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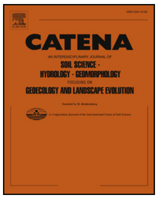

Distribution of soil organic carbon in Wadi Al-Thulaima, Saudi Arabia: A hyper-arid habitat altered by wastewater reuse

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ABSTRACT

The carbon cycle is being altered as a result of human-induced changes in the Earth's system. Therefore, ecosystems such as wetlands, authentic CO_2 sinks, are becoming especially important. Little information exits on the soil organic carbon (SOC) stock for the middle east-countries man-made wetlands making wadis permanent with the outflow of wastewater treatment plants. This paper presents the vertical distribution of SOC content, soil bulk density (SBD) and SOC density in soil of vegetated and bare sites in Wadi Al-Thulaima, one of the artificial wetlands in central Saudi Arabia. The mean distribution of SBD in the vegetated and bare sites increased significantly with depth. Inversely, the SOC content declined significantly with depth, from 17.1 g C kg^{-1} at 0–3 cm depth to 3.3 g C kg^{-1} at 15–18 cm depth in vegetated sites and from 4.7 g C kg^{-1} at 0–3 cm depth to 0.7 g C kg^{-1} at the 15–18 cm depth in bared sites. Vegetation significantly affected the SOC pool, the total mean SOC pool of the vegetated sites (2.0 kg C m^{-2}) was higher than that of the bare sites (0.5 kg C m^{-2}). Therefore, arid regions could contribute to carbon sequestration with appropriate management, which would result in the enhancement of soil quality.

1. Introduction

Main causes of the increasing concentration of atmospheric CO_2 are the combustion of fossil fuel and changes in land use, such as those resulting from deforestation (IPCC, 2007). Currently, this increase has raised scientific and public concern about the carbon sequestration efficiency of various terrestrial ecosystems. The Kyoto Protocol was an agreement to diminish the greenhouse gas concentrations in the atmosphere through the reduction of the emissions and improvement of terrestrial carbon sinks (mostly soil and plants) (Eid and Shaltout, 2013).

The United Nations includes the soil as a relevant issue for sustainable development playing a central role to reach several of the Sustainable Development Goals (Keesstra et al., 2012). However, the impact of human activities for millennia, such as tillage, grazing, fire and mining, has damaged the soil system affecting good, services and soil resources and compromised soils ability to assimilate CO_2 (Brevik et al., 2015; Keesstra et al., 2012). Land management is the key to understand the fate of carbon in the Earth's system because soils can act as carbon sources or sinks. The carbon content in soil is sensitive to management such as, abandonment (Novara et al., 2016), changes in land use (Eid et al., 2017; Muñoz-Rojas et al., 2011), and climate (Willaarts et al., 2016). Agricultural soils that have suffered organic matter exhaustion for years (Bruun et al., 2015; García-Díaz et al., 2016) can become a sink for carbon recovering its organic matter content (Eid et al., 2017; Novara et al., 2016). Moreover, expected climate change will also affect crop production, and as a result, the amount of carbon that is returned to the soil (Muluneh et al., 2015). This can be crucial in arid and hyper-arid areas typical from the Middle East. In Saudi Arabia, the reuse of treated wastewater for irrigation is considered a strategic solution that will enable the restoration of dryland soils and growth of perennial vegetation. Soils with vegetation are better carbon sinks in comparison with bare, dry soils. One example of this policy is the transformation of ephemeral streams of wadis in

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permanent ones using non-conventional water resources, such as reclaimed water. This shift allows the growth of a natural vegetation cover and a significant increase in soil organic carbon (SOC) content. However, there is no information about the distribution of SOC in the wadi ecosystems in Saudi Arabia. Thus, the aim of this study was to determine the vertical distribution of SOC content, soil bulk density (SBD) and SOC density in the soil of vegetated and bare sites in Wadi Al-Thulaima, Saudi Arabia. This research also established baseline data on SOC stocks that is important for future evaluation of SOC evolution and status, as well as for deriving the information needed to establish policies to reduce carbon emissions and to use soil as a terrestrial carbon sink. Furthermore, the identification of a baseline for the SOC pool in Wadi Al-Thulaima could contribute to the assessment of this ecosystem's potential as a CO_2 sink. Such types of data are vital for putting any management plan into place for the wadi ecosystems in Saudi Arabia. The present study could potentially provide a new design of wadis to increase efficiency of soil carbon sequestration by increasing vegetation cover and improving the organic matter source that could be also applicable to other arid and hyper-arid areas elsewhere. This information is also useful for future studies on SOC dynamics to meet the requirements of the Kyoto Protocol.

2. Material and methods

2.1. Study area

Wadi Al-Thulaima is located in the southern part of Al-Kharj City, an oasis south east of Riyadh, Saudi Arabia (from 24° 04′ 25.15″N, 47° 22′ 12.62″E to 24° 11′ 05.53″N, 47° 26′ 14.84″E), and extends up to 35 km in length and approximately 400–500 m in width. Wadi Al-Thulaima receives approximately 120,000 m^3 day^{-1} of sewage water/effluent (Fig. 1). This water comprises industrial effluents, sewage water and overflow of landscape irrigation from Al-Kharj City. The wastewater from the city is collected at the Wastewater Treatment Plant and is released to the Wadi Al-Thulaima either treated or untreated (Hussain and Alquwaizany, 2014). The natural vegetation around the main channel of the wadi has different plant associations and is classified as a sedge wetland, and it includes *Tamarix* trees and shrubs, reeds, grass, forbs, rushes and therophytes (Table 1). The soils of the Al-Thulaima wadi are typical from alluvial basins, rich in smectites that have been transported from highlands into the basin rather than formed in situ. Moreover, the alluvial fans are very common along the wadi side slopes. The hard rock is present in many places at 18 cm depth. The sediment type of Wadi Al-Thulaima is silty loam finer than the surroundings, this could be caused by the perennial water flow that increase water deposition of fine suspended sediments against wind transport and sedimentation of coarse sand. The soil texture of the study area ranged between loamy fine sand and sandy loam. Rainfall is rare and unpredictable from January to March with maximum 25 mL/year (Vincent, 2008).

2.2. Soil sampling

Sampling has been done from four different stands which represent the vegetated and bare sites along Wadi Al-Thulaima (Fig. 1). Sampling was carried out during the spring season of 2015 when most species were expected to be growing. Our null hypothesis is that the vegetated and bare sites have the same SBD, SOC content, SOC density and SOC stock. Therefore, the sampled stands were classified into vegetated and bare (adjacent area) sites. Sample stands were selected randomly to cover all variations of the vegetation wadi channel and bare sites (4 stands in each site); the size of each stand was 50 m × 50 m. Three soil cores (spaced in a triangular pattern with 15 m between each core) were taken in each of the sampling stands to represent each of the vegetated and bare sites. The soil samples were taken using a 7-cm diameter hand soil corer that provides a core without distortion, compaction, or disturbance (Eid et al., 2016; Tan, 2005). The soil corer was forced into the soil to a depth of 18 cm (hard rock is present below 18 cm). After pulling out the corer, the whole length of the soil was cut into 6 sections, each of 3 cm interval to a depth of 18 cm from the core top i.e., (0–3, 3–6, 6–9, 9–12, 12–15 and 15–18 cm), and packed in plastic containers. The sample containers were sealed with parafilm and stored on ice until the analysis to prevent volatilization losses and reduce microbial activity (Bernal and Mitsch, 2008).

2.3. Sample analysis

Each soil sample was dried in an oven at 105 °C for three days, made to cool down to room temperature in a desiccator, and weighed to determine the SBD (g cm^{-3}) (Wilke, 2005):

$$\rho_{sj} = \frac{m_j}{v_j} \tag{1}$$

where ρ_{sj} is SBD (g cm^{-3}) of the j^{th} layer, m_j is mass of soil sample (g) of the j^{th} layer dried at 105 °C and v_j is the volume of soil sample (cm^3) of the j^{th} layer. Each sample was analysed for SOC content by measuring the soil organic matter (SOM) using the loss-on-ignition method at 550 °C for 2 h as follows (Jones, 2001):

$$\begin{aligned} \text{SOM content (g C kg}^{-1}) = 1000 &\times \{(\text{weight of oven dried sample (g)} \\ &- \text{weight of sample after ignition (g)}) \\ &/\text{weight of oven dried sample (g)}\} \end{aligned} \tag{2}$$

SOM was recalculated to SOC by multiplying with a factor 0.58 (Yue et al., 2017}.

SOC density (kg C m^{-3}) was estimated as follows (Han et al., 2010):

$$SOC_{dj} = \rho_{sj} \times SOC_j \tag{3}$$

where SOC_{dj} is SOC density (kg C m^{-3}) of j^{th} layer, ρ_{sj} is SBD (g cm^{-3}) of the j^{th} layer, SOC_j is SOC content (g C kg^{-1}) of the j^{th} layer.

SOC stock (kg C m^{-2}), expressed as mass per unit surface area to a fixed depth of a profile, was calculated as follows (Meersmans et al., 2008):

$$SOC_p = \frac{\sum_{j=1}^{k} SOC_{dj} \times T_j}{\sum_{j=1}^{k} T_j} \times D_r \tag{4}$$

where SOC_p is SOC stock (kg C m^{-2}), D_r is reference depth (=0.18 m), T_j is thickness (m) of the j^{th} layer and k is the number of layers (=6).

2.4. Statistical analysis

Before performing analysis of variance (ANOVA), the data were tested for their normality of distribution and homogeneity of variance, and when necessary, data were log-transformed. Two-way analysis of variance (ANOVA-2) was used to identify statistically significant differences in SOC content, SBD and SOC density among the vegetated and bare sites and six soil depths. The least significant difference (LSD) test was used at $P < 0.05$ to identify the significant differences between the means among the six soil depths. The relationship existing between the SBD and the SOC content was evaluated using non-linear regression (Eid et al., 2017). One-way analysis of variance (ANOVA-1) was used to identify statistically significant differences in SOC stock among the vegetated and bare sites. The SPSS 15.0 software (SPSS, 2006) was used to perform the statistical analysis.

3. Results

The SBD of the bare sites was insignificantly higher than that of the