N m^{-2} in 2013 and 0.54 and 0.50 kg N m^{-2} in 2016, respectively. Furthermore, only in the MAN, N stock decreased significantly (19%) between 2013 and 2016. In 2020, the soil N stock has the same evolution over time as for the soil OC stock. However, there is a clear difference between the N stocks at the level of the deep layers compared to the surface layers. In fact, over a depth of 50 cm, almost 1/3 of the N stock resides in the 20–50cm layer (Figure 3).



(**A**) (**B**) (**C**)

Figure 3. Change in N stocks over 8 years under the different treatments. ((**A**–**C**) are respectively N stocks in 2013, 2016, and 2020).

Table 4 summarizes the main data on OC and N stocks according to the types of organic additions to the soil. Referring to the CON plot, after the addition of compost and manure in 2013 (CMP and MAN 2013), the soil OC stock increased by 241% and 337%, respectively. For N, the respective increases are 12% and 47%. After almost four years, by comparing soil OC and N stocks between 2016 and 2013, the decrease is very clear. Indeed, the loss of the soil OC stock is more than 40% for the two additions compost and manure, respectively 43% and 41%. For N, the respective decrease for CMP and MAN was 2% and 19%. It is remarkable that the N stock of compost has decreased very little compared to the manure. After eight years, comparing OC and N stocks between 2020 and 2013, the decrease is very clear; the loss of soil OC stock is almost 69% for compost and 59% for manure, and for N stock it is 65% and 48%, respectively. Comparing the stocks of 2020 with those of 2016, the N stock of compost fell rapidly from 2 to 65%, while that of manure decreased slowly from 19 to 48%.

Based on the motivating price of compost and especially its availability (obtained from waste the size of date palms), opting for an organic amendment of oasis soils with compost seems a very interesting technique in comparison with organic amendment by manure, which is expensive. Indeed, putting the double quantity in compost would be cheaper than manure and would increase soil OC and N stocks more than manure.

3.4. Evolution of Soil Variables as a Function of Time and Depth

The descriptive measures (Table 2) show that the OC content decreases with depth regardless of the mode of use (CON, CMP, and MAN). However, the N content under CON shows an increase with depth ranging from 0.89 g N kg^{-1} in the 0–10 cm surface layer to 1.48 g N kg^{-1} in the layer 30–50 cm. Under CMP, the TN content shows some stability with a content of 1.13 g N kg^{-1} in 0–10 cm and 1.11 g N kg^{-1} in the 30–50 cm layer, almost the same with the MAN mode where the values are 2.1 and 1.86 g N kg^{-1}, respectively. The values of the BD in the 0–10cm layer decrease under MAN and CMP modes compared to CON, but in all cases the BD increases with depth under the effect of soil compaction.

The stocks of OC and N follow the same pattern as the contents of these two elements, and we notice that the stocks of OC have decreased according to the depth. The N stocks go up in reverse of what we have seen with the OC stocks, for the CON, CMP, and MAN mode going from the surface layer 0–10 cm to the deepest layer 30–50 cm, N stocks are 1.37; 1.69; 3.08 kg N m^{-2} and 5.08; 3.84; 6.28 kg N m^{-2}.

In the three plots (CON, CMP, and MAN), OC is significantly correlated with the temporal variability (Years) which *p*-value is 0.00 and Wilks' Lambda is 0.41, which implies that a unit variation in the time variable leads to a decrease in the OC content at a rate of 0.41% (Table 5).

Table 5. ANOVA test for year, depth, and mode of treatment factors.

Fixed Factor		Dependent Variable	*p*-Value	Wilks' Lambda
	Year	OC N	0.00 *** 0.00 ***	0.41
	Depth	OC N	0.00 *** 0.91	0.52
	Mode of treatment	OC N	0.00 *** 0.00 ***	0.67
	Depth × Mode of treatment	OC N	0.63 0.87	0.93
R^2 = 0.63				
	Year	N stock OC stock	0.00 *** 0.00 ***	0.42
	Depth	N stock OC stock	0.00 *** 0.16	0.51
	Mode of treatment	N stock OC stock	0.00 *** 0.00 ***	0.67
	Depth × Mode of treatment	N stock OC stock	0.93 0.97	0.9
R^2 = 0.63				
	Year	BD pH	0.26 0.01 **	0.94
	Depth	BD pH	0.00 *** 0.01 **	0.12
	Mode of use	BD pH	0.00 *** 0.00 ***	0.37
	Depth × Mode of treatment	BD pH	0.00 *** 0.01 **	0.69
R^2 = 0.54				

** $p < 0.01$ and *** $p < 0.001$.

Concerning the quality of fit between the two variables OC and N with the depth and year variables, we note that the value of R^2 is 0.63. It should be noted that the depth variable has no effect on the N stock in the soil (p-value 0.91), a finding already advanced in the descriptive statistics (Table 5).

4. Discussion

4.1. Physico-Chemical Variables

The pH results were predictable as they are attributed to the high salt contents encrusted in soil layers which stem from the gypsum crust, resulting from irrigation with saline water and rises of the underground watertable [24]. The pH in the soils studied at the Gataaya oasis varies from 7.44 to 7.68. The high pH values could be explained by an upcoming of water from already saline aquifers (3.3 g L^{-1}) of which all of the oases are irrigated from [12]. Dryland soils in Tunisia are very poor in organic matter; their contents do not exceed 0.8% [1]. However, at the oasis level, levels exceed 1% in surface layers [25,26]. Oasis soils are not considered as pedogenic soils but rather as anthropogenic soils [27]. Our analyses in the Gataaya oasis corroborate with these results and the soil OC levels under CON are between 0.40 and 1.64%.

For the CMP and MAN treatments (soil with addition of compost and soil with addition of manure), we recorded very high levels of organic matter and soil OC immediately after their addition. The biodegradation of organic compounds depends on the nature of organic inputs, simple compounds, whole debris, and organo–mineral complexes [28]. Mineralization of organic matter is greater in coarse and low textured soils [1]. Soil OC contents (%) are generally higher values in the soil surface layers. Our values showed a decreasing trend with soil depth. Accumulation of soil OC result from surface organic matter amendments (crop residues mixed with animal manure), applied by most farmers in this oasis. Nevertheless, the annual temperatures at Gataaya oasis favor a high decomposition rate of organic matter [29].

Outside the Gataaya oasis, at Chott Djerid, the soil OC contents were highly affected by soil depth. In another study for oases of Balad Seet in Oman, a soil OC content of 30.7 g kg^{-1} in the upper soil layer was reported due to regular application of animal manure [30]. In contrast, low soil OC contents result from large patches of bare ground between small shrubs, with large variations in soil OC density and low carbon input in the soil [12].

Moreover, adding soil organic matter and sand amendments to the base of the palm by some farmers in this oasis might have led to higher soil OC concentration especially in near palm position [31]. In addition, high salt accumulation requires the oasis to be irrigated; as a result soil OC is leached and easily transported by water to the soil's surface [32]. In a similar oasis agrosystem in the arid region of Northwest China, Li et al. (2013) [33] attributed the high accumulation of soil OC in the upper soil layer to the same reason. In warm arid areas, such as the southern Tunisia region, plenty of factors can affect soil OC accumulation, including soil texture, vegetation type, and climatic conditions. For instance, high temperatures affect soil water use efficiency and thus impact biomass production and level of soil OC input [34,35]. Locally, Kebili area characterized by frequent wind blowing and sand dunes which affect soil properties and thus the soil OC concentration in these areas [34].

The variation in the means of the soil N contents among all three plots followed the soil OC contents. The concentration was higher in the upper soil layers and decreased gradually with soil depth, except for CON soil where deeper layers greater than 10 cm were richer in N, 0.029% to 0–10 cm and 0.063% in 30–50 cm. The soil N results found in the current study were close to those reported by Mlih et al. (2016) [12] (for Gataaya oasis) of 0.029 to 0.103%; in his study, the content displayed no significant trend with depth but remained high in the most upper soil layers. The higher accumulation of soil N in the upper layer, particularly for oasis soils, is due to high content of soil organic matter in this layer [36]. Soil containing greater organic matter will have higher microbial activity and thus higher N output. Moreover, Liu et al. (2013) [37] and Gao et al. 2019 [38] indicated that the spatial distributions of soil N in a typical oasis ecosystem in the arid region of Northwest

China were influenced by farming practices (e.g., application of chemical fertilizers and organic manure) and regional soil parent materials. Low N concentration levels, especially in Gataaya oasis and the bare lands of Gabes desert and Chott Djerid, could be attributed to low organic matter input in the soil, water scarcity, and soil erosion [39]. High temperature and heat waves in these areas may also affect microbial growth and their activity in the soil [40]. Salinity can reduce the decomposition rate of organic matter, which in turn may increase the risk of N immobilization in the deep layer [41]. Loss of N takes many forms, such as volatilization of ammonium or accumulation of nitrate in the soil beyond the root zones [42].

Based on the results of the BD obtained, it is noted that it is low on the surface, which shows the abundance of the organic amendment on the surface [43]. This apparent density increases as a function of the depth, it is conditioned by the reduction of the organic matter as a function of the depth on the one hand, and on the other hand by the pressure exerted on the soil layers, that is, the settling effect is very pronounced at depth and manifests itself in high values of BD. The rate of soil organic matter is influenced by the physical properties of texture and BD. This result corroborates with BD presented by Abdelbaki (2018) [44]. In soils of the three plots, BD ranged from 1.38 to 1.74 g cm^{-3}. Fine textured soils in general have lower BD than sandy soils and thus tend to organize in porous grains; this can also be enhanced by adequate organic matter content, which results in pore space and enhanced soil aggregation [45]. Compaction of soil at higher depths may have contributed to increasing BD at depth [46].

4.2. Soil OC and N Stocks

Soil OC stocks are important in organic horizons as mineral horizons; they are influenced by the amount of humus and its thickness. The variation of the parameters, which characterize the composition of the soil, organization, and the functioning of the soil, such as, the particle size, BD, and the pH value, influence the rate of soil OC and thus the soil OC stock. Brahim and Ibrahim (2018) [47] have shown that several landscape factors, such as drainage, slope position, texture, and humus thickness influence soil OC stockpiles.

The type of soil influences the potential storage of soil OC [48]. For example, in hydromorphic soils, characterized by the presence of the excess of water, the decomposition of the soil organic matter is very slow because of the conditions of anaerobic; this favors increasing the soil OC residence time. In contrast, coarse aerated, nutrient rich soils favor the decomposition of the soil organic matter.

According to the FAO classification, our soils are of type solonchaks. Their soil OC contents were highest under the amended MAN and CMP compared to CON. Omar et al. (2017) [49] found on the same solonchaks soils, mean soil OC stocks of 0.70 and 2.40 kg C m^{-2} for the 0–5 cm and 0–30 cm depth intervals, respectively. These are values which are very close to our results for the plot without any addition (CON). Our results corroborate those for 0–30 cm depth of Tunisian solonchaks soil OC stores, estimated by Brahim et al. [50], to be on average 2.82 kg C m^{-2}. Our values are close to what is presented by Batjes [51], where he showed that solonchaks had average stocks of the order of 2.60 kg C m^{-2} in the upper 50 cm.

For the two CMP and MAN plots, the carbon stocks are relatively high after the addition of the amendments, in line with the results observed by Fusillier et al. (2009) [52]. In oases soils, high stocks of soil OC were related to organic matter derived from palm date and careful soil management consisting of a shallow tillage associated with permanent fodder cultivation. Furthermore, this difference may be associated with the dense roots with high turnover rate in the subsoil [42]. This confirms that arid soils can store OC [50]. According to Munoz-Rojas et al. [53], the upper 0–30 cm layer contains the highest soil OC stock because organic matter is preferentially accumulated at this depth.

What is remarkable in our study is that the soil OC stock fell very rapidly after four years in MAN and COM, even though the earlier stock levels obtained after the addition of the amendments were at very high levels (CON) compared to the usual stocks in the solonchaks. We attribute this decrease of nearly 50% to the very high temperature in this desert area which accelerates mineralization, and due to the coarse and sandy texture poor in clay which favors the OC sequestration [54]. Furthermore, the good permeability of these soils means that OC can be transported by leaching. In fact, soil salinity is a limiting factor for microbial activity [55,56]. Soil microorganisms, especially fungi, are very sensitive to salinity [57]. Long-term lime and gypsum amendment increases N fixation in the soil and decreases the abundance of total prokaryotes (archaea and bacteria) related to the N cycle [58]. Carter (1985) [59] studied the long-term effect of adding gypsum to soil in the field and his laboratory study showed a reduction in microbial soil N of 10–43%. The results show the direct effect of gypsum on decreased microbial activity and the interrelationships between changes in soil chemistry, biomass, and microbial activity [59]. Desertification can significantly decrease both soil OC storage in the whole 0–30 cm soil profile [60].

The general figure observed for N stock followed the pattern of soil OC stock distribution since most N forms part of the soil organic matter [61,62]. On a depth of 50 cm in the reference C plot, N stock was between 0.46 in 2013 and 0.48 g N m^{-2} in 2016. This result coincides perfectly with the solonchaks values given by Batjes [51], i.e., for 0–50 cm depth equal to 0.44 g N m^{-2}.

What is quite remarkable is that after this stability in the N stock of the CON plot over the depth of 0.5 m, the stock fell from 0.4 g N m^{-2} to in 2013 and 2016 to 0.2 g N m^{-2} in 2020. This same result is observed in the two other plots with MAN and CMP where the total N stock shows a clear decrease, going for example under MAN of 0.67 and 0.54 g N m^{-2} respectively for the years 2013 and 2016 to 0.35 g N m^{-2} for the year 2020. The decrease was very pronounced under CMP, stocks dropped 0.51 (2013) and 0.50 (2016) to 0.18 g N m^{-2} in the year 2020.

This could be due to climate changes in the area. Indeed, for measurements from 1985 to 2016, the average annual precipitation (MAP) was 102.4 mm/year and the average annual temperature (MAT) was 21.4 °C, whereas from 2016 to 2020, MAP was 36.8 mm/year and MAT 22.2 °C [63].

According to Christensen (1996) [64], clay fraction generally accounts for over 50% of soil organic matter, while silt and clay together (<50 μm) may account for over 90%. Furthermore, the organic matter bound to the fine silt- and clay-sized fractions is more humified than that associated with the coarse fraction [65,66]. Dominant factors which explain soil OC stocks variability are probably due to microclimate drivers within each soil type. Altitude and soil temperature significant explained soil OC and N stocks variability [67]. The high-temperature regime in the oasis production systems in the middle of the desert, the irrigation, and the rise of the water by capillarity of the water table could leave the soils always more wet at depth. This observation confirms generally accepted temperature and moisture controls on the rate at which biochemical processes occur in soils of diverse genesis and chemical nature [68,69].

The N Stocks increased after compost and manure were applied, but were more stable for manure applied soil. The N stocks in CMP at 50 cm depth in 2013 and 2016 are 0.51 and 0.50 kg N m^{-2} and under MAN were 0.67 and 0.54 kg N m^{-2}. In fact, soil in the upper 50 cm varied between 0.50 and 0.60 kg N m^{-2}, but also showed their capacity to sequester N despite salinity and high ambient temperatures. These values (Table 3) place the solonchaks of Tunisia close to the Planosols, Podzoluvisols, Regosols, Luvisols, Ferralsols, and Acrisols, which have an average stock of 0.55, 0.55 0.57, 0.63, 0.64, and 0.66 kg N m^{-2}, respectively [51]. The deep layers were the richest in N (Figure 3), explained by the abundance of gypsum. As according to Raju and Zouggari (1988) [70], a high gypsum content (>10%) decreases N mineralization.

Our results show that in desert soils, the storage of OC and N is temporary but reversible. The soil OC and N sequestration may be therefore possible in saline desert soils, but the rate of increase is of course severely hampered by prevailing major environmental constraints, notably the low quantities of clay, high temperatures, and salinity throughout the profile. Compared to control soil, crop yields and their organic restitution drop by up to 47% in saline soil [71].

5. Conclusions

Manure and compost significantly enhanced soil OC and N after being added compared to a non-amended control. However, the initial enhanced OC stocks after the organic amendment, both for compost and manure, were very quickly lost and after eight years the values virtually returned to the initial OC state. After eight years, the N stock remained higher in the deepest layer 30–50 cm compared to other depth layers, which suggests that a high gypsum content can inhibit N mineralization. As livestock numbers are low in oases, local manure is scarce, and costs are high, we recommend using date palm residue-based compost as appropriate solution to preserve and restore the soil OC and N stocks in these fragile ecosystems.

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