

Bentonite clay combined with organic amendments to enhance soil fertility in oasis agrosystem

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Abstract: Soils in arid and semi-arid lands are vulnerable to climate change, erosion, and mismanagement practices that contribute to organic matter depletion and nutrients imbalances. Oasis agrosystems are considered one of the major farming systems in some parts of these lands in the Middle East and North Africa region. However, oases soils are inherently low in organic carbon due to their sandy texture which retains little water and binds low organic matter contents, and the accelerated decomposition rates of organic matter under high temperature, which makes its accumulation difficult. Traditional farming practices in oasis agrosystems have always integrated organic matter derived from livestock to enhance organic carbon (OC) and total nitrogen (TN) stocks in the soil. This study aims to examine the potential effects of a new mixture of organic amendments and bentonite clay on organic carbon and total nitrogen stock accumulation in the soil. Five amendments were applied including sand and compost (SC), sand and manure (SM), sand, bentonite, and compost (SBC), sand, bentonite, and manure (SBM), and sand mixed with bentonite (SB). These treatments were compared to untreated soil (U). The results showed that OC and TN stocks increased significantly ($p<0.05$) in all three depths of the five treatments compared to the untreated soil. Higher organic carbon stocks ($2862\pm3.4 \text{ g m}^{-2}$) were detected in SBM treatment. The combined organic and mineral amendment retarded OC and TN decomposition. After two years of the amendments' application, 30% of OC remained in the soil for SBC treatment. In conclusion, the mixed mineral and organic amendment is a better choice to preserve OC, and thus, maintain oasis soil fertility.

Keywords: Bentonite clay, manure, compost, organic carbon, total nitrogen, oasis agrosystem, Tunisia.

1 Introduction

Nearly 41% of the terrestrial land surface is encompassed within arid and semi-arid lands, the great proportion of these areas locates in the developing countries and inhabited with almost one-third of the world population (Lal 2004; Wang et al. 2012). Land degradation in the drylands is driven by inherent climatic features such as drought, high evaporation rates, and wind erosion (Dregne 2002). The mismanagement practices such as excessive grazing and removal of the vegetation cover contribute significantly to the depletion of soil organic matter (Plaza-Bonilla et al. 2015), besides the natural factors such as soil salinity, wind erosion, and drought events (de Nijs and Cammeraat 2020; Jemai et al. 2018). Inherently, arid and semi-arid lands are low in soil organic carbon (OC), its content barely exceeds 1% due to the low productivity of the agroecosystems these lands support (Brahim and Ibrahim 2018; Fu and Feng 2014; Reynolds et al. 2007; Seager et al. 2007). Nevertheless, due to the massive size of these lands' area, drylands account for about 241 Pg ($1\text{Pg}=10^{15}\text{g}$) OC, which represent 15.5 % of the world's total soil organic carbon stock (Glenn et al. 1993; Lal 2004). Besides cereal cultivation and livestock production, oasis agrosystems are considered one of the major farming systems in these lands. Most of the oases groves are condensed in the arid areas of the Middle East and North Africa (MENA) region. Oases soils have low OC contents mainly because of their sandy texture, which retains little water and binds low organic matter contents (Su et al. 2010). Their unfavourable texture and low clay contents induce strong leaching of soil minerals and essential nutrients like N and P (Bronick and Lal 2005). Additionally, oases, especially the continental ones, are lacking for a substantial vegetation cover that provides soil organic matter upon decomposition (Allbed et al. 2014; Mlih et al. 2019). Grazing and repetitive removal of the crop residues from oasis lands have significantly affected the accumulation of the soil organic matter and thus the OC stock and other essential elements in oasis soils (Mlih et al. 2016; Wichern et al. 2004). Moreover, the accumulation of organic matter in oases soils is difficult due to the accelerated turnover and decomposition rates under high temperatures and frequent irrigation intervals (Buerkert et al. 2018; Franzluebbers et al. 2001).

In Tunisia, oases cover about 40,803 ha, most of them are located in the south. They support a wide range of agriculture, such as fruit trees, vegetables, and other herbaceous plants beside the dominant crop, the date palm (*Phoenix dactylifera* L.) (Tengberg 2012). Over half of the rural population in Tunisia is directly dependent on date palm production. Date, especially the *Deglet Nour* variety plays an important role in rural development and Tunisian economy (Amor et al. 2015). However, over the last decades, the area planted with date palm has declined and the production decreased as a consequence of oases land degradation (King and Thomas 2014). The expansion of the adjacent Chott Jerid and Gharsa salt plains in the south of the country to the oases are

threatening the sustainability of these oases and contribute extensively to the oases degradation (Kadri and Van Ranst 2002; Marlet et al. 2009). Several field studies have shown that oases soils need both continuous nutrients and organic matter application (Al-Kharusi et al. 2009; Marzouk and Kassem 2011; Mlih et al. 2016; Wichern et al. 2004). Animal and green manure are considered excellent sources of organic matter and are essential for soil fertility (Ayuke et al. 2011; Wichern et al. 2004). Compost can serve as a source of organic matter that builds up soil humus, which is important for maintaining soil structure and moisture, and supply the crops with the essential nutrients, as it has stable forms of organic matter and optimal nutrients stocks compared to manure (Bernal et al. 2009). Additionally, compost can help in reducing weed seeds and plant pathogens if treated before application (Wang et al. 2012). Traditionally, local farmers in Tunisian oases have always depended on manure derived from farms livestock to maintain soil fertility. However, over the last years, manure has become scarce and expensive as livestock production declines (personal observations). Many farmers are nowadays using chemical fertilizers i.e. NPK instead of manure, as they are easy to apply and their effects are almost immediate (Hannachi et al. 2015). For small scale farmers, using either manure or chemical fertilizers means additional production costs. Therefore, soil fertility in oasis agrosystems needs to be maintained through introducing new materials that are cost-efficient, locally available and can be deployed through traditional management practices. Previous studies have emphasized the role of clay in stabilizing soil organic matter and the accumulation of the SOC (Hassink 1997; Liao et al. 2006; Mureva et al. 2018; Six et al. 2004) and in enhancing water holding capacity and retaining moisture in the soil (English et al. 2005; Ma and Zhang 2016; Qiu et al. 2015). Bentonite clay has been used as a soil amendment for sandy soils to enhance their water retention capacity (Al-Omran et al. 2004) soil physical features (Ameta et al. 2007), and cation exchange capacity (Mojid et al. 2009; Steele et al. 2001; Suzuki et al. 2007). Previous studies conducted in Tunisia have shown that use of bentonite clay has a positive influence on oasis soil physical and chemical characteristics (Belgacem 1986; Bousnina and Mhiri 1998; Karbout et al. 2015).

The present study aims to examine the viability of the new proposed amendment materials, consisting of mixtures of organic (manure and compost) and mineral (bentonite clay) materials. We hypothesize that this combination integrated with the common traditional management practices in Fatnassa oasis in Tunisia will help to reduce the rapid mineralization of organic matter, enhances SOC stock, and the available nitrogen (N), and hence maintain soil fertility.

2 Materials and Methods

2.1 Site characteristics and experimental design

The experiment setup took place in Fatnassa oasis in Kebilli governorate southern Tunisia (33.8° N; 8.7° E), 24 m above sea level (see map figure 1). The oasis climate is Mediterranean dry, hot in summer, and mild in winter. Rainfall is low and erratic with an annual average of 40 mm. The annual mean temperatures range from 1.9 °C in winter to 46.6 °C in the summer. The annual potential evapotranspiration exceeds 2000 mm. The soils of the oasis can be classified as Gypsisol according to WRB (Boulbaba et al. 2012). The sandy soils of the oasis are characterized by high permeability and low water retention (Kadri and Van Ranst 2002). The experimental design was composed of a randomized selected block with six treatments and three replicates with plots of 3 m² size, the plots were planted with only date palm crop in the course of the two-year study. The six treatments were: sandy soil + manure (SM), sandy soil + compost (SC), sandy soil + bentonite clay (SB), sandy soil + bentonite + manure (SBM), sandy soil + bentonite + compost (SBC), and untreated control treatment (U). The manure used in the experiment is similar to the one used by the farmers (derived from goat and sheep), the compost was originated from the waste of date palm and was processed at the Institute of Arid Regions in Kebilli. The bentonite clay was taken from a geological source in Gabe's region Latitude: 33°53'29" North, Longitude: 9°47'46" East. The chemical characteristics for the amendment used are presented in Table 1. The plots were managed traditionally throughout the two years. The aim was to copy the management practices followed by the local farmers in the oasis. The plots were irrigated using the flooding technique through traditional channels with a water delivery return schedule of 22 days in winter and 28 days in summer. The amount and timing of irrigation were controlled by the Agricultural Development Group (GDA) of the Regional Agricultural Development Commission (RADC).

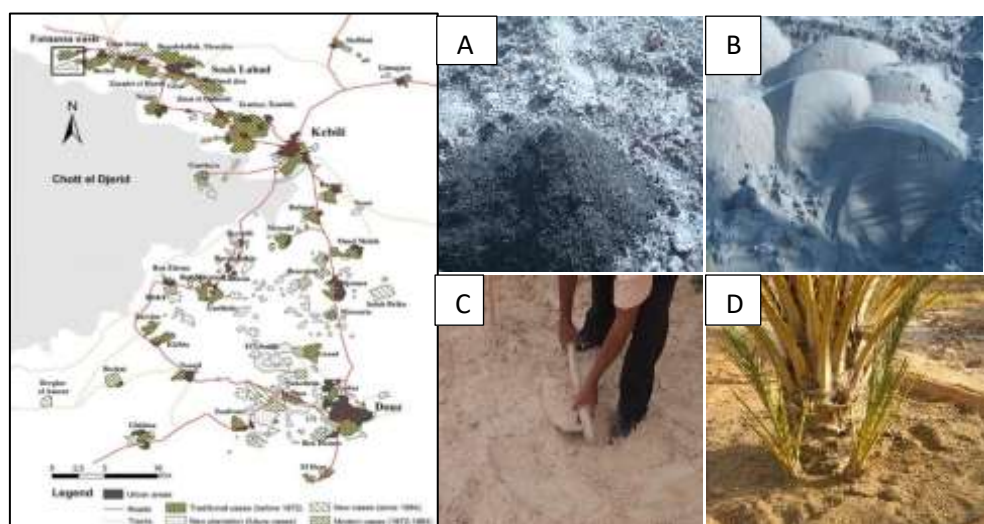


Fig.1 Left: location of Fatnassa oasis in south Tunisia adapted from Marini and Ongaro (1988). Right: Compost (A); sand dune (B); mixing of bentonite, manure and sand dune (C); and (D) soil after the application of the amendments to the palm followed by manual tillage.

Table 1. Chemical characteristics for the amendments used for the treatments.

	Type of amendment*			
	Farm Manure	Compost	Bentonite	Sand dune
pH	6.2	7.9	7.2	8.7
Organic carbon (g kg ⁻¹)	468	372	0.0	0.0
Extractable P (mg kg ⁻¹)	629	463	0.0	0.0
Total nitrogen (g kg ⁻¹)	62	58	0.0	0.0

*The applied farm manure (derived from goats and sheep) is traditionally used by farmers. The compost was derived from the waste of date palm in the Kebili oases and was processed at the Institute of Arid Land also in Kebili. The bentonite clay is derived from a geological source in Gabe's region.

All treatment amendments were applied in January 2016. The amendments were mixed in the plots into the top layer of 0-20 cm and then were tilled up to a depth of 30 cm using traditional tools (Fig. S1). The manure was applied at a rate equivalent to 3 kg m⁻²; the compost at a rate of 1 kg m⁻²; the bentonite at a rate of 0,8 kg m⁻²; and the sand dune was added at 6 kg m⁻². The previous rates for each amendment were applied for both single and multiple treatments. The ratios used for the current study were based on our previous study results (Karbout et al. 2016; Karbout et al. 2015). Soil samples from three depths (0-20, 20-40, and 40-60 cm) were directly collected after the amendments were applied ($t = 0$, January 2016), three months after the application ($t = 0.25$ year), one year later ($t = 1$ year), and two years later ($t = 2$ years).

2.2 Chemical and physical analysis

The soil organic matter in soil samples was measured with the Walkley-Black method (Black et al. 1965). Nitrogen in the digest was determined by the Kjeldahl distillation and titration method (Bremner and Mulvaney 1982). The method initially involves semi-micro Kjeldahl digestion where NaOH solution is added to release NH_3 by steam distillation. The NH_3 released is quantitatively absorbed in dilute boric acid, with total soil N determined by titration with standard acid. The C and N concentrations were determined using the following equations:

$$OC (g\ kg^{-1}) = 4 \times ((V_{HCL-V})/V_{HCL}) \times 10 \quad [1]$$

$$TN (g\ kg^{-1}) = 0.14 \times V_{HCL} \times 10 \quad [2]$$

where V_{HCL} is the control titration volume after distillation and V is the titration volume of the samples.

The OC and TN stocks were calculated by the equivalent soil mass method (Bernoux et al., 2011) after considering the soil bulk density (BD) of each depth using the following equations:

$$OC\ stock (g\ m^{-2}) = BD \times OC \times H \times 1000 \quad [3]$$

$$TN\ stock (g\ m^{-2}) = BD \times TN \times H \times 1000 \quad [4]$$

where H is soil depth (m).

The SOC and TN stock values immediately after the amendment application ($t = 0$) were estimated based on a bulk density (BD) which was set to $1.4\ g\ cm^{-3}$, equating to a soil weight of $280\ kg\ m^{-2}$ for the 20 cm depth interval. We then used measured SOC and TN concentration data to calculate their stocks at $t = -0.05$ (i.e. the SOC and TN stocks before any amendment). We then separately calculated the actual SOC and TN amounts added by applying the amendments, per specific area (e.g. $1\ kg\ m^{-2}$) and for the amendments SOC or TN contents (e.g. $372\ g\ C\ kg^{-1}$). Together, this then provided the actual amendment amount added to the soil (e.g. $372\ g\ m^{-2}$). As mentioned, the amendments were initially mixed in the top 20 cm but the soil was subsequently

tilled to 30 cm, meaning that the amendments were distributed in the top 30 cm. Therefore, overall $\frac{2}{3}$ of the amendment SOC or TN was added to the $t = -0.05$ stock for the 0-20 cm depth, and the remaining $\frac{1}{3}$ to the 20-40 cm depth. However, no SOC and TN from the amendments were thus added below 40 cm depth and we sampled 20-40 cm as the downward movement by leaching and /or bioturbation cannot be excluded. We summed the amendment and existing stocks ($t = -0.05$) SOC and TN to get the estimated $t = 0$ SOC and TN stock values (immediately after amendment). By comparing the estimated SOC and TN at $t = 0$, with those measured at $t = 0.25$, 1, and 2 years, we could then reconstruct the temporal trends of the relative loss of SOC and TN since the start of the experimental period at $t = 0$. The remaining SOC and TN in percentage (%) in the soil was calculated by dividing the SOC and TN stocks obtained for $t = 0.25$, $t = 1$, and $t = 2$ by the values calculated for $t = 0$.

2.3 Statistical Analyses

All reported data represent the mean of the three replicates for each soil sample. The statistical analyses were performed with SAS software 9.0. Differences between treatments 0-60 cm soil layer were analysed using one-way analysis of variance (ANOVA) using GML procedure with Tukey's Honstley Significant Difference (HSD) test ($p < 0.05$). The significant differences between the treatments are marked by different letters, the homogenous groups (not significantly different) are symbolized by a common letter.

3 Results and discussion

3.1 Initial soil OC and TN stocks distribution

Before the adding of amendments ($t = -0.05$), the oasis soil within the plots showed a different concentration of OC and TN stocks but the variation was not significant ($p > 0.05$). Maximum OC and TN stocks in the surface layer (0-20 cm) and (20-40 cm) layers were $2110 \pm 0.8 \text{ g m}^{-2}$ and $530 \pm 0.1 \text{ g m}^{-2}$ respectively.

This stock is the result of years of accumulation of organic amendment in the oases systems, in this context Omar et al. (2017) affirmed that the proportion of SOC at the 0-5 cm layer is on average about 23.3 % of the total SOC stocks at 30 cm depth. Preserving this layer in arid soils is crucial to protect organic carbon in the soil, and to limit the production of soil-borne dust. OC stocks in the 0–30 cm layer contain the highest SOC stocks because organic matter is preferentially accumulated at this depth (Perie and Ouimet 2008).

In (40-60 cm) the OC stocks at $t = -0.05$ were very low with $819 \pm 3.5 \text{ g m}^{-2}$. The results are in line with findings by Brahim and Ibrahim (2018) where SOC storage reached 700 g m^{-2} in the depth of 40-100 cm.

The OC concentration and stocks after amending ($t = 0$) the soils with carbon-rich amendments (SM, SBM, and SBC) was significantly affected ($p = 0.05$) and increased by 51, 48, and 12 % for SM, SBM, and SBC for the 0-20 cm layer, respectively. For the next deeper layer (20-40 cm) the increase in carbon stock was significantly negligible after the addition of carbon-rich amendments with only 2 and 4 % for the SM and SBM treatment, whereby the SBC treatment showed a comparable enrichment as for the uppermost layer with 13 %. Rasmussen et al. (2018) observed high organic matter retention in soil amended with minerals. Several other studies confirmed that soil with high clay contents has better retention to organic matter compared to sand soils (Dosskey and Bertsch 1997; Oades 1988; Van Veen et al. 1985; Wattel-Koekkoek et al. 2001). As the soil was only tilled to 30 cm depth no changes were detectable in the layer below the plow horizon (40-60 cm).

The SBM treatment showed the highest OC with 2860 g m^{-2} followed by SM with 2770, SBC with 2370, and SC with 1790 g m^{-2} for the 0-20 cm sampling depth compared to 1160 g m^{-2} for the untreated soil (U). On the other hand, the carbon stock declined for the bentonite only amendment (SB) as no additional carbon was added to the soil but the existing OC was diluted by adding more mineral phase (bentonite). At the next deeper layer, a slightly different picture was detectable with the largest stocks in the SBC treatment followed by SBM, SC, and SM (see Table 2). This inconsistency might be attributed to the differences in the soil tillage between the plots and different mixing into greater soil depths (Kay and VandenBygaart 2002; Zhao et al. 2016).

The TN concentration and stocks after amending ($t = 0$) the soils with nitrogen-rich materials like manure and compost (SBC, SBM, SM, and SC) was significantly affected by the amendment ($p = 0.05$) and increased significantly by 7, 8, 10, and 9 % for SBC, SBM, SM and SC for the 0-20 cm layer, respectively. For the next deeper layer (20-40 cm) the increase in nitrogen stock was minor after the addition of carbon-rich amendments with 3 and 5 % for the SBC and SBM treatment, whereby the SM treatment showed a comparable enrichment as for the uppermost layer with 6%.

The C/N ratio generally declined with increasing depth in the soil from values >4 (0-20 cm) to less <4 (40-60 cm), most pronounced for the dual amendments treatments SBM and SBC, with C/N_{max} value of 19 and 32 in 0-20 cm falling at 40-60 cm to below <9 and <7 , respectively. These high C/N were mostly found 1 year after the amendments, as in that period the total C content initially decline faster than total N (data not shown). Low C/N ratio $<6-8$ generally point to a dominance of inorganic C within the soil total C pool. Which is more common in semi-arid and arid soils (Ojima et al. 1993). The C/N ratios found in our study are comparable to those found by Al-Busaidi et al. (2014) in South Al Batinah Oman oasis after amending soil with manure and straw materials.

236 The accumulation of TN stocks in the depth of 20–40 cm might be attributed to the irrigation and tillage activities
237 of the sandy soils, which enhances high filtration rates and thus leaching of organic matter to larger soil depths
238 as shown also by several studies (Cleveland et al. 2004; Jinbo et al. 2006; Wang et al. 2014; Yang et al. 2018).
239 As for the OC case, no changes in TN stocks were found in deeper layers (20–40) below the 30 cm tillage layer.
240 The SBC amendment showed significant TN values with 560 g m⁻² followed by SBM with 520, SM with 490,
241 and SC with 420 g m⁻² for the 0–20 cm depth compared to 280 g m⁻² for the untreated soil (U). The TN values
242 reflect the previous findings of OC which declined with bentonite amendment only, however high stocks were
243 observed in carbon-rich treatments as SBC, SC, and SM (Table 2) (Bandian et al. 2019).

Table 2. Soil organic carbon (OC) and total nitrogen (TN) stocks (g m^{-2}) with standard deviation for mineral and organic amendments at different treatment time.

OC [g m^{-2}]							TN [g m^{-2}]					
Soil depth [cm]	U	SB	SC	SM	SBM	SBC	U	SB	SC	SM	SBM	SBC
<i>t</i> = - 0.05												
0-20	1156±2.5 ^a	1060±2.6 ^a	1541±2.4 ^a	1830±2.8 ^a	1926±3.4 ^a	2119±0.8 ^a	289±0.6 ^a	265±0.1 ^b	385±0.2 ^b	458±0.0 ^c	482±0.5 ^c	530±0.1 ^c
20-40	1975±1.5 ^a	1975±1.0 ^{ab}	1830±3.9 ^a	1397±1.2 ^a	1541±5.0 ^a	2264±1.6 ^a	494±1.0 ^c	494±0.2 ^c	458±0.0 ^c	349±0.1 ^b	385±0.6 ^b	566±0.2 ^c
40-60	819±3.5 ^b	674±0.6 ^b	1011±1.6 ^a	530±1.4 ^b	530±1.0 ^b	626±1.2 ^b	205±0.2 ^b	169±0.4 ^a	253±0.0 ^a	132±0.0 ^a	132±0.1 ^a	157±0.1 ^a
<i>t</i> = 0												
0-20	1156±2.5 ^a	1060±2.6 ^b	1789±2.4 ^{ab}	2766±2.8 ^c	2862±3.4 ^c	2367±0.8 ^c	289±0.6 ^a	265±0.1 ^b	423±0.2 ^b	499±0.1 ^c	523±0.5 ^c	567±0.4 ^b
20-40	1975±1.5 ^b	1975±0.1 ^c	1954±3.9 ^b	1865±1.2 ^b	2009±5.0 ^b	2388±1.6 ^c	494±1.0 ^b	494±0.2 ^c	476±0.0 ^c	369±0.2 ^b	406±0.6 ^b	585±0.6 ^b
40-60	819±3.5 ^c	674±0.6 ^a	1011±1.6 ^{ac}	530±1.4 ^a	530±1.0 ^a	626±1.2 ^a	205±0.2 ^a	169±0.4 ^a	253±0.0 ^a	132±0.1 ^a	132±0.1 ^a	157±0.7 ^a
<i>t</i> = 0.25												
0-20	560±0.0 ^b	840±4.2 ^{ab}	1568±1.5 ^{ab}	1708±1.9 ^{ab}	1736±2.0 ^{ab}	1596±0.3 ^a	56±0.2 ^b	84±0.0 ^b	156.8±0.0 ^{ab}	196±0.1 ^a	140±0.2 ^a	126±0.1 ^{ab}
20-40	1120±1.0 ^b	560±2.7 ^{ab}	896±2.2 ^a	1148±2.4 ^{ab}	1092±5.3 ^{ab}	784±0.5 ^a	112±0.2 ^b	84±0.1 ^b	56±0.1 ^a	168±0.1 ^a	84±0.2 ^a	56±0.2 ^{ab}
40-60	196±3.0 ^b	196±4.0 ^{ab}	252±4.1 ^{ab}	224±3.3 ^{ab}	252±0.3 ^{ab}	196±3.4 ^a	224±0.3 ^b	252±0.1 ^b	28±0.1 ^a	28±0.0 ^a	28±0.2 ^a	22.4±0.1 ^{ab}
<i>t</i> = 1												
0-20	84±0.3 ^b	56±1.1 ^b	336±2.3 ^{ab}	252±0.9 ^a	644±0.5 ^{ab}	896±0.6 ^{ab}	8.4±0.0 ^b	5.6±0.1 ^{ab}	36.4±0.0 ^{ab}	25.2±0.2 ^b	56±0.0 ^b	42±0.1 ^{ab}
20-40	28±0.3 ^b	84±2.0 ^{ab}	252±1.6 ^a	224±2.6 ^a	420±3.8 ^{ab}	532±0.6 ^{ab}	2.8±0.1 ^b	11.2±0.0 ^{ab}	28±0.0 ^b	28±0.6 ^b	56±0.0 ^b	44.8±0.1 ^{ab}
40-60	140±0.4 ^b	112±1.7 ^{ab}	112±0.8 ^a	84±2.8 ^a	140±0.9 ^{ab}	112±1.4 ^{ab}	16.8±0.1 ^b	14±0.0 ^{ab}	16.8±0.0 ^b	14±0.0 ^b	16.8±0.2 ^b	14±0.4 ^{ab}
<i>t</i> = 2												
0-20	28±0.1 ^b	28±0.5 ^{ab}	168±1.3 ^{ab}	112±1.2 ^{ab}	308±5.4 ^{ab}	700±2.5 ^a	2.8±0.1 ^a	2.8±0.5 ^a	16.8±0.5 ^a	11.2±0.1 ^a	22.4±1.9 ^a	28±0.1 ^a
20-40	28±0.6 ^b	28±0.5 ^{ab}	112±2.8 ^{ab}	56±2.8 ^{ab}	112±2.7 ^{ab}	196±3.1 ^a	2.8±0.2 ^a	8.4±0.8 ^a	8.4±0.2 ^a	16.8±0.2 ^a	8.4±1.2 ^a	19.6±0.2 ^a
40-60	56±0.5 ^b	28±0.7 ^{ab}	28±1.5 ^{ab}	56±3.1 ^a	84±5.7 ^a	28±5.4 ^{ab}	5.6±1.6 ^a	2.8±0.2 ^a	2.8±0.2 ^a	5.6±0.4 ^a	8.4±0.1 ^a	2.8±0.4 ^a

3.2 Persistence of OC and TN stocks over time

The stocks of TN decreased sharply in the years after application ($t = 1$ and 2). The decrease in the OC and TN overtime was associated with soil depth as also found by previous studies (Al-Busaidi et al. 2014; Diacono and Montemurro 2011; Gregory et al. 2016). In drylands, the mineralization of OC and TN responds mainly to microbial activity under high soil temperature and moisture changes (Hu et al. 2014). In addition, the sandy soil texture favors the leaching of the OC and TN into deeper regions (Hagin and Tucker 2012; Li et al. 2014). The declining trend has also been observed for K stocks which recorded a sharp decrease in the following two-years of the application of the amendments, unlike P stocks which revealed more persistence in soil layers over time (Preliminary results, not published). Different studies in oasis agrosystem reported that frequent irrigation in combination with warm soil conditions can result in quick mineralization of OC and TN (Buerkert et al. 2018; Wichern et al. 2004). The results showed, that the decomposition of organic matter was more pronounced in SM treatment compared to bentonite clay amended treatments i.e. SBC and SBM (Table 2). The application of compost or manure to the sandy soils increased the degradation of organic matter in the soil (Kimetu et al. 2008). Several studies confirmed the positive effects of the mineral fractions on organic matter stabilization against decomposition in soil (Bol et al. 2008; Chenu et al. 2000; Feller and Beare 1997; Lützow et al. 2006). The higher OC and TN stocks in the top and subsoil under SBC and SBM may be attributed to organic matter conservation under the sheets of bentonite and the formation of organic-mineral complexes in the soil (Wattel-Koekkoek et al. 2001). Mikutta et al. (2006) indicated that stabilization of organic matter by interaction with minerals is the most important mechanism for organic matter preservation in subsoil horizons.

The remaining stocks of the OC and TN throughout the treatment period reflect the decomposition characteristics of these stocks. Figure 2 shows that after three months of the amendment application ($t = 0.25$ year) 88 and 79 % of OC in SC and SB treatments were preserved in the soil, followed by SBC with 67, SBM with 62, and SM with 61 %. The percentage dropped sharply in the following years at $t = 1$ and $t = 2$. However, in the SBM treatment, the drop of the remaining OC stocks occurred more steadily with 38 % at $t = 1$ and 30 % at $t = 2$ compared to the other treatments. The decomposition was more pronounced at 20-40 cm depth as less OC was leftover in the soil compared to 0-20 cm soil depth. TN stock loss was more pronounced at 20-40 cm soil depth, while the lowest decomposition occurred in the treatments amended with manure and compost. Nevertheless, even after two years, the added TN stock remained in the soil as also shown in other studies (Mayes et al. 2014; Mlih et al. 2019; Xu et al. 2013).

The results indicated that integrating bentonite with the OM has altered the decomposition and preserved SOC in the soil for a long time i.e. under the SBM amendment. However, the slightly higher decomposition recorded in larger soil depths (20-40 cm) might be attributed to the robust microbial activity in this layer favored by the presence of moisture resulted from the nearby shallow water-table at this depth (Askri et al. 2014; Wang et al. 2006). Our previous work also confirmed the positive feedback of bentonite on soil moisture (Karbout et al. 2016). The larger decomposition of N can be possibly explained by the soil texture, as sandy soils can lose N in nitrate form by leaching (Zotarelli et al. 2007).

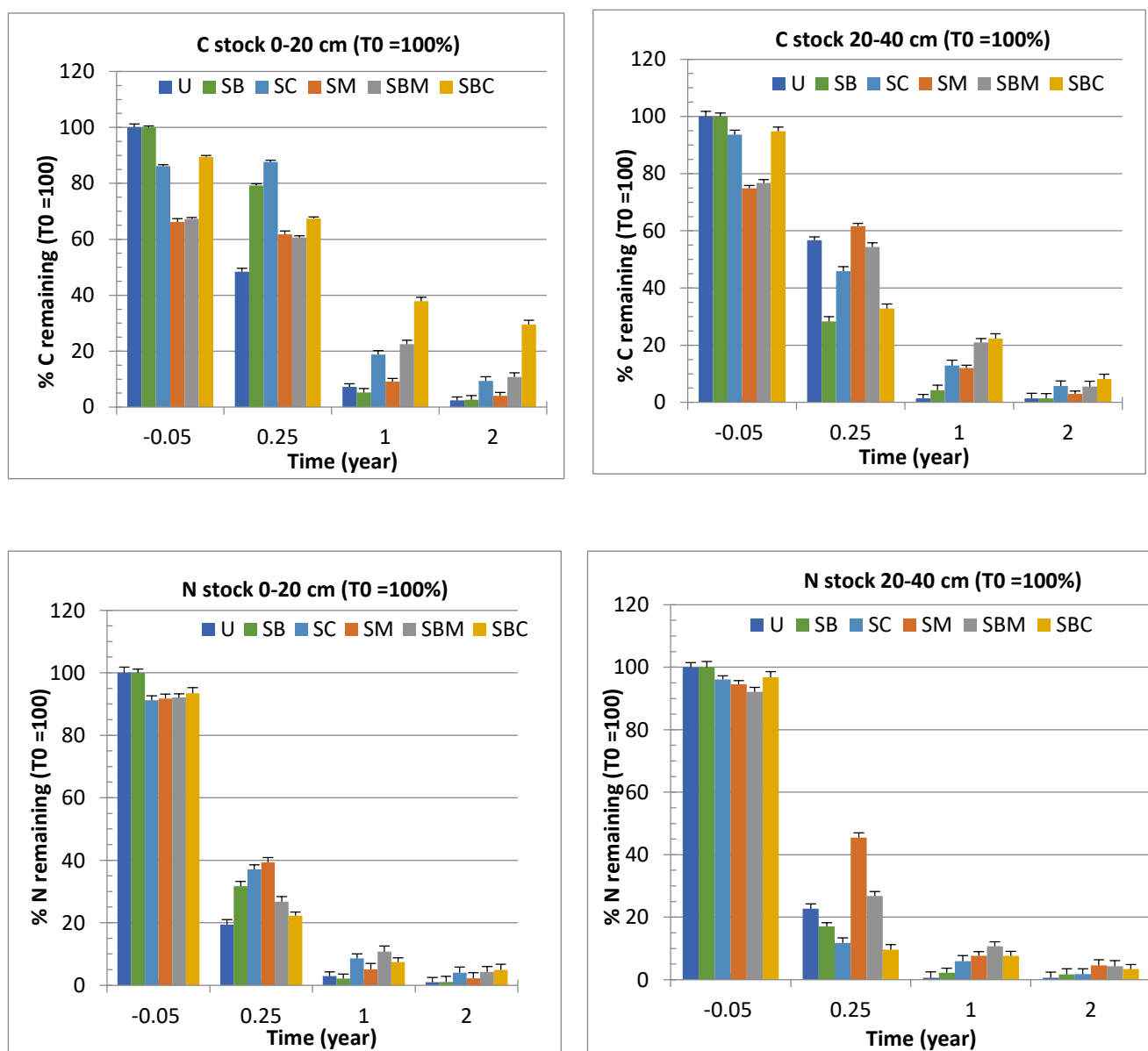


Fig. 2 Changes on the remaining SOC and TN stocks (%) under different amendments for soil depths 0-20 and 20-40 throughout the experiment period.

4 Conclusion

Our study provided the first experimental field-based evidence of integrating bentonite clay with organic amendments for improving soil fertility in an oasis agrosystem. The combined amendment mixture has enhanced OC and TN stock in the oasis soil studied and retarded their decomposition and preserved their stocks in the soil throughout the experiment of 2 years. Both mineral and organic amendments are derived locally thus they can be the best and durable practice for enhancing and maintaining oasis soil OC and TN and should be considered as an alternative option for managing soil fertility in Tunisian oasis agrosystems in a more sustainable way.

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References:

- Al-Busaidi KT, Buerkert A, Joergensen RG (2014) Carbon and nitrogen mineralization at different salinity levels in Omani low organic matter soils. *J Arid Environ* 100:106-110. doi:<https://doi.org/10.1016/j.jaridenv.2013.10.013>
- Al-Kharusi LM, Elmardi MO, Ali A, Al-Said FAJ, Abdelbasit KM, Al-Rawahi S (2009) Effect of mineral and organic fertilizers on the chemical characteristics and quality of date fruits. *Int J Agric Biol* 11:290-296.
- Al-Omran A, Falatah A, Sheta A, Al-Harbi A (2004) Clay deposits for water management of sandy soils. *Arid Land Res Manage* 18:171-183. doi:<https://doi.org/10.1080/15324980490280825>
- Allbed A, Kumar L, Sinha P (2014) Mapping and modelling spatial variation in soil salinity in the Al Hassa Oasis based on remote sensing indicators and regression techniques. *Remote Sens* 6:1137-1157. doi:<https://doi.org/10.3390/rs6021137>
- Ameta N, Purohit D, Wayal A, Sandeep D (2007) Economics of stabilizing bentonite soil with lime-gypsum. *Electron J Geotech Eng* 12.
- Amor RB, Giménez EA, de Miguel Gómez MD (2015) The competitive advantage of the Tunisian palm date sector in the Mediterranean region. *Span J Agric Res* 13:10.
- Askri B, Ahmed AT, Abichou T, Bouhlila R (2014) Effects of shallow water table, salinity and frequency of irrigation water on the date palm water use. *J Hydrol* 513:81-90. doi:<https://doi.org/10.1016/j.jhydrol.2014.03.030>
- Ayuke FO, Brussaard L, Vanlauwe B, Six J, Lelei D, Kibunja C, Pulleman M (2011) Soil fertility management: impacts on soil macrofauna, soil aggregation and soil organic matter allocation. *Appl Soil Ecol* 48:53-62.
- Bandian L, Nemati H, Moghaddam M (2019) Effects of bentonite application and urea fertilization time on growth, development and nitrate accumulation in spinach (*Spinacia oleracea* L.). *Commun Soil Sci Plant Anal* 50:1-9.

- Belgacem B (1986) Contribution à l'étude de bonification des sols sableux par un amendement argileux [Contribution to the study of the reclamation of sandy soils with a clay amendment] Mémoire de cycle de spécialisation de l'INAT Tunisie [Dissertation of the specialisation cycle of INAT Tunisia].
- Bernal MP, Alburquerque J, Moral R (2009) Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresour Technol* 100:5444-5453.
- Black C, Evans D, Dinanuer R (1965) Methods of soil analysis *J Am Soc Agron* 9:653-708.
- Bol R, Ostle N, Petzke K, Chenu C, Balesdent J (2008) Amino acid 15N in long-term bare fallow soils: Influence of annual N fertilizer and manure applications. *Eur J Soil Sci* 59:617-629.
- Boulbaba A, Marzouk L, Rabah Rb, Najet S (2012) Variations of Natural Soil Salinity in an Arid Environment Using Underground Watertable Effects on Salinization of Soils in Irrigated Perimeters in South Tunisia. *Int J Geosci* 3:8. doi:10.4236/ijg.2012.35105
- Bousnina H, Mhiri A (1998) Amélioration de la réserve d'eau utile des sols sableux des régions arides par un amendement argileux [Improvement of the useful water reserve of sandy soils in arid regions by means of a clay amendment]. *Science et changements planétaires/Sécheresse* 8:241-245.
- Brahim N, Ibrahim H (2018) Effect of Land Use on Organic Carbon Distribution in a North African Region: Tunisia Case Study. In: *Soil Management and Climate Change*. Elsevier, pp 15-24
- Bremner J, Mulvaney C (1982) Nitrogen-Total 1. Methods of soil analysis. Part 2. Chemical and microbiological properties,(methodsofsoilan2). Madison, Wisconsin: American Society of Agronomy,
- Bronick CJ, Lal R (2005) Soil structure and management: a review. *Geoderma* 124:3-22. doi:<https://doi.org/10.1016/j.geoderma.2004.03.005>
- Buerkert A, Al-Rawahi MN, Melapie M, Schlecht E (2018) Carbon and nutrient balances in three mountain oases in Northern Oman. *Journal of Agricultural and Marine Sciences [JAMS]* 22:75-86.

- Chenu C, Le Bissonnais Y, Arrouays D (2000) Organic matter influence on clay wettability and soil aggregate stability. *Soil Sci Soc Am J* 64:1479-1486.
- Cleveland CC, Neff JC, Townsend AR, Hood E (2004) Composition, Dynamics, and Fate of Leached Dissolved Organic Matter in Terrestrial Ecosystems: Results from a Decomposition Experiment. *Ecosystems* 7:175-285. doi:10.1007/s10021-003-0236-7
- de Nijs EA, Cammeraat EL (2020) The stability and fate of Soil Organic Carbon during the transport phase of soil erosion. *Earth-Sci Rev* 201:103067.
- Diacono M, Montemurro F (2011) Long-Term Effects of Organic Amendments on Soil Fertility. In: Lichtfouse E, Hamelin M, Navarrete M, Debaeke P (eds) *Sustainable Agriculture Volume 2*. Springer Netherlands, Dordrecht, pp 761-786. doi:10.1007/978-94-007-0394-0_34
- Dosskey MG, Bertsch PM (1997) Transport of Dissolved Organic Matter through a Sandy Forest Soil. *Soil Sci Soc Am J* 61:920-927. doi:<https://doi.org/10.2136/sssaj1997.03615995006100030030x>
- Dregne HE (2002) Land degradation in the drylands. *Arid Land Res Manage* 16:99-132.
- English NB, Weltzin JF, Fravolini A, Thomas L, Williams DG (2005) The influence of soil texture and vegetation on soil moisture under rainout shelters in a semi-desert grassland. *J Arid Environ* 63:324-343. doi:<https://doi.org/10.1016/j.jaridenv.2005.03.013>
- Feller C, Beare MH (1997) Physical control of soil organic matter dynamics in the tropics. *Geoderma* 79:69-116. doi:[https://doi.org/10.1016/S0016-7061\(97\)00039-6](https://doi.org/10.1016/S0016-7061(97)00039-6)
- Franzluebbers AJ, Haney RL, Honeycutt CW, Arshad MA, Schomberg HH, Hons FM (2001) Climatic influences on active fractions of soil organic matter. *Soil Biol Biochem* 33:1103-1111. doi:[https://doi.org/10.1016/S0038-0717\(01\)00016-5](https://doi.org/10.1016/S0038-0717(01)00016-5)
- Fu Q, Feng S (2014) Responses of terrestrial aridity to global warming. *J Geophys Res Atmos* 119:7863-7875.
- Glenn E, Squires V, Olsen M, Frye R (1993) Potential for Carbon Sequestration in the Drylands. In: Wisniewski J, Sampson RN (eds) *Terrestrial Biospheric Carbon Fluxes Quantification of*

Sinks and Sources of CO₂. Springer Netherlands, Dordrecht, pp 341-355. doi:10.1007/978-94-011-1982-5_22

Gregory AS, Dungait JAJ, Watts CW, Bol R, Dixon ER, White RP, Whitmore AP (2016) Long-term management changes topsoil and subsoil organic carbon and nitrogen dynamics in a temperate agricultural system. *Eur J Soil Sci* 67:421-430. doi:<https://doi.org/10.1111/ejss.12359>

Hagin J, Tucker B (2012) Fertilization of dryland and irrigated soils vol 12. Springer Science & Business Media,

Hannachi N et al. (2015) Effects of cultivation on chemical and biochemical properties of dryland soils from southern Tunisia. *Agric Ecosyst Environ* 199:249-260. doi:<https://doi.org/10.1016/j.agee.2014.09.009>

Hassink J (1997) The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant Soil* 191:77-87. doi:10.1023/A:1004213929699

Hu R, Wang X-p, Pan Y-x, Zhang Y-f, Zhang H (2014) The response mechanisms of soil N mineralization under biological soil crusts to temperature and moisture in temperate desert regions. *Eur J Soil Biol* 62:66-73. doi:<https://doi.org/10.1016/j.ejsobi.2014.02.008>

Jemai S, Kallel A, Abida H (2018) Drought distribution using the standardized precipitation index: case of Gabes Basin, South Tunisia. *Arab J Geosci* 11:737.

Jinbo Z, Changchun S, Wenyan Y (2006) Land Use Effects on the Distribution of Labile Organic Carbon Fractions through Soil Profiles. *Soil Sci Soc Am J* 70:660-667. doi:<https://doi.org/10.2136/sssaj2005.0007>

Kadri A, Van Ranst E (2002) Contraintes de la production oasienne et stratégies pour un développement durable. Cas des oasis de Nefzaoua (Sud tunisien), [Limitations of oasis production and strategies for sustainable development, South Tunisia]. *Science et changements planétaires / Sécheresse* 13:5-12.

- Karbout N, Gasmi I, Moussa M, Bousnina H (2016) Effect of clay amendment on the conservation of moisture in sandy soils of South East Tunisia. *J Res Environ Earth Sci* 4:125-131.
- Karbout N, Moussa M, Gasmi I, Bousnina H (2015) Effect of clay amendment on physical and chemical characteristics of sandy soil in arid areas: the case of ground south-eastern Tunisian. *Appl Sci Reports* 11:43-48.
- Kay BD, VandenBygaart AJ (2002) Conservation tillage and depth stratification of porosity and soil organic matter. *Soil Till Res* 66:107-118. doi:[https://doi.org/10.1016/S0167-1987\(02\)00019-3](https://doi.org/10.1016/S0167-1987(02)00019-3)
- Kimetu JM et al. (2008) Reversibility of Soil Productivity Decline with Organic Matter of Differing Quality Along a Degradation Gradient. *Ecosystems* 11:726. doi:10.1007/s10021-008-9154-z
- King C, Thomas DSG (2014) Monitoring environmental change and degradation in the irrigated oases of the Northern Sahara. *J Arid Environ* 103:36-45. doi:<https://doi.org/10.1016/j.jaridenv.2013.12.009>
- Lal R (2004) Carbon sequestration in dryland ecosystems. *Environ Manage* 33:528-544.
- Li Y, Liu Y, Wang Y, Niu L, Xu X, Tian Y (2014) Interactive effects of soil temperature and moisture on soil N mineralization in a *Stipa krylovii* grassland in Inner Mongolia, China. *J Arid Land* 6:571-580. doi:10.1007/s40333-014-0025-5
- Liao JD, Boutton TW, Jastrow JD (2006) Storage and dynamics of carbon and nitrogen in soil physical fractions following woody plant invasion of grassland. *Soil Biol Biochem* 38:3184-3196. doi:<https://doi.org/10.1016/j.soilbio.2006.04.003>
- Lützow Mv, Kögel-Knabner I, Ekschmitt K, Matzner E, Guggenberger G, Marschner B, Flessa H (2006) Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions – a review. *Eur J Soil Sci* 57:426-445. doi:<https://doi.org/10.1111/j.1365-2389.2006.00809.x>

- Ma W, Zhang X (2016) Effect of Pisha sandstone on water infiltration of different soils on the Chinese Loess Plateau. *J arid land* 8:331-340. doi:10.1007/s40333-016-0122-8
- Marlet S, Bouksila F, Bahri A (2009) Water and salt balance at irrigation scheme scale: A comprehensive approach for salinity assessment in a Saharan oasis. *Agric Water Manage* 96:1311-1322. doi:<https://doi.org/10.1016/j.agwat.2009.04.016>
- Marzouk HA, Kassem HA (2011) Improving fruit quality, nutritional value and yield of Zaghloul dates by the application of organic and/or mineral fertilizers. *Scientia Horticulturae* 127:249-254. doi:<https://doi.org/10.1016/j.scienta.2010.10.005>
- Mayes M, Marin-Spiotta E, Szymanski L, Akif Erdoğan M, Ozdoğan M, Clayton M (2014) Soil type mediates effects of land use on soil carbon and nitrogen in the Konya Basin, Turkey. *Geoderma* 232-234:517-527. doi:<https://doi.org/10.1016/j.geoderma.2014.06.002>
- Mikutta R, Kleber M, Torn MS, Jahn R (2006) Stabilization of Soil Organic Matter: Association with Minerals or Chemical Recalcitrance? *Biogeochemistry* 77:25-56. doi:10.1007/s10533-005-0712-6
- Mlih R, Bol R, Amelung W, Brahim N (2016) Soil organic matter amendments in date palm groves of the Middle Eastern and North African region: a mini-review. *J Arid Land* 8:77-92. doi:<https://doi.org/10.1007/s40333-015-0054-8>
- Mlih RK, Gocke MI, Bol R, Berns AE, Fuhrmann I, Brahim N (2019) Soil Organic Matter Composition in Coastal and Continental Date Palm Systems: Insights from Tunisian Oases. *Pedosphere* 29:444-456. doi:[https://doi.org/10.1016/S1002-0160\(19\)60814-3](https://doi.org/10.1016/S1002-0160(19)60814-3)
- Mojid M, Mustafa S, Wyseure G (2009) Growth, yield and water use efficiency of wheat in silt loam-amended loamy sand. *J Bangladesh Agril Univ* 7:403-410.
- Mureva A, Ward D, Pillay T, Chivenge P, Cramer M (2018) Soil Organic Carbon Increases in Semi-Arid Regions while it Decreases in Humid Regions Due to Woody-Plant Encroachment of Grasslands in South Africa. *Sci Rep* 8:15506. doi:10.1038/s41598-018-33701-7

- Oades JM (1988) The retention of organic matter in soils. *Biogeochemistry* 5:35-70.
doi:<https://doi.org/10.1007/BF02180317>
- Ojima DS, Dirks BOM, Glenn EP, Owensby CE, Scurlock JO (1993) Assessment of C budget for grasslands and drylands of the world. *Water, Air, Soil Pollut* 70:95-109.
doi:<https://doi.org/10.1007/BF01104990>
- Omar Z, Bouajila A, Brahim N, Grira M (2017) Soil property and soil organic carbon pools and stocks of soil under oases in arid regions of Tunisia. *Environ Earth Sci* 76:415.
doi:10.1007/s12665-017-6745-z
- Perie C, Ouimet R (2008) Organic carbon, organic matter and bulk density relationships in boreal forest soils. *Can J Soil Sci* 88:315-325.
- Plaza-Bonilla D, Arrúe JL, Cantero-Martínez C, Fanlo R, Iglesias A, Álvaro-Fuentes J (2015) Carbon management in dryland agricultural systems. A review. *Agron Sustain Dev* 35:1319-1334.
- Qiu Y, Xie Z, Wang Y, Malhi SS, Ren J (2015) Long-term effects of gravel—sand mulch on soil organic carbon and nitrogen in the Loess Plateau of northwestern China. *J Arid Land* 7:46-53.
doi:<https://doi.org/10.1007/s40333-014-0076-7>
- Rasmussen C et al. (2018) Beyond clay: towards an improved set of variables for predicting soil organic matter content. *Biogeochemistry* 137:297-306. doi:<https://doi.org/10.1007/s10533-018-0424-3>
- Reynolds JF et al. (2007) Global desertification: building a science for dryland development. *Science* 316:847-851.
- Seager R et al. (2007) Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America. *Science* 316:1181-1184. doi:10.1126/science.1139601
- Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res* 79:7-31.
doi:<https://doi.org/10.1016/j.still.2004.03.008>

- Steele R, Evans D, Booth M, Proper M (2001) Soil amendment product and process. Google Patents,
- Su YZ, Wang XF, Yang R, Lee J (2010) Effects of sandy desertified land rehabilitation on soil carbon sequestration and aggregation in an arid region in China. *J Environ Manage* 91:2109-2116. doi:<https://doi.org/10.1016/j.jenvman.2009.12.014>
- Suzuki S, Noble AD, Ruaysoongnern S, Chinabut N (2007) Improvement in Water-Holding Capacity and Structural Stability of a Sandy Soil in Northeast Thailand. *Arid Land Res Manag* 21:37-49. doi:<https://doi.org/10.1080/15324980601087430>
- Tengberg M (2012) Beginnings and early history of date palm garden cultivation in the Middle East. *J Arid Environ* 86:139-147. doi:<https://doi.org/10.1016/j.jaridenv.2011.11.022>
- Van Veen JA, Ladd JN, Amato M (1985) Turnover of carbon and nitrogen through the microbial biomass in a sandy loam and a clay soil incubated with [¹⁴C(U)]glucose and [¹⁵N](NH₄)₂SO₄ under different moisture regimes. *Soil Biol Biochem* 17:747-756. doi:[https://doi.org/10.1016/0038-0717\(85\)90128-2](https://doi.org/10.1016/0038-0717(85)90128-2)
- Wang C, Wan S, Xing X, Zhang L, Han X (2006) Temperature and soil moisture interactively affected soil net N mineralization in temperate grassland in Northern China. *Soil Biol Biochem* 38:1101-1110. doi:<https://doi.org/10.1016/j.soilbio.2005.09.009>
- Wang L, d'Odorico P, Evans J, Eldridge D, McCabe M, Caylor K, King E (2012) Dryland ecohydrology and climate change: critical issues and technical advances. *Hydrol Earth Syst Sci* 6:2585-2603.
- Wang M, Su Y, Yang X (2014) Spatial Distribution of Soil Organic Carbon and Its Influencing Factors in Desert Grasslands of the Hexi Corridor, Northwest China. *PLoS One* 9:e94652. doi:<https://doi.org/10.1371/journal.pone.0094652>
- Wattel-Koekkoek EJW, van Genuchten PPL, Buurman P, van Lagen B (2001) Amount and composition of clay-associated soil organic matter in a range of kaolinitic and smectitic soils. *Geoderma* 99:27-49. doi:[https://doi.org/10.1016/S0016-7061\(00\)00062-8](https://doi.org/10.1016/S0016-7061(00)00062-8)

- Wichern F, Müller T, Joergensen RG, Buerkert A (2004) Effects of manure quality and application forms on soil C and N turnover of a subtropical oasis soil under laboratory conditions. *Biol Fertility Soils* 39:165-171. doi:<http://doi.org/10.1007/s00374-003-0689-z>
- Xu X, Thornton PE, Post WM (2013) A global analysis of soil microbial biomass carbon, nitrogen and phosphorus in terrestrial ecosystems. *Global Ecol Biogeogr* 22:737-749. doi:<https://doi.org/10.1111/geb.12029>
- Yang F et al. (2018) Vertical distribution and storage of soil organic and inorganic carbon in a typical inland river basin, Northwest China. *J Arid Land* 10:183-201. doi:<http://doi.org/10.1007/s40333-018-0051-9>
- Zhao W, Zhang R, Huang C, Wang B, Cao H, Koopal LK, Tan W (2016) Effect of different vegetation cover on the vertical distribution of soil organic and inorganic carbon in the Zhifanggou Watershed on the loess plateau. *CATENA* 139:191-198. doi:<https://doi.org/10.1016/j.catena.2016.01.003>
- Zotarelli L, Scholberg JM, Dukes MD, Muñoz-Carpena R (2007) Monitoring of Nitrate Leaching in Sandy Soils. *J Environ Qual* 36:953-962. doi:<https://doi.org/10.2134/jeq2006.0292>

Supplementary materials

Table S1. SOC, TN concentrations (g kg^{-1}) and C/N ratio under various amendment treatments and experimental periods.

	Period (years)	U	SB	SC	SM	SBM	SBC
Soil depth: 0-20 cm							
OC (g kg^{-1})	t=-0.05	4.1±0.1 ^a	3.7±0.1 ^a	5.5±0.1 ^a	6.5±0.1 ^a	6.8±0.1 ^a	7.5±0.1 ^a
	t=0	4.1±0.1 ^a	3.7±0.1 ^a	6.3±0.2 ^b	9.8±0.2 ^c	10.2±0.1 ^d	8.4±0.1 ^c
	t=0.25	0.2±0.0 ^b	0.3±0.1 ^{ab}	5.6±0.1 ^{ab}	6.1±0.1 ^{ab}	6.2±0.3 ^{ab}	5.7±0.1 ^a
	t=1	0.3±0.1 ^b	0.2±0.1 ^{ab}	1.2±0.2 ^{ab}	0.9±0.2 ^a	2.3±0.1 ^{ab}	3.2±0.5 ^{ab}
	t=2	0.1±0.1 ^b	0.1±0.0 ^{ab}	0.6±0.1 ^{ab}	0.4±0.0 ^{ab}	1.1±0.1 ^{ab}	2.5±0.3 ^a
TN (g kg^{-1})	t=-0.05	1.0±0.2 ^a	0.9±0.1 ^a	1.3±0.1 ^a	1.6±0.1 ^a	1.7±0.1 ^a	1.8±0.1 ^a
	t=0	1.0±0.1 ^a	0.9±0.1 ^a	1.5±0.2 ^b	1.7±0.2 ^b	1.8±0.1 ^b	2.0±0.2 ^c
	t=0.25	0.0±0.0 ^b	0.0±0.0 ^b	0.5±0.1 ^{ab}	0.7±0.3 ^a	0.5±0.3 ^a	0.4±0.1 ^{ab}
	t=1	0.0±0.0 ^b	0.0±0.0 ^{ab}	0.1±0.0 ^{ab}	0.1±0.0 ^b	0.2±0.1 ^b	0.1±0.1 ^{ab}
	t=2	0.0±0.0 ^a	0.0±0.0 ^a	0.1±0.0 ^a	0.0±0.0 ^a	0.1±0.0 ^a	0.1±0.0 ^a
Soil depth: 20-40 cm							
OC (g kg^{-1})	t=-0.05	7.0±0.1 ^a	7.0±0.1 ^a	6.5±0.1 ^a	4.9±0.1 ^a	5.5±0.1 ^a	8.0±0.1 ^a
	t=0	7.0±0.1 ^a	7.0±0.1 ^a	6.9±0.2 ^b	6.6±0.1 ^b	7.1±0.2 ^{ab}	8.5±0.2 ^c
	t=0.25	0.4±0.4 ^a	0.2±0.2 ^a	3.2±0.5 ^a	4.1±0.6 ^a	3.9±0.8 ^a	2.8±0.4 ^a
	t=1	0.1±0.1 ^c	0.3±0.1 ^{ab}	0.9±0.3 ^{bc}	0.8±0.3 ^{abc}	1.5±0.5 ^a	1.9±0.2 ^{ab}
	t=2	0.1±0.0 ^b	0.1±0.1 ^{ab}	0.4±0.1 ^{ab}	0.2±0.1 ^{ab}	0.4±0.1 ^a	0.7±0.1 ^{ab}
TN (g kg^{-1})	t=-0.05	1.7±0.1 ^a	1.7±0.1 ^a	1.6±0.1 ^a	1.2±0.1 ^a	1.3±0.1 ^a	2.0±0.1 ^a
	t=0	1.7±0.1 ^a	1.7±0.1 ^a	1.7±0.2 ^a	1.3±0.2 ^b	1.4±0.1 ^b	2.0±0.2 ^c
	t=0.25	0.0±0.2 ^b	0.0±0.4 ^b	0.2±0.3 ^a	0.6±0.8 ^a	0.3±0.1 ^{ab}	0.2±0.1 ^b
	t=1	0.0±0.1 ^a	0.0±0.1 ^a	0.1±0.1 ^a	0.1±0.1 ^a	0.2±0.1 ^a	0.1±0.0 ^a
	t=2	0.0±0.0 ^b	0.0±0.1 ^a	0.0±0.2 ^a	0.0±0.0 ^a	0.0±0.0 ^a	0.1±0.0 ^a
Soil depth: 40-60 cm							
OC (g kg^{-1})	t=-0.05	2.9±0.1 ^a	2.4±0.1 ^a	3.6±0.1 ^a	1.8±0.1 ^a	1.8±0.1 ^a	2.2±0.1 ^a
	t=0	2.9±0.1 ^a	2.4±0.1 ^a	3.6±0.1 ^a	1.8±0.1 ^a	1.8±0.1 ^a	2.2±0.1 ^a
	t=0.25	0.7±0.3 ^a	0.7±0.1 ^a	0.9±0.1 ^a	0.8±0.0 ^a	0.9±0.1 ^a	0.7±0.1 ^a
	t=1	0.5±0.1 ^a	0.4±0.1 ^a	0.4±0.3 ^a	0.3±0.2 ^a	0.5±0.2 ^a	0.4±0.2
	t=2	0.2±0.1 ^a	0.1±0.1 ^a	0.1±0.0 ^a	0.2±0.1 ^a	0.3±0.1 ^a	0.1±0.0 ^a
TN (g kg^{-1})	t=-0.05	0.7±0.1 ^a	0.6±0.1 ^a	0.9±0.1 ^a	0.4±0.1 ^a	0.4±0.1 ^a	0.5±0.1 ^a
	t=0	0.7±0.1 ^a	0.6±0.1 ^a	0.9±0.1 ^a	0.4±0.1 ^b	0.4±0.1 ^b	0.5±0.1 ^c
	t=0.25	0.1±0.2 ^b	0.1±0.2 ^b	0.1±0.2 ^a	0.1±0.8 ^a	0.1±0.3 ^{ab}	0.1±0.1 ^b
	t=1	0.1±0.0 ^a	0.1±0.0 ^a	0.1±0.1 ^a	0.1±0.0 ^a	0.1±0.1	0.1±0.0
	t=2	0.0±0.0 ^b	0.0±0.0 ^a	0.0±0.0 ^a	0.0±0.0 ^a	0.0±0.0 ^a	0.0±0.0 ^a

U: Untreated soil; SB: Sand dune +Bentonite; SC: Sand dune + compost; SM: Sand dune + manure; SBM: Sand dune+ Bentonite+ manure;

SBC: Sand dune+ Bentonite + Compost

Table S2. Bulk density at 0-60 cm soil depth under various amendment treatments for different experimental periods

Soil depth (cm)	Period (years)	U	SB	SC	SM	SBM	SBC
0-20	t=-0.05	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a
	t=0	1.4±0.3 ^a	1.4±0.1 ^a	1.3±0.1 ^a	1.3±0.4 ^a	1.3±0.1 ^a	1.3±0.1 ^a
	t=0.25	1.4±0.3 ^a	1.3±0.1 ^a	1.3±0.1 ^a	1.3±0.0 ^a	1.3±0.1 ^a	1.3±0.1 ^a
	t=1	1.4±0.1 ^a	1.3±0.1 ^a	1.3±0.3 ^a	1.3±0.0 ^a	1.3±0.2 ^a	1.4±0.2 ^a
	t=2	1.4±0.1 ^a	1.4±0.1 ^a	1.3±0.05 ^a	1.3±0.1 ^a	1.4±0.1 ^a	1.4±0.0 ^a
20-40	t=-0.05	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a
	t=0	1.4±0.3 ^a	1.4±0.1 ^a	1.3±0.1 ^a	1.3±0.4 ^a	1.3±0.1 ^a	1.3±0.1 ^a
	t=0.25	1.3±0.2 ^a	1.4±0.2 ^b	1.3±0.2 ^b	1.3±0.8 ^a	1.4±0.3 ^a	1.3±0.1 ^a
	t=1	1.4±0.1 ^a	1.4±0.0 ^a	1.3±0.03 ^a	1.3±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a
	t=2	1.4±0.1 ^a	1.4±0.0 ^a	1.3±0.02 ^a	1.3±0.3 ^a	1.4±0.1 ^a	1.4±0.1 ^a
40-60	t=-0.05	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a
	t=0	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.2 ^a	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a
	t=0.25	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.2 ^a	1.4±0.1 ^a	1.4±0.1 ^a	1.4±0.1 ^a
	t=1	1.5±0.2 ^a	1.5±0.1 ^a	1.5±0.4 ^a	1.5±0.1 ^a	1.5±0.1 ^a	1.5±0.1 ^a
	t=2	1.5±0.5 ^a	1.5±0.1 ^a	1.5±0.8 ^a	1.5±0.1 ^a	1.5±0.4 ^a	1.5±0.2 ^a

U: Untreated soil; SB: Sand dune +Bentonite; SC: Sand dune + compost; SM: Sand dune + manure; SBM: Sand dune+ Bentonite+ manure; SBC: Sand dune+ Bentonite + Compost

