Effects of cultivation on chemical and biochemical properties of dryland soils from southern Tunisia

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ABSTRACT

The progressive degradation of cultivated drylands has been mainly ascribed to adoption of intensive soil use, namely repeated soil cultivation with external inputs and disturbances. Consequently, soil managements in equilibrium with environmental and social constrains are required to conserve and improve the soil fertility. We evaluated the impact of soil cultivation and management on chemical and biochemical properties of dryland soils from the Tunisian Jeffara Plain. This study considered three sites (Chenini Nahel, Matmata Nouvelle, Menzel Habib), with both non-cultivated and cultivated soils. These latter were subjected to different soil management: organic fertilisation and irrigation by submersion, chemical fertilisation and drip irrigation, no fertilisation and sporadic watering. The results showed that the addition of

organic matter as compost or manure combined with irrigation may favour pH reduction, with consequently higher enzymatic activity and organic matter storage. The latter occurred because of the encapsulation of organic particles into collars made of re-precipitated gypsum and calcite. In cases where chemical fertilization and drip irrigation were applied, the organic matter stabilisation occurred only at the surface; at depth we observed a reduction of organics due to microbially-mediated mineralisation processes. When neither organic amendment nor water was supplied, no substantial difference occurred between cultivated and non-cultivated soils. We concluded that, in drylands, agricultural managements providing the use of water and organic amendments is the way to increase soil organic matter storage and improve physical, chemical and biological properties so to enhance the soil fertility.

Keywords: coastal oasis; soil genesis; henna plant; gypsum; alluvial soils; soil organic matter; enzyme activity

1. INTRODUCTION

With respect to world land surface (148.94 million km^2), the current distribution of drylands includes 13.6% as semi-arid environments, 15.7% as arid environments, and 5.6% as hyper-arid environments (Thomas, 2011). This means that about 52 million km^2 are drylands – about one third of the global land surface. These areas are diffused in all the continents except Antarctica (Thomas, 2011), and are mostly made of Aridisols and Entisols (FAO, 2002). Most drylands are too dry for agriculture (Creswell and Martin, 1998). However, some arid lands have been cultivated for a long time, while others have been cultivated only in recent decades because of the population increase many countries have experienced (Creswell and Martin,

1998). The cultivation of these lands has been accomplished via dryland farming or thanks to irrigation where groundwater can be easily or economically extracted.

In many places, because of the even warmer climatic conditions and higher vulnerability of the drylands due to wind erosion and excess cultivation, a progressive soil degradation has occurred. Degradation of cultivated dryland soils has been ascribed to two factors, both far from the environmental equilibrium (Lal, 2000): *i*) changes of land use, and *ii*) adoption of intensive soil management represented by repeated soil cultivation with external inputs and disturbances. Thus, it is necessary to find or develop techniques for appropriate management and protection of soil fertility worldwide, especially given global climate change. This issue is even more important for the management of dryland soils in a way that can ensure soil conservation and stabilization of the agricultural production in the mid-to-long term (Creswell and Martin, 1998). To reach this goal, we have to increase knowledge of the relationships between soil management and chemical and biochemical properties on dryland soils.

It is known that soil microbial activity is related to ecosystem stability and fertility, and that soil fertility is a great problem in drylands. Few researches have investigated the impact of management on the biochemical properties of dryland soils. Most of these studies have dealt with soil physico-chemical properties (e.g., Ben Moussa-Machraoui et al., 2010; Jordan et al., 2010), or have taken into account the biochemical properties of the soil surface only (e.g., Pascual et al., 1999; Armas et al., 2007). To better understand soil-plant interactions and for a successful soil conservation under dry climates, a good knowledge of the chemical and biochemical properties of a considerable soil thickness (at least that of the *solum*) is required.

The main aim of this work was to test the hypothesis if a certain agricultural management in arid environments may improve soil fertility and foster soil evolution. To achieve this goal, we assessed the impact of cultivation on physico-chemical and biochemical properties of pre-

desert soils with respect to non-cultivated soils. The cultivated soils were subjected to different management: *i*) organic fertilisation and irrigation by submersion, *ii*) chemical fertilisation and drip irrigation, and *iii*) no fertilisation and sporadic watering.

2. MATERIAL AND METHODS

2.1. Site description, climatic features and soil uses

The region selected for this study was located in the Tunisian Djeffara Plain, which spans from the low plains located south of the Gafsa Mountains to the Sahara boundary in Southern Tunisia. Three sites were selected as they featured both non-cultivated and cultivated soils: Chenini Nahel, Matmata Nouvelle, and Menzel Habib (Figure 1). Geomorphologic, physiographic and climatic details are given in the Supplementary File.

2.1.1. Chenini Nahel

The oasis of Chenini Nahel, located along the coast of the Gulf of Gabès, is one of the few coastal oases in the Mediterranean. The climate is arid Mediterranean with a mean annual precipitation of 185 mm, a mean annual air temperature of 22.5°C and an Aridity Index of 0.12, corresponding to a land with an arid type of dryness (UNEP, 1997).

As a non-cultivated soil we selected one densely covered by cane [*Phragmites australis* (Cav.) Trin. ex Steud] and tamarisk (*Tamarix* sp.) that has not been cultivated at least during the last 30 years; no specific information was available on the previous use except that this soil has never been used for vegetable crops. For the cultivated soil we chose one at about 40 m apart that had been cultivated for 9 years with henna (*Lawsonia inermis* L.) and that had been previously devoted to vegetables for an unknown period. The henna crop was watered

by submersion and the soil received about 10 Mg ha^{-1} y^{-1} compost derived from dry wastes of different vegetal and animal sources that are often mixed with manure.

2.1.2. Matmata Nouvelle

The site of Matmata Nouvelle is at about 7 km (north-west) from the city of Matmata Nouvelle. The climate is arid Mediterranean with a mean annual precipitation of 175 mm, a mean annual air temperature of 19.8°C, and an Aridity Index of 0.09, corresponding to a land with an arid type of dryness (UNEP, 1997).

As a non-cultivated soil we chose one with about 80% barren surface and about 20% of plant cover dominated by Gymnocarpos (*Gymnocarpos decandrus* Forssk.) and field wormwood (*Artemisia campestris* L.). A few hundred meters from the non-cultivated one, we selected a soil that had been cultivated with vegetables over the last two decades and featured a red pepper (*Capsicum annuum* L.) crop at the time of sampling. The red pepper crop was watered by drip irrigation and chemically fertilised with 30-40 kg ha^{-1} y^{-1} of N and 10 kg ha^{-1} y^{-1} of P.

2.1.3. Menzel Habib

The site of Menzel Habib is at about 5 km (south-east) from the city of Menzel Habib. The climate is arid Mediterranean with a mean annual precipitation of 155 mm, a mean annual air temperature of 23.5°C, and an Aridity Index of 0.13, corresponding to a land with an arid type of dryness (UNEP, 1997).

The non-cultivated soil is covered by a shrub steppe made of plants such as lotus fruit, albardine, esparto grass, and cooba (*Acacia salicina* Lindl.). A few hundred meters from the non-cultivated one, we selected a cultivated soil under an olive grove. The cultivated soil was not fertilized and sporadically irrigated (one or two times per year) by means of tank cars.

2.3. Soil sampling and sample preparation

In September 2010, at each site, a geomorphological survey was conducted together with the opening of several auger holes and mini-pits. Due to the dynamicity of the alluvial, fluvial and aeolian processes that generated these soils, a certain spatial variability of some soil physical property was rather expected. Because of this, in each study site we selected non-cultivated and cultivated soils with the most similar physical properties in terms of texture and drainage. Since the type of climate, we attributed the eventual chemical and biological differences between non-cultivated and cultivated soils to cultivation induced changes.

In both non-cultivated and cultivated soils, two profiles large enough to include superficial micro-variability were opened at about 10-15 m far apart and described (Schoeneberger et al., 2002). For each profile, every soil horizon was sampled from the exposed width by collecting about 1 kg of soil. Hence, for both non-cultivated and cultivated soil, each horizon was sampled in duplicate. The samples were stored cold in bags for transport to the lab. Within one week from sampling, the field moist samples were sieved at 2 mm to separate the rock fragments from the fine earth and an aliquot of the latter was stored at -20°C for biochemical assays. The remainder of the fine earth was air dried for physico-chemical analyses.

2.4. Physical and chemical analyses

Soil texture was obtained by the pipette method (Day, 1965) after the specimens were submerged in NaClO (pH 9) for 24 h to destroy the organic cements. Soil pH was measured in a suspension (solid:liquid ratio 1:2.5) by a combined glass-calomel electrode. Soil mineralogy was assessed by x-ray diffraction with a Philips PW 1830 diffractometer (Fe-filtered Co Kα1 radiation, 35 kV and 25 mA). A semi-quantitative estimation was obtained after identification

of the minerals on the basis of their characteristic peaks. Separates of 0.5–2 mm diameter, recovered from the extraction residue of the organic matter fractionation protocol prior the 0.5 M HCl solution treatment (see below), were observed under an optical microscope. Total C and N were determined by a Carlo Erba EA1110 dry combustion analyzer. The amount of total organic C (TOC) was measured by dichromate digestion, heating the suspension at 180°C for 30 min (Allison, 1965). As the Walkley-Black method without application of heat is considered not able to oxidize the coarse particulate organic matter, it was used to estimate the amount of the most oxidizable organic matter (e.g., Frink, 1995), here called organic C (OC). The content of inorganic C was obtained from the difference between total C and TOC.

2.5. Fractionation of organic matter

The organic matter pools were extracted by a sequential fractionation procedure (Agnelli et al., 2014). Briefly, 100 g of sample were placed into a beaker, submerged with water (solid:liquid ratio 1:5) and shaken overnight. Afterward, the suspension was left to stand for a few hours and the supernatant was passed through a 0.05-mm sieve. The fraction coarser than 0.05 mm was washed with distilled water over the sieve, washed with a 0.25 M HCl solution to eliminate carbonates, washed again with distilled water, dried at 40°C, and weighed. This fraction contained the free particulate organic matter (POM), which is mainly made of partially decomposed vegetal and animal debris. The solution used to wash the POM was added to the fraction finer than 0.05 mm and suspended in a cylinder for 24 h. The liquid phase was then recovered, acidified to pH 3.5 with a 0.25 M HCl solution to eliminate carbonates, filtered through Whatman 42 filter paper, and its volume quantitatively determined. According to Ghani et al. (2003), the organics dissolved in the solution represented the water-extractable organic matter (WEOM). The solid phase was submitted to

alkaline extraction (Nelson and Summers, 1996) by transferring it into a centrifuge tube together with the material retained on the Whatman 42 filter and 50 ml of a 0.1 M NaOH solution. The suspension was gently shaken overnight; then, it was centrifuged for 15 min at about 15,000 *g* and filtered through Whatman 42 filter. The extraction with 0.1 M NaOH solution was repeated another time. The residue was then washed twice with 50 ml of distilled water, recovered by centrifugation and filtration, and added to the 0.1 M NaOH extract. The organics dissolved in this extract represented the humic extractable organic matter (HEOM). The extraction residue containing the non-extractable organic matter (NEOM) was treated with a 0.5 M HCl solution to eliminate carbonates, washed with distilled water, dried at 40°C, and weighed. All the liquid and solid fractions were analyzed for their organic C content by dichromate digestion at 180°C for 30 min (Allison, 1965), and their content expressed in terms of C as WEOM (WEOC), POM (POC), HEOM (HEOC) and NEOM (NEOC).

2.6. Biochemical analyses

The microbial biomass carbon (Cmic) was estimated using the fumigation-extraction method of Vance et al. (1987), after 34 days of conditioning at 25°C and about 50% of the total water holding capacity. Basal respiration was estimated by alkali (1 M NaOH solution) absorption of the CO_2 developed during the incubation period, followed by titration of residual OH with a 0.1 M HCl solution (Alef, 1995). During the first days, the measure of the respired CO_2 was made every 12 h, then every 24 h and, when respiration decreased, after longer time intervals (48, 72, 96 h). The basal respiration and the Cmic allowed us to calculate the metabolic quotient as follows: qCO_2 = μg CO_2-C mg^{-1} Cmic h^{-1} (Anderson and Domsch, 1990).

Enzymes were desorbed by heteromolecular exchange using an excess of exogenous protein. According to Fornasier and Margon (2007), 500 mg of sample were placed in a 2-mL

eppendorf tube and added to glass beads and 1 ml of 50 mM TRIS-HCl solution at pH 7.5 containing lysozyme as a desorbing protein. The tube was subjected to bead-beating (3 min, 30 strokes s^{-1}) using a Retsch MM400 mill, then centrifuged for 5 min at 20,000 *g*. Enzyme activity was assayed fluorometrically in microplates using 4-methyl-umbelliferyl and 7-amino-4-methyl coumarine derivatives. The activity of arylsulfatase, β-glucosidase, and chitinase was determined in 200 mM MES (morpholineptansulfonic acid) solution at pH 6, that of leucine aminopeptidase in 50 mM TRIS-HCl solution at pH 7.5, and that of alkaline phosphatase in 200 mM TRIS-HCl solution at pH 9.0.

The double-strand DNA (dsDNA) was quantified according to the following protocol. Aliquots of 500 mg of sample were placed in a 2-mL eppendorf tube and added to glass beads and 1 ml of 0.12 M sodium phosphate buffer (pH 8.0) solution. The tubes were submitted to bead-beating (2 min, 30 strokes s^{-1}) and subsequently centrifuged for 5 min at 20,000 *g*. The dsDNA content was quantified on aliquots of the supernatant by fluorometry using PicoGreen® reagent (Life Technologies) according to the instructions of the manufacturer.

2.7. Replicates and statistics

For each sample collected we ran 4 replicates for pH, total C, total N, TOC and OC, 3 replicates for basal respiration, microbial biomass C, enzyme activities and dsDNA quantification, and 2 replicates for particle-size distribution and mineralogy. For each sample, the results obtained were averaged. The values reported in the tables are the means of the two sample-averages obtained for each horizon.

After evaluation of the normal distribution of the data, statistical analyses to compare differences among data-sets were performed by the one-way ANOVA with Fisher's LSD test

($P<0.05$) by using XLSTAT software. The tendencies with soil depth were evaluated by the linear trend post-test (GraphPad Instat 3.1 software).

3. RESULTS

3.1. Chenini Nahel

Both non-cultivated soil (NS) and cultivated soil (CS) showed slight saline efflorescences at the surface and were made by horizons with a light yellowish brown colour (Table 1). In NS, the structure was moderately developed in the A horizon, but poorly developed in the deeper horizons. In CS, a moderately developed structure was found in the Ap and By horizons, but it became poorly developed with depth. Both NS and CS showed a very friable consistence, a scarce rock fragments content (Table 1), and a soil texture dominated by sand (Table 2). From these results and field observations made during crop irrigation, both NS and CS were determined to be "moderately well drained" (Schoeneberger et al., 2002). Such conditions often occur in oases of the Governorates of Gabès, Gafsa, Kébili and Tozeur, where artificial drainage systems were developed beginning in 1996 (Sakairi and Kawabata, 2008).

The NS reaction was alkaline, while the pH values of CS ranged between 7.8 and 8.1, with the lowest values in the upper horizons (Table 2). The mineralogical composition was dominated by gypsum and quartz (Table 2) and showed different proportions in NS and CS. In NS, gypsum was more abundant than quartz in the first three horizons and the opposite was true with depth, while for CS the reverse occurred. Smaller amounts of calcite and plagioclases were also found, with traces of dolomite and amphiboles. The contents of total C and inorganic C of NS showed no significant difference with those of CS (Table 3). The TOC content was higher in the uppermost horizon of NS than in CS, while the contrary was true in the two horizons underneath (Table 3). Conversely, the OC was in major amount in CS than

in NS, with the only exception of the lowermost horizon. The TOC and OC concentrations showed a decreasing trend with increasing soil depth in both NS and CS (P<0.0001). For the total N, no difference between NS and CS or trend with depth was found (Table 3).

In the two superficial horizons of both NS and CS, the most represented organic fraction was NEOC, which formed the majority of TOC (Table 4). In the A horizon of NS, POC and HEOC showed the largest values among the horizons analysed, while WEOC was not detected. In the horizon below, WEOC, POC, and HEOC were present in small amounts. With respect to the A horizon of NS, the lower content of TOC in the Ap horizon of CS was mostly due to POC and, to a much smaller amount, HEOC. By contrast, the larger TOC content in the By1 horizon of CS relative to the BCyy horizon of NS was mainly due to NEOC and, in small part, to POC.

The microbial biomass C and the basal respiration were higher in NS than in CS (Table 5). The microbial community of NS represented a larger proportion of OC (6.9%) and appeared able to utilise a larger amount of organic resources (4.2%) as energetic substrate than CS. The qCO_2 was low and similar for the two soils (Table 5).

In NS, three enzymatic activity patterns were observed along the soil profile (Table 6): 1) arylsulfatase, β-glucosidase, and chitinase displayed activity only in the A horizon; 2) the activity of the leucine aminopeptidase was detected only in the A and BCyy1 horizons; and 3) alkaline phosphatase displayed activity all throughout the profile, even though it sharply decreased from the BCyy1 to the BCyy2 horizon. In CS, all enzymes displayed a relatively high activity until the By2 horizon and, further, the leucine aminopeptidase activity was detected until the BCyy1, and alkaline phosphatase up to the BCyy2. All the enzymes displayed higher enzymatic activity in CS than in NS. In both soils, the content of dsDNA decreased with depth, becoming undetectable at about 40 cm in NS and about 50 cm in CS

(Table 6). However, CS had a relatively larger concentration of dsDNA in the Ap horizon (about 2-fold higher than the A horizon of NS) and in the horizons below (about 9-fold higher in the By1 horizon than the BCyy1 of NS).

3.2. Matmata Nouvelle

Both soils had a superficial crust, which was softer in NS than in CS (Table 1). Both crusts showed a platy structure that in the Ap1 horizon of CS was accompanied by a few sub-angular blocks (Table 1). The two soils featured some Bx horizons, which were characterized by a marked firmness associated to brittleness probably due to their alluvial origin. Only in CS the Bx horizons showed a few carbonate concretions as filaments and masses, which were interpreted as a product of the leaching due to irrigation. The skeleton content was scarce in both soils with the only exception of the Bx3 horizon of NS, where 10-15% limestone rock fragments were present (Table 1). The texture was sand to loamy sand for both NS and CS (Table 2), similar to that (sandy loam) found by Fleskens et al. (2005) in a close terraced soil on the Matmata mountains. From these observations and those made during crop irrigation, both NS and CS were recognized as "well drained" (Schoeneberger et al., 2002), supporting the findings of Ben Rouina (1994) for southern Tunisia inland soils with sandy texture.

The pH was alkaline, with values around 9 in the deepest horizons (Table 2). In both soils, the mineralogy was dominated by quartz, with smaller amounts of calcite and plagioclases and traces of dolomite (Table 2). The content of total C and inorganic C did not show a significant trend throughout the profiles (Table 3), while the concentrations of TOC and OC tended to decrease with depth ($P<0.04$). In the Ap horizons of CS, TOC was higher than in the A horizon of NS, but for the Bx horizons the opposite was true. By contrast, the OC was

generally higher in NS than in CS. The total N content displayed no significant trend with depth for both NS and CS, with the highest value in the Bx1 horizon of CS (Table 3).

The most represented organic fraction was NEOC, followed at a great distance by POC, HEOC, and very small amounts of WEOC (Table 4). Among all the organic fractions, NEOC was higher in CS than in NS and represented almost the whole organic C pool.

The Ap1 horizon of CS showed a larger amount of Cmic and a larger proportion of OC as Cmic than the A horizon of NS (Table 5). Conversely, during the basal respiration experiments, NS produced a great amount of CO_2-C (about 9-fold higher than CS), which accounted for 37% of its OC content. As a consequence of the lower Cmic content and the higher ΣCO_2-C, the qCO_2 of NS was much greater than that of CS (Table 5).

The enzyme activities were higher in NS than in CS, where arylsulfatase and β-glucosidase activities were below the detection limit (Table 6). However, the activity of these two enzymes was undetectable also in the Bx2 and Bx3 horizons of NS. In this latter soil, the activity of all enzymes decreased with depth, while in CS the activity of leucine aminopeptidase, alkaline phosphatase, and chitinase decreased from the Ap1 to Ap2 horizons, increased in the Ap3, and decreased again (alkaline phosphatase) or became undetectable (leucine aminopeptidase and chitinase) with depth. The dsDNA content decreased with depth in both soils ($P<0.001$), but showed the highest concentrations throughout NS (Table 6).

3.3. Menzel Habib

The two soils showed a superficial crust with a strongly developed platy structure and a weakly to moderately developed angular blocky structure in the sub-superficial horizons (Table 1). Shells of the terrestrial gasteropode *Sphincterochila candidissima* Draparnaud abounded at the surface of both soils, while shell fragments of the same species were present

from the surface until about 65 cm of depth (Bk3 horizon) in NS and 80 cm of depth (Bk1 horizon) in CS. In both soils, the rock fragments content was scarce until a depth of 20-25 cm and increased with depth (Table 1), while the texture was loamy sand to sandy loam. Both NS and CS featured small and roughly circular depressions with ripple marks due to water oscillations. From these results and the field observations made during crop irrigation, both NS and CS were determined to be "moderately well drained" (Schoeneberger et al., 2002).

The soil reaction was alkaline, with the highest pH in the Bk2 horizon of NS and the Bw horizon of CS (Table 2). Soil mineralogy was comprised of quartz with smaller amounts of calcite, few plagioclases and dolomite, and traces of micas and 2:1 clay minerals (Table 2). Gypsum abounded only in the deepest horizon of both soils (Byy horizon). The greatest total C and inorganic C contents were found in the Bk and Byy horizons of both soils, but no significant increasing trend with depth occurred (Table 3). The contents of TOC and OC were similar between NS and CS (Table 3), except for the C and A horizons where both TOC and OC were higher in CS than in NS. Only the TOC content tended to decrease with depth in both soils ($P<0.004$). The total N content in NS was low in the two superficial horizons, sharply increased in the Bk horizons, and decreased in the Byy horizon (Table 3). In CS, the total N did not show significant variations along the profile (Table 3).

In the two soils most of the TOC was comprised of NEOC, which showed higher values in CS than in NS (Table 4). As in the soils of the other sites, the WEOC content was very small. Between the C horizons, the contents of POC and HEOC were higher of NS than in CS, while for the A horizons the contrary was true.

The content of Cmic was higher in CS than in NS when contrasted horizon by horizon (Table 5). However, in both soils the A horizon contained a larger Cmic than the overlying C horizon. The data of basal respiration were similar in the two soils but, conversely to the Cmic

content, the evolved CO_2-C of the C horizons was more than twice that of the A horizons. Both soils contained a relatively large proportion of OC as Cmic, higher in the A than in the C horizons. The ΣCO_2-C/OC ratio was greater in NS than in CS, and in the C rather than in the A horizons. The qCO_2 values were higher in the C than in the A horizons of both NS and CS.

In both soils, no enzyme activity was detected for arylsulfatase, whereas β-glucosidase and chitinase were detected only in the C and A horizons (Table 6). By contrasting the soils horizon by horizon, β-glucosidase, leucine aminopeptidase, and chitinase showed a lower activity in the C horizon of CS than NS. In the other cases, the enzyme activities displayed values of similar magnitude, although often significantly different. The greatest dsDNA contents of NS (Table 6) were recorded in the C and A horizons, while in CS they were observed in the Bw and Bk1 horizons.

4. DISCUSSION

4.1. Chenini Nahel

The presence of gypsum along the profiles was attributed to the presence of gypsum-bearing rocks close to the site (Pouget, 1968) and to the leaching of Ca^{2+} and SO_4^{2-} due to the moderately well drainage. The leaching of these ions with strong evapotranspiration have been considered as responsible for the formation of gypsum in the soil (Russo, 1986; FAO, 1990). The different distribution of gypsum along the profiles between NS and CS was considered an effect of irrigation. In fact, the irrigation of gypsiferous soils induces gypsum translocation toward deeper horizons (e.g., Russo, 1986; FAO, 1990). According to Al-Barrak and Rowell (2006), a high gypsum content combined with solubilisation-reprecipitation cycles reduce soil aggregation. By contrast, plant roots favour formation of aggregates (Fageria and Stone, 2006). The balancing between these constructive and destructive forces of

aggregation gave a moderately developed structure in the horizons where micro, very fine, and fine roots were plentiful or abundant, and a poorly developed structure in the horizons where these roots were few. In CS, the structure of the Ap and By horizons induced drainage conditions that favoured leaching and, probably, pH reduction (about 0.7 to 1 pH points less than NS). However, other reasons might have contributed to soil pH dropping across decades of cultivation: 1) application of acid fertilizers such as sulphur or iron sulphate and, 2) removal of base cations by crop harvesting (Raut et al., 2012). Further, as an excessive root absorption of cations relative to anions leads to an excretion of H^+ (Haynes, 1990), some farming practices may have accelerated the decrease of pH: a) application of excess of NH_4^+-based nitrogen fertilizers (Schroder et al., 2011); b) leaching of NO_3^- derived from mineralization and nitrification of organic N or nitrification of NH_4^+-based nitrogen fertilizers (Singh et al., 2012). In alkaline soils, a pH lowering can be considered as an ameliorating process as it may help provide nutrients to plants. In fact, as the decrease of soil pH is often promoted by an acidification of the rhizosphere (Hinsinger et al., 2003; Cocco et al., 2012), the lowering of pH may increase the rate of mineral alteration and release of nutrients, especially close to the roots. In the cultivated soils of Chenini Nahel, while the application of acid fertilizer is not known, other acidifying practises such as the distribution of composted wastes from vegetal and animal sources mixed with manure, irrigation by submersion, and considerable vegetable and henna harvests have been carried out.

Conversely to other studies that reported a decline of soil organic matter levels due to agricultural practices in arid and semi-arid ecosystems (García-Orense et al., 2010; Ramos et al., 2011), our results showed an increase of TOC and OC content in CS with respect to NS. This was ascribed to the input of compost, manure, crop residues, and root exudates, but also to the effect of irrigation. Although irrigation is considered favourable for organic matter

mineralisation as a consequence of greater microbial activity (Wang et al., 2010), in arid and semi-arid environments watering can improve soil C sequestration when higher water availability enables higher crop biomass production and therefore a higher amount of crop residues (Denef et al., 2008; Blanco-Canqui et al., 2009). At Chenini Nahel, the main difference in TOC was due to the more stabilised soil organic matter fraction (NEOC), which abounded in the two upper horizons of CS (about 27 cm of thickness), while in NS it was mostly represented in the A horizon (about 9 cm thick). This high content of NEOC was ascribed to the formation of organo-mineral associations in which organic matter is protected from microbial degradation. As the clay fraction was absent, gypsum and calcite were likely responsible for these associations. Observations at the optical microscope of separates recovered from the residue of the organic matter fractionation protocol confirmed the hypothesis as many organic matter particles were glued or enveloped by gypsum or calcite (Figure 2). Hence, irrigation has favoured leaching of gypsum and calcite that successively re-precipitated onto organic particles, which then resulted protected from microbial degradation.

In the upper horizon, the lower amount of Cmic in CS than in NS was attributed to the loss of soluble and easily biodegradable compounds added with the amendment because of the combined effect of irrigation, drainage and absence of clay minerals able to retain these molecules. Hence in CS, the microbial community had to survive mostly on the less easily available organic particles such as those protected by gypsum and carbonates. Another reason for the low amount of Cmic in CS was probably the antibacterial activity of the henna plant (Habbal et al., 2011). The NS, though not receiving any application of fertilizer, had a dense spontaneous vegetal cover that supplied the upper soil horizon with organic material mainly as POM (Table 4). The heterogeneity of the organic substrate favours the development of a more abundant and efficient soil microbial community in NS than CS.

Several studies have recognized that enzyme activity is an early indicator of soil property changes as a consequence of land management in dryland soils (Acosta-Martínez et al., 2008; García-Orense et al., 2010; Ramos et al., 2011), and that the activity of most enzymes increases as organic matter content increases (Lagomarsino et al., 2009). The fact that in NS the activities of arylsulfatase, β-glucosidase, and chitinase were restricted to the upper horizon while in CS they were detected until the By2 horizon was attributed to the increase of organic matter that, in this soil, occurred also with depth. However, these three enzymes have their soil pH optima at acid pH (Niemi and Vepsäläinen, 2005; Turner, 2010), and a drop of soil pH from alkaline to sub-alkaline levels could have increased their activities. The same was probably true for leucine aminopeptidase, whose soil pH optima are at pH 7.5 or higher (Niemi and Vepsäläinen, 2005), and its activity was found only in the A and BCyy1 horizons of NS (38 cm of depth), while in CS it was detected until the BCyy1 horizon (72 cm of depth). In this case, the leucine aminopeptidase activity possibly increased because of the decline in pH from 8.5-8.8 to 7.7-8.1. As alkaline phosphatase has soil pH optima from 8 to 10 (Turner, 2010), its activity was higher than those of the other enzymes. In CS, the alkaline phosphatase activity was higher than in NS, notwithstanding the decrease of soil pH; for this enzyme the increase of organic matter was probably more efficient than pH in increasing its activity. The fact that enzymatic activities in CS were higher and detected deeper than in NS was also attributed to irrigation, which probably translocated extracellular enzymes and microbial cells because of the lack of clay minerals able to retain them. The higher enzyme activities of CS were also ascribed to the addition of compost/manure (Acosta-Martínez et al., 2008), which supplies food for microbes, and/or to the higher soil humidity due to irrigation (Steinweg et al., 2012). Similar results were reported by Crecchio et al. (2001), who found higher enzymatic activity in cropped plots of a Vertisol than in uncropped ones; among the

cropped plots, the highest enzymatic activities were measured in those amended with compost derived from municipal solid waste. As dsDNA is directly related to microbial biomass carbon (Tomlinson et al., 2008), the long term addition of composted organic residues has been likely responsible for the relatively greater content of dsDNA in CS.

4.2. Matmata Nouvelle

Both soils showed a superficial crust that was thicker and harder in CS than in NS (Table 1). These crusts appeared to be "slacking crusts" *sensu* Valentin and Bresson (1992). This type of crust forms because of aggregate breakdown due to entrapped air compression in soils with a loam texture, when the soil is dry before rainfall (Le Bissonnais, 1990; Valentin and Bresson, 1992). These conditions apply to Matmata Nouvelle soils. Instead, it is impossible that the crusts were "swelling crusts" because of the absence of clay fraction and clay minerals. Therefore, the formation of these crusts was attributed to water impact: in NS the crust was thin (1 cm) and formed during a recent rainfall event, whereas in CS it was thicker (3 cm) and formed by irrigation. The platy structure dominating the crustous horizons was acquired during the formation of the crust and, despite these soils being well drained, this structure was responsible for the development of ephemeral water ponds during irrigation of CS.

With respect to NS, cultivation increased the content of TOC in the Ap horizons but reduced it in the Bx ones. In the Ap horizons, where the effect of the drip irrigation was predominant, TOC content increased because of organic particles stabilized by calcite that incremented the amount of NEOC. In the Bx horizons of CS, the calcite reprecipitation was poor and the TOC content was reduced because of accelerated mineralization of the organic matter probably due to the N added as fertilizer and leached by irrigation and drainage. The amount of OC was lower in CS than NS. In this situation, the agricultural practices have led to the expected

decline of soil organic matter (e.g., García-Orense et al., 2010; Ramos et al., 2011), here ascribed to the combined effect of high temperatures, chemical fertilization and irrigation (Vineela et al., 2008; Wang et al., 2010). In NS, the low amount of Cmic and the high amount of CO_2 evolved during the incubation experiment suggest that the native microbial population was scarcely efficient in incorporating the available C in its tissues, and that much of the organic substrate was consumed by catabolic reactions. The high qCO_2 value obtained for NS, confirmed the scarce microbial efficiency in the use of energy (Anderson and Domsch, 1990; Moscatelli et al., 2007). However, we cannot exclude that a small part of the CO_2 evolved during the incubation experiment had an inorganic origin. Indeed, in arid environments, the re-wetting of the dry soil increases organic matter mineralisation and microbial activity (Austin et al., 2004), with a possible release of carbonate-CO_2 to atmosphere (Monger and Gallegos, 2000). Conversely, in CS, the greater amount of Cmic and the lower consumption of organics indicate a good adeptness of the microbial community in using the available substrates. Despite the better microbial efficiency, the activity of all enzymes was lower in CS than in NS. As the soil pH was substantially similar in NS and CS, we ascribed the lower enzymatic activity to the lower content of OC in CS. This agreed with Bastida et al. (2006) and Lagomarsino et al. (2009), who assessed that the activity of the enzymes are mainly correlated with the content of less stabilized and easily available organic matter that, as reported by Tabatabai (1994), acts as 1) a precursor for enzyme synthesis by favouring the development of a microbial population, and 2) a physical stabilizer for the enzymes. In CS, the use of chemical fertilizer and irrigation, together with good drainage, increased TOC because of the particle stabilization due to calcite reprecipitation, but decreased the easily oxidizable organic matter with a consequent drop of the enzyme activities and of the size of the microbial community, as shown by the lower amount of dsDNA (Tomlinson et al., 2008).

4.3. Menzel Habib

The fact that both NS and CS displayed superficial slacking crusts with a strongly developed platy structure and the same thickness and hardness (Table 1) indicated that the crusts formed recently, probably during a rainfall event of relatively high intensity. In fact, the presence of roughly circular depressions with ripple marks due to water oscillations denoted that in this area some intense rainfall events are able to form ephemeral water ponds.

The absence of strong differences in terms of morphology and main physico-chemical properties between NS and CS suggested that soil management has a low impact that has produced negligible modifications. Farther, as seen for the non-cultivated soil of Matmata Nouvelle, the great amount of CO_2-C respired by the C horizons of both NS and CS during the incubation experiment, together with the high ΣCO_2-C/OC ratio, suggested a scarce efficiency in the use of the organic resources by the microflora harbouring at the soil surface. Also in this case, we cannot exclude a release of carbonate-CO_2 during the incubation experiment. Contrary to the C horizons, in the sub-superficial A horizons, the Cmic represented a greater proportion of the OC and the microbial community showed a more efficient use of energetic resources. This behaviour was ascribed mainly to the lower soil temperature and, although scarce on absolute values, higher soil moisture in the A than in the C horizons. Hence, per Jauffret and Visser (2003), the high soil temperature and dryness were considered the main causes of the scarce efficiency and the high stress conditions of the microbial community harbouring the C horizons. In terms of enzyme activity, the slight differences between NS and CS further testified that the cultivation of olive-trees with no addition of organic amendments and scarce irrigation had a negligible impact on this soil.

5. CONCLUSIONS

The main results obtained with this study are here below summarized.

- The management of dryland soils comprising the addition of organic amendments and the systematic irrigation, and the activity of plants were able to lower soil pH and increase the solum thickness with a higher enzymatic activity and lower gypsum content. Further, this soil management increased the organic C storage through the formation of organo-mineral associations in which organic fragments were encapsulated by re-precipitated gypsum and/or carbonates. This mechanism of organic matter stabilization might play an important role in controlling organics mineralisation in these oxidative environments, so to reduce CO_2 emissions toward the atmosphere.

- When chemical fertilizers and drip irrigation were applied, the formation of organo-mineral associations occurred in the Ap horizons where more intense processes of solubilisation and reprecipitation of the carbonates occurred. With depth, this type of organic matter stabilization was not efficient, and the processes of mineralization prevailed because of the leaching of N added as fertilizer and to the presence of a microbial community efficient in using the available resources.

- When no fertilizer was applied and watering was sporadic, no substantial effect was produced by cultivation in terms of soil chemical and biochemical properties here considered.

Our study shows that in the way to assess proper agricultural managements for drylands, it is unavoidable the use of water and organic amendments, which are able to increase soil organic matter storage and improve physico-chemical and biological properties so to boost soil fertility.

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Figure 1

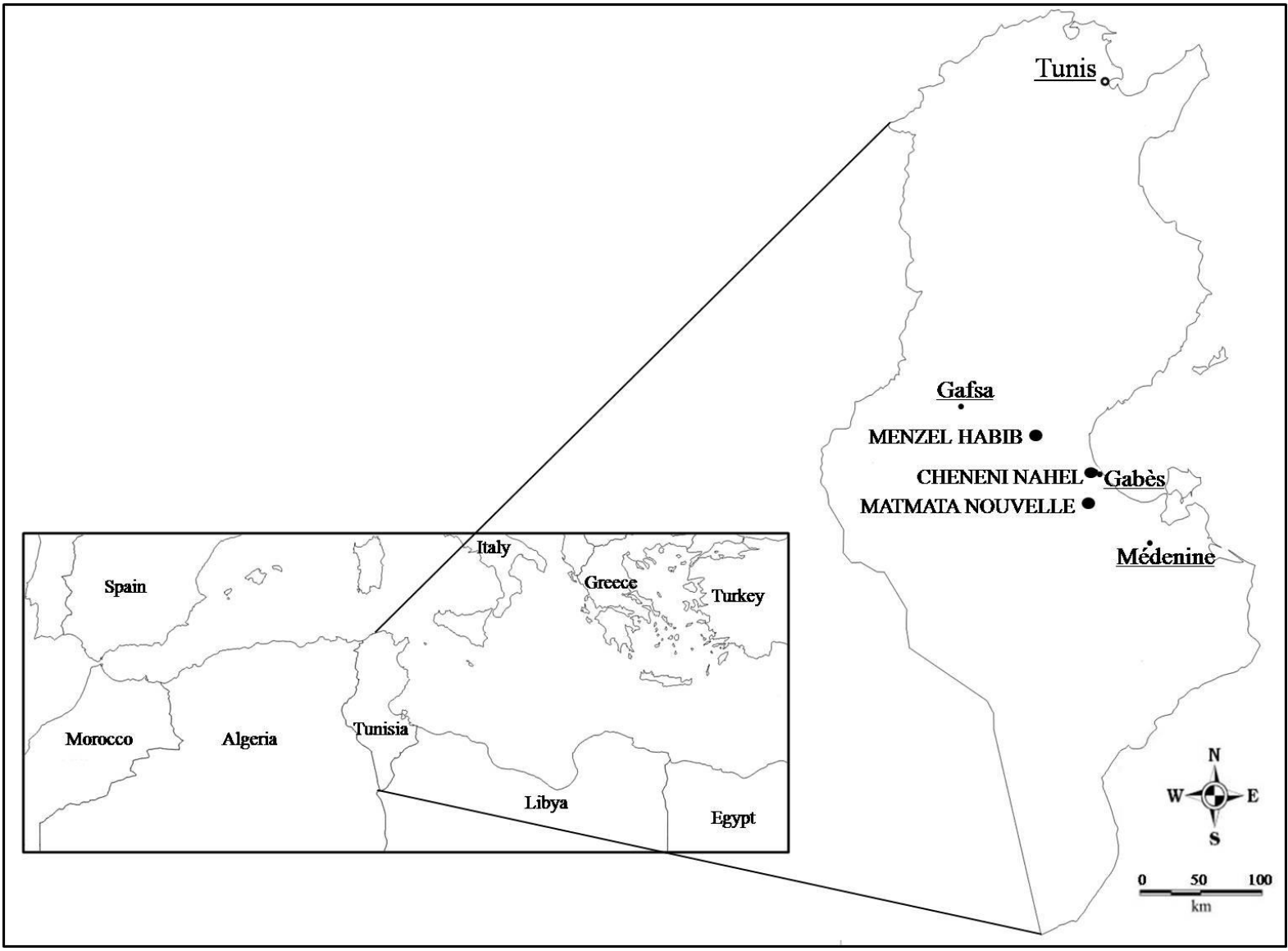
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Figure 2

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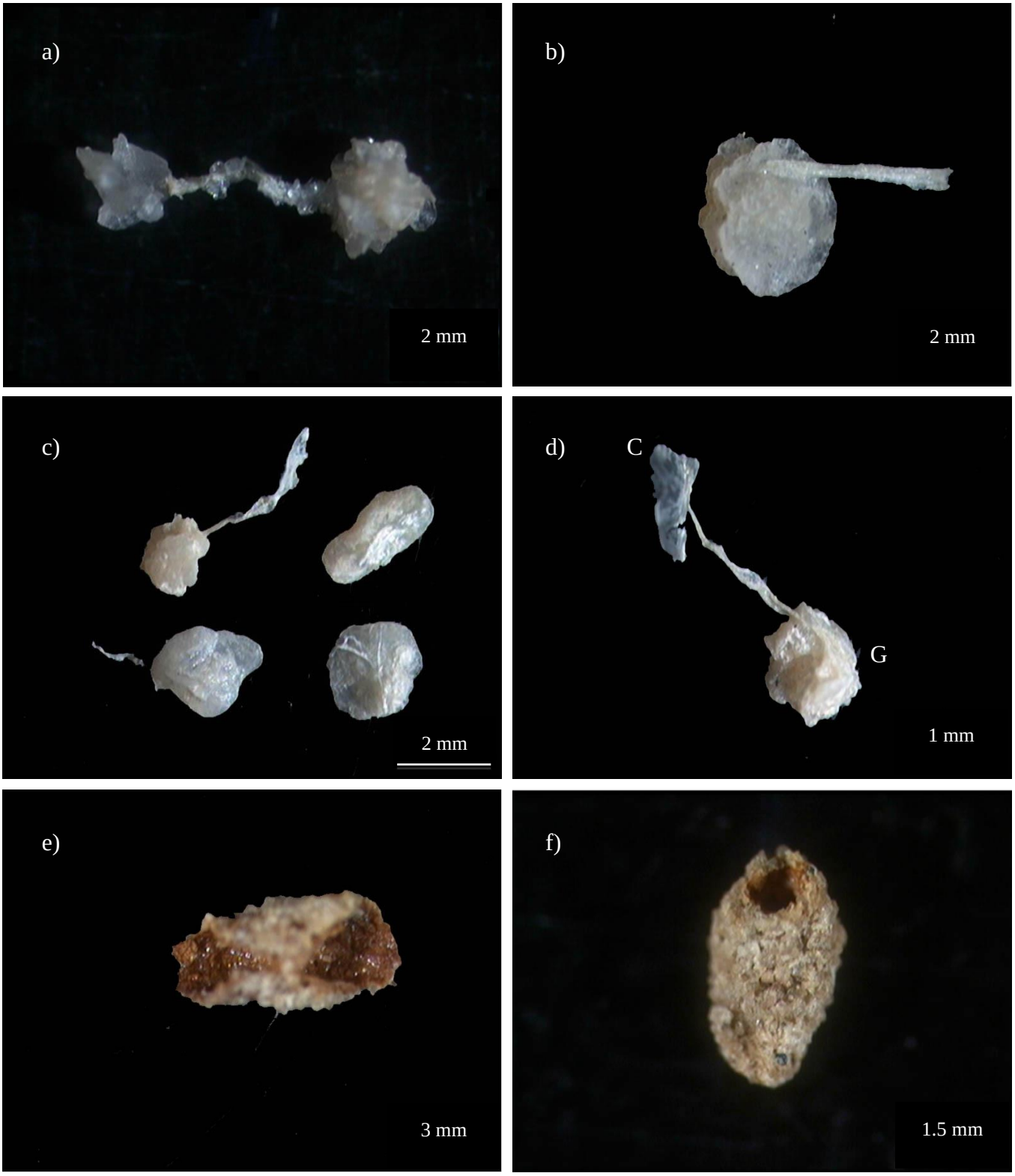

Figure 1. Map of Tunisia with indication of the study sites (Governorat de Gabès, Tunisia).

Figure 2. Optical microscope micrographs of different objects from the soils of Chenini Nahel, Governorat de Gabès, Tunisia. a) rootlet encrusted by and bridging gypsum crystals, BCyy1 horizon of NS; b) rootlet glued into lenticular gypsum crystal, Cyyg horizon of NS; c) rootlets glued or enveloped by lenticular gypsum crystals, By2 horizon of CS; d) rootlet bridging gypsum crystals (G) and calcite crystals (C), BCyy1 horizon of CS; e) collar of gypsum with the external side encrusted by calcite and the internal side coated by organic residues derived from degradation of former enveloped root, BCyy1 horizon of CS; f) collar of gypsum with the external side encrusted by calcite and the internal side coated by organic residues derived from degradation of former enveloped root, BCyy1 horizon of CS.

Table 1
Morphological description of one out of the two profiles opened in the non-cultivated (NS) and cultivated (CS) soils at Chenini Nahel, Matmata Nouvelle, Menzel Habib (Governorat de Gabès, Tunisia). For symbols see legend.

Site	Horizon	Depth	Colour†	Structure‡	Consistence§	Roots#	Skeleton$^{\xi}$	Observations$^{\phi}$
		cm						
Chenini Nahel								
NS - *coarse-loamy, gypsic, thermic, Leptic Haplogypsid* (Soil Survey Staff, 2010)								
	A	0-9	10YR 7/4	2m,c abk -sbk	mvfr, wss	2mi,vf	sc	saline effl
	BCyy1	9-38	10YR 6/3	l'm,c abk	mvfr, wss	$v_1$mi,vf,f; 3m,c	sc	
	BCyy2	38-66	10YR 6/4	l'm,c abk	mvfr, wss	$v_1$mi,vf,f; 3m,c	sc	few Mn-cnc
	BCyyg	66-75	10YR 6/4	1c abk	mvfr, wss	$v_1$mi,vf,f; 2 m,c	sc	
	Cyyg	75-85+	10YR 6/3	l'm,c abk-sbk, th pl	mvfr, wss	$v_1$mi,vf,f; 1 m,c	sc	diffuse Mn-cnc
CS - *coarse-loamy, gypsic, thermic, Leptic Haplogypsid* (Soil Survey Staff, 2010)								
	Ap	0-10	10YR 6/3	2m-c abk-sbk	mvfr, wss	3mi,vf,f	sc	saline effl, ch-f, sh-f
	By1	10-27	10YR 6/4	2f,m,c sbk	mvfr, wss	3mi,vf,f,m,c	sc	ch-f, sh-f
	By2	27-51	10YR 6/4	2m,c abk-sbk	mfr, wss	3,mi,vf,f,m,c	sc	ch-f
	BCyy1	51-72	10YR 7/6	l'm,c abk	mvfr, wss	$v_1$mi,vf,f; 2m,c	0	few Mn-cnc
	BCyy2	72-123+	10YR 7/6	l'f,m,c abk	mvfr, wss	$v_1$mi,vf,f; 1-2m,c	0	few Mn-cnc
Matmata Nouvelle								
NS - *loamy, mixed, calcareous, thermic, Lithic Torripsamment* (Soil Survey Staff, 2010)								
	A	0-1	7.5YR 7/6	2th pl	mfr, wss	v_1f ; 2m	sc	soft crust
	Bx1	1-9	7.5YR 7/6	2m,c abk	mfr, wss	1mi,vf,f; 2m,c	sc	F&B
	Bx2	9-27	7.5YR 5/6	2m,c abk	mfr, wss	1mi,vf,f; 2m,c	sc	F&B

Bx3	27-36	7.5YR 6/4	2m,c abk	mfr, wss	1mi,vf,f; 2m,c	com	F&B
Cr	36-80+	-	-	-	$v_1$mi,vf,f	-	limestone

CS - *loamy, mixed, thermic, Haploduridic Haplocambid* (Soil Survey Staff, 2010)

Ap1	0-3	7.5YR 7/6	2th,m pl & 1f-m sbk	mfr, wss	1mi,vf	sc	crust
Ap2	3-13	7.5YR 6/6	1f,m gr & 1f sbk	mfr, wss	1mi,vf	sc	sh-f
Ap3	13-34	7.5YR 6/6	1f gr & 1f sbk	mfr, wss	2mi,f,vf; v_1m	sc	
Bx1	34-62	10YR 7/6	3m,c abk	mfr, wss	2f,m	sc	F&B, few carbonate f&m
Bx2	62-81	10YR 7/6	2m abk	mfr, wss	2f,vf; 1m	sc	F&B, few carbonate f&m
Bx3	81-100+	10YR 7/6	2m,c abk-sbk	mfr, wss	1f,m	sc	F&B, few carbonate f&m

Menzel Habib

NS - *coarse-silty, mixed, thermic, Typic Calcigypsid* (Soil Survey Staff, 2010)

C	0-3	7.5YR 7/6	3th,m pl	mfr, wss	1mi,vf,f; v_1m,c	sc	crust, shells and sh-f, rplm
A	3-10	7.5YR 7/6	1m,c abk	mfr, wss	2mi,vf,f; v_1m,c	0	sh-f
Bk1	10-25	7.5YR 6/8	2f,m,c abk	mfr, wss	2mi,vf,f; v_1m,c	sc	sh-f
Bk2	25-55	7.5YR 6/6	2f,m,c abk	mfr, wss	2mi,vf,f; v_1m,c	com	sh-f
Bk3	55-65	7.5YR 6/6	2f,m abk	mfr, wss	2mi,vf,f; 1m,c	com	sh-f
Byy	65-92+	7.5YR 6/8	1'f abk	mfr, wss	0	com	

CS - *coarse-silty, mixed, thermic, Typic Calcigypsid* (Soil Survey Staff, 2010)

C	0-3	7.5 YR 7/6	3th,m pl	mfr, wss	2mi,vf,f; 1m,c	sc	crust, shells and sh-f, rplm
Ap	3-6	7.5YR 7/6	1m,c sbk	mfr, wss	2mi,vf,f; 1m,c	sc	sh-f, few carbonate f&m
Bw	6-19	7.5YR 7/6	1m,c abk	mfr, wss	1-2mi,vf	sc	sh-f, few carbonate f&m
Bk1	19-80	7.5YR 6/6	1m,c abk	mfr, wss	2mi,vf; 1f,m,c	com	sh-f, few carbonate f&m
Bk2	80-97	7.5YR 7/6	2m,c abk	mfr, wss	v_1m,c; 1mi,vf,f	fre	
Byy	97-118	7.5YR 6/8	1'f abk	mfr, wss	0	com	

[†]moist and crushed, according to the Munsell Soil Color Chart (1954 edition).
[‡]1'=little, 1=weak, 2=moderate, 3=strong; f=fine, m=medium, c=coarse, th=thin; gr=granular, abk=angular blocky, sbk=sub-angular blocky, pl=platy.
[§]m=moist, fr=friable , vfr=very friable; w=wet, ss=slightly sticky.
[#]0=absent, v_1=very few, 1=few, 2=plentiful, 3=abundant; mi=micro, vf=very fine, f=fine, m=medium, co=coarse.
[ξ]by sight, 0=absent, sc=scarce (<5%), com=common (5-15%), fre=frequent (15-35%).
[ϕ]effl=efflorescence; Mn-cnc=manganese concretions; ch-f=charcoal fragments; sh-f=shell fragments; F&B=firm and brittle; f&m=filaments and masses; rplm=ripple marks.

Table 2
Texture, pH in water, and principal mineralogical composition of the non-cultivated (NS) and cultivated (CS) soils at Chenini Nahel, Matmata Nouvelle, and Menzel Habib (Governorat de Gabès, Tunisia). Numbers in parentheses are the standard errors. For each site and column, mean values with different letters significantly differ for $P<0.05$.

		Horizon	Texture[a]	pH_{H2O}	Mineralogy[b]
Chenini Nahel	NS	A	ls	8.57 (0.00)d	G Q C P D A
		BCyy1	s	8.70 (0.03)c	G Q C P D A
		BCyy2	s	8.86 (0.00)a	G Q C P D A
		BCyyg	ls	8.81 (0.00)b	Q G C P D A
		Cyyg	ls	8.48 (0.03)e	Q G C P D A
	CS	Ap	s	7.79 (0.02)h	Q G C P D A
		By1	s	7.71 (0.03)i	Q G C P D A
		By2	s	7.94 (0.02)g	Q G C P D A
		BCyy1	s	8.14 (0.00)f	G Q C P A D
		BCyy2	s	8.14 (0.03)f	G Q C P A D
Matmata Nouvelle	NS	A	s	8.58 (0.02)g	Q C P D
		Bx1	s	8.83 (0.00)d	Q C P D
		Bx2	ls	8.97 (0.02)b	Q C P D
		Bx3	ls	8.89 (0.03)c	Q C P D
	CS	Ap1	ls	8.73 (0.01)e	Q C P D
		Ap2	ls	8.62 (0.01)f	Q C P D
		Ap3	ls	8.85 (0.01)d	Q C P D
		Bx1	sl	9.03 (0.01)a	Q C P D
		Bx2	ls	8.99 (0.02)b	Q C P D
		Bx3	ls	8.99 (0.04)b	Q C P D
Menzel Habib	NS	C	s	8.53 (0.03)g	Q C P D G M CM
		A	ls	8.87 (0.01)cd	Q C P D G M CM
		Bk1	ls	8.94 (0.04)b	Q C P D M CM
		Bk2	sl	9.03 (0.00)a	Q C P D G M CM
		Bk3	sl	8.80 (0.01)e	Q C P D M CM
		Byy	ls	8.39 (0.02)h	G Q C D P M CM
	CS	C	ls	8.67 (0.05)f	Q C P D M CM
		Ap	ls	8.89 (0.01)c	Q C P D M CM
		Bw	ls	9.04 (0.01)a	Q C P D M CM
		Bk1	sl	8.85 (0.00)cd	Q C P D M CM
		Bk2	sl	8.83 (0.04)de	Q C P M CM
		Byy	ls	8.50 (0.00)g	G Q C P M CM

[a]ls=loamy sand, s=sand, sl=sandy loam.
[b]minerals listed in order of abundance; G=gypsum, Q=quartz, C=carbonates, P=plagioclases, D=dolomite, A=amphiboles, M=mica, CM=2:1 clay minerals.

Table 3

Contents of total C (TC), inorganic C (IC), total organic C (TOC), organic C (OC) and total N (TN) of the non-cultivated (NS) and cultivated (CS) soils at Chenini Nahel, Matmata Nouvelle, and Menzel Habib (Governorat de Gabès, Tunisia). Numbers in parentheses are the standard errors. For each site and column, mean values with different letters significantly differ for $P<0.05$.

		Horizon	TC	IC*	TOC	OC	TN
					g kg^{-1}		
Chenini Nahel	NS	A	21.95(11.62)a	3.45(11.72)a	18.50(1.53)a	9.49(0.09)b	0.89(0.55)a
		BCyy1	17.07(13.18)a	14.04(13.22)a	3.03(0.96)e	2.13(0.11)ef	0.49(0.33)a
		BCyy2	18.15(12.54)a	14.45(12.57)a	3.70(0.96)e	1.29(0.20)f	1.40(1.29)a
		BCyyg	19.30(11.99)a	17.80(11.99)a	2.50(0.08)e	1.35(0.22)f	1.47(4.11)a
		Cyyg	26.99(16.77)a	25.11(16.77)a	1.88(0.27)e	1.59(0.14)f	0.08(0.08)a
	CS	Ap	19.45(8.03)a	5.07(8.3)a	14.38(0.29)b	10.72(0.42)a	0.62(0.28)a
		By1	28.43(8.87)a	18.52(8.88)a	9.91(0.38)c	8.00(0.29)c	1.13(0.69)a
		By2	25.80(10.19)a	19.85(10.19)a	5.95(0.05)d	4.17(0.21)d	0.87(0.60)a
		BCyy1	24.53(18.19)a	22.39(18.22)a	3.14(1.10)e	2.84(1.10)e	0.15(0.15)a
		BCyy2	24.80(18.14)a	23.23(18.14)a	1.57(0.05)e	0.94(0.27)f	0.14(0.00)a
Matmata Nouvelle	NS	A	29.60(7.14)a	21.77(7.23)ac	7.83(1.09)d	5.54(0.18)a	1.84(0.68)ab
		Bx1	22.59(9.47)a	17.40(9.47)ad	5.19(0.34)e	4.63(0.24)b	0.79(0.79)b
		Bx2	22.24(11.05)a	17.71(11.07)ad	4.53(0.64)e	2.29(0.05)f	0.78(0.76)b
		Bx3	36.64(8.26)a	33.53(8.26)a	3.11(0.23)f	2.66(0.02)e	1.12(1.12)b
	CS	Ap1	21.05(12.96)a	4.53(13.00)d	16.52(0.94)a	4.12(0.08)e	0.73(0.73)b
		Ap2	24.75(9.55)a	11.72(9.55)cd	13.03(0.28)b	3.43(0.06)d	1.53(0.54)ab
		Ap3	25.68(9.03)a	14.31(9.17)bd	11.37(1.60)c	3.92(0.11)c	0.87(0.68)b
		Bx1	34.65(9.60)a	32.92(9.60)a	1.73(0.06)g	1.68(0.18)g	2.94(0.76)a
		Bx2	33.53(10.44)a	32.15(10.44)a	1.38(0.08)g	1.37(0.03)h	1.08(1.08)b
		Bx3	29.71(12.49)a	28.72(12.49)ab	0.99(0.02)g	1.25(0.16)h	1.08(1.08)b
Menzel Habib	NS	C	22.31(9.52)ef	19.08(9.52)e	3.23(0.04)c	2.54(0.31)bc	0.07(0.00)c
		A	20.08(12.18)f	17.19(12.18)e	2.89(0.39)ce	1.89(0.26)e	0.07(0.00)c
		Bk1	38.41(4.17)ad	34.61(4.18)ad	3.80(0.13)b	2.83(0.18)b	3.00(1.23)a
		Bk2	40.04(0.00)ac	38.07(0.14)ac	1.97(0.14)g	2.28(0.18)ce	3.08(2.59)a
		Bk3	43.71(3.51)ab	41.62(3.51)ab	2.09(0.03)fg	2.33(0.08)cd	2.23(1.29)ab
		Byy	34.89(9.66)ae	34.11(9.66)ad	0.78(0.19)h	0.80(0.04)f	0.23(0.00)c
	CS	C	30.89(7.82)bf	26.89(7.82)ce	4.00(0.19)ab	3.76(0.13)a	0.34(0.33)c
		Ap	25.90(8.58)cf	21.47(8.61)de	4.43(0.62)a	2.68(0.19)bc	1.18(0.82)bc
		Bw	25.36(9.17)df	22.36(9.17)de	3.00(0.05)cd	2.08(0.51)de	0.22(0.00)c
		Bk1	31.55(9.41)bf	29.07(9.41)be	2.48(0.21)eg	2.51(0.08)bc	0.28(0.02)c
		Bk2	48.14(1.43)a	45.60(1.49)a	2.54(0.43)df	1.86(0.05)e	0.17(0.00)c
		Byy	38.30(7.36)ad	37.35(7.37)ac	0.95(0.20)h	0.88(0.26)f	0.21(0.00)c

*Standard errors calculated according to the propagation error technique.

Table 4

Fractionation of the total organic C into C as water-extractable organic matter (WEOC), particulate organic matter (POC), humic extractable organic matter (HEOC), non-extractable organic matter (NEOC) and NEOC/TOC ratio of the horizons atop the non-cultivated (NS) and cultivated (CS) soils at Chenini Nahel, Matmata Nouvelle, and Menzel Habib (Governorat de Gabès, Tunisia). Numbers in parentheses are the standard errors. For each site and column, mean values with different letters significantly differ for $P<0.05$.

	Horizon	WEOC	POC	HEOC	NEOC	NEOC/TOC
		g kg^{-1}				
Chenini Nahel						
NS	A	<dl	5.10(0.01)a	0.88(0.03)a	12.52(0.15)a	0.676a
	BCyy1	0.09(0.01)a	0.08(0.00)d	0.06(0.00)c	2.80(0.08)c	0.924a
CS	Ap	<dl	1.60(0.01)b	0.69(0.04)b	12.09(0.61)a	0.841a
	By1	0.06(0.01)b	0.30(0.00)c	0.07(0.01)c	9.48(0.10)b	0.954a
Matmata Nouvelle						
NS	A	0.02(0.00)c	0.53(0.05)b	0.50(0.01)a	6.78(0.40)c	0.866b
	Bx1	0.01(0.00)c	1.05(0.08)a	0.21(0.00)d	3.92(0.47)d	0.755c
CS	Ap1	0.05(0.00)b	0.58(0.03)b	0.39(0.02)b	15.50(1.06)a	0.938a
	Ap2	0.10(0.00)a	0.55(0.03)b	0.39(0.01)b	11.99(0.26)b	0.920ab
	Ap3	<dl	0.43(0.02)c	0.27(0.09)c	10.67(2.10)b	0.938a
Menzel Habib						
NS	C	0.10(0.01)a	0.58(0.04)b	0.24(0.03)a	2.31(0.33)b	0.715b
	A	0.09(0.01)b	0.18(0.01)d	0.09(0.01)c	2.53(0.18)b	0.875a
CS	C	0.08(0.00)c	0.25(0.02)c	0.19(0.01)b	3.48(0.61)a	0.870a
	Ap	0.07(0.01)d	0.87(0.02)a	0.20(0.01)b	3.29(0.28)a	0.743b

* <dl = below the detection limit.

Table 5

Microbial biomass C (Cmic), CO_2-C evolved during 33 days of incubation (ΣCO_2-C), percentage of organic C present as microbial biomass (Cmic/OC), percentage of organic C consumed as CO_2-C (ΣCO_2-C/OC), and metabolic quotient (qCO_2) of the upper horizons of the non-cultivated (NS) and cultivated (CS) soils at Chenini Nahel, Matmata Nouvelle, and Menzel Habib (Governorat de Gabès, Tunisia). Numbers in parentheses are the standard errors. For each site and column, mean values with different letters significantly differ for $P<0.05$.

	Cmic	ΣCO_2-C	Cmic/OC	ΣCO_2-C/OC	qCO_2
	mg kg^{-1}		%		μg CO_2-C mg^{-1} Cmic h^{-1}
Chenini Nahel					
NS – A horizon	657.6 (16.0)a	397.6 (18.4)a	6.9 (0.1)a	4.2 (0.2)a	0.8 (0.0)a
CS – Ap horizon	202.8 (16.5)b	174.5 (8.9)b	1.9 (0.1)b	1.7 (0.1)b	1.1 (0.1)a
Matmata Nouvelle					
NS – A horizon	189.6 (12.2)b	2048.8 (54.7)a	3.5 (0.3)b	37.4 (0.2)a	13.8 (1.3)a
CS – Ap1 horizon	273.9 (17.4)a	231.9 (14.1)b	6.7 (0.5)a	5.7 (0.3)b	1.1 (0.1)b
Menzel Habib					
NS – C horizon	284.5 (20.2)c	456.9 (23.6)a	12.0 (1.7)c	19.2 (2.4)a	2.0 (0.0)a
NS – A horizon	413.5 (18.6)b	191.8 (16.7)b	23.5 (2.9)a	10.9 (1.7)b	0.6 (0.0)c
CS – C horizon	397.6 (17.2)b	426.4 (22.6)a	10.7 (0.4)c	11.5 (0.5)b	1.4 (0.0)b
CS – Ap horizon	467.8 (28.4)a	199.5 (11.9)b	17.9 (0.3)b	7.7 (0.8)c	0.5 (0.1)c

Table 6

Enzyme activities and double-stranded DNA content of the non-cultivated (NS) and cultivated (CS) soils at Chenini Nahel, Matmata Nouvelle, and Menzel Habib (Governorat de Gabès, Tunisia). For each site and column, mean values with different letters significantly differ for $P<0.05$. For symbols see legend.

		Horizon	Enzymes†					dsDNA
			AryS	β-gluc	Leu	AlkP	Chit	
			nM g^{-1} h^{-1}					μg g^{-1}
Chenini Nahel	NS	A	19(0)c	5(0)d	85(3)c	535(15)c	3(0)c	6.1(3.2)b
		BCyy1	<dl‡	<dl	30(1)e	183(1)e	<dl	0.4(0.1)c
		BCyy2	<dl	<dl	<dl	12(0)f	<dl	<dl
		BCyyg	<dl	<dl	<dl	12(0)f	<dl	<dl
		Cyg	<dl	<dl	<dl	15(0)f	<dl	<dl
	CS	Ap	28(0)b	74(1)a	274(2)a	1463(24)a	18(1)a	13.5(2.5)a
		By1	29(0)a	43(0)b	196(1)b	1030(17)b	11(0)b	3.7(0.8)b
		By2	10(1)d	17(0)c	66(0)d	427(8)d	3(0)c	1.3(0.5)c
		BCyy1	<dl	<dl	7(0)f	39(1)f	<dl	<dl
		BCyy2	<dl	<dl	<dl	21(0)f	<dl	<dl
Matmata Nouvelle	NS	A	17(0)a	216(0)a	1090(4)a	1269(15)a	129(1)a	14.2(0.9)a
		Bx1	7(0)ab	42(1)b	201(7)b	658(6)b	21(1)b	13.0(0.1)b
		Bx2	<dl	<dl	36(2)c	139(0)c	3(0)d	10.6(0.1)c
		Bx3	<dl	<dl	18(0)d	70(1)e	<dl	6.6(0.2)e
	CS	Ap1	<dl	<dl	18(0)d	86(0)d	5(0)c	8.0(0.2)d
		Ap2	<dl	<dl	13(0)de	54(0)f	<dl	8.4(0.1)d
		Ap3	<dl	<dl	25(1)d	82(1)d	3(0)d	5.0(0.4)f
		Bx1	<dl	<dl	<dl	25(0)g	<dl	4.5(0.1)f
		Bx2	<dl	<dl	<dl	20(0)gh	<dl	2.4(0.1)g
		Bx3	<dl	<dl	<dl	16(0)h	<dl	2.3(0.1)g
Menzel Habib	NS	C	<dl	33(0)a	120(1)a	359(0)b	28(1)a	9.0(0.2)b
		A	<dl	7(0)c	60(1)c	255(1)d	5(0)d	9.8(0.6)a
		Bk1	<dl	<dl	24(0)f	106(1)f	<dl	7.7(0.2)c
		Bk2	<dl	<dl	5(0)h	31(0)h	<dl	5.9(0.4)d
		Bk3	<dl	<dl	5(0)h	19(0)i	<dl	7.3(0.1)c
		Byy	<dl	<dl	<dl	4(0)k	<dl	0.4(0.1)f
	CS	C	<dl	21(0)b	93(0)b	364(0)a	17(0)b	6.3(0.1)d
		Ap	<dl	8(0)c	56(0)d	264(2)c	8(0)c	5.2(0.3)e
		Bw	<dl	<dl	26(0)e	132(0)e	<dl	10.2(0.1)a
		Bk1	<dl	<dl	6(0)g	57(2)g	<dl	9.6(0.7)ab
		Bk2	<dl	<dl	<dl	15(0)j	<dl	5.2(0.4)e
		Byy	<dl	<dl	<dl	2(0)l	<dl	0.5(0.1)f

The activities are expressed as nanomoles of 4-methylumbelliferone per g of soil per hour.
[†]AryS=arylsulfatase, β-gluc=β-glucosidase, Leu=leucine aminopeptidase, AlkP=alkaline phosphatase, Chit=chitinase.

[‡]<dl = below the detection limit, which is <5 nM g^{-1} h^{-1} for arylsulfatase, β-glucosidase, leucine and alkaline phosphatase, <3 nM g^{-1} h^{-1} for chitinase, and <0.4 µg g^{-1} for dsDNA.