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Changes in quality and quantity of soil organic matter stocks resulting from wastewater irrigation in formerly forested land

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ABSTRACT

Land use changes often diminish soil carbon stocks and alter soil organic matter (SOM) quality affecting soil productivity. Therefore, intensively managed agricultural systems are intended to maintain and even increase SOM stocks. Here we compared soil organic carbon (SOC) stocks and their quality in fields under natural vegetation (mesquite forest and xerophytic shrubs), converted first to rain fed maize cultivation and then to irrigated alfalfa-maize rotation systems in a semiarid region of Central Mexico. Fields under the alfalfa-maize rotation have been irrigated for different lengths of time (15, 35, 51, 85 and 100 years) with untreated wastewater from Mexico City. We tested if the SOC stocks of the irrigated land use system were similar or even larger than those found under natural vegetation, and investigated if the quality of the SOM changed under the different covers. We collected composite soil surface samples and soil profile samples from fields under the different land uses and irrigation lengths and determined their organic carbon concentrations; we also quantified root residues and analyzed their bromatological composition. Mid infrared spectra of the soil samples were recorded and analyzed by multivariate procedures to determine changes in SOM quality.

We found the smallest SOC stocks in soils under rain fed maize (mean: 45 Mg ha^{-1} in 30 cm depth). In the alfalfa-maize rotation SOC stocks increased 1.5 fold during the first 40 years under wastewater irrigation, thereafter reaching an apparent new steady state, with similar C stocks to soils under xerophytic shrub cover (65 Mg ha^{-1}). SOM in rain fed soils was more hydrophobic and more metabolized by microorganisms, while the SOM in irrigated soils had a more hydrophilic character. Lignin in surface horizons of long term irrigated soils has a lesser degree of condensation than in deeper soil horizons or in soils irrigated for shorter periods of time, indicating a less intensive microbial degradation. We conclude that wastewater irrigation increases SOM stocks due to the greater lignin rich root biomass produced by alfalfa in this land use system, which helps to recover the SOC loss of 17–34% of the rain fed agriculture system.

1. Introduction

Each ecosystem has an intrinsic capacity to store soil organic carbon (SOC) (King et al., 1997; Schmidt et al., 2011). This capacity depends on several factors, among which the most widely recognized are vegetation structure and composition, rain fall and temperature regime, and soil moisture, temperature and nutrient contents (Stockmann et al., 2013). All these factors determine the amount and the quality of the organic debris and its turn over rates by the soil biota. Clay and iron oxides contents, as well as soil properties like aggregation, stabilize organic compounds and protect them from microbiological attack (Schmidt et al., 2011; Stockmann et al., 2013). In natural ecosystems SOC stocks approach a dynamic equilibrium, resulting of the balance between the net primary production and the heterotrophic respiration of the organic debris (Stockmann et al., 2013), both depending on the prevailing environmental conditions.

Largest SOC stocks are reported for arctic and alpine tundra (250 Mg ha^{-1}) and cold deciduous subalpine or sub polar shrub lands (192 Mg ha^{-1}), while smallest SOM stocks are found in deserts and xeromorphic shrub lands (68 Mg ha^{-1}) (King et al., 1997). Globally, land use change (LUC) to agriculture has diminished SOC stocks by approximately 60–75% (Guo and Gifford, 2002; Lal, 2004). Conversion

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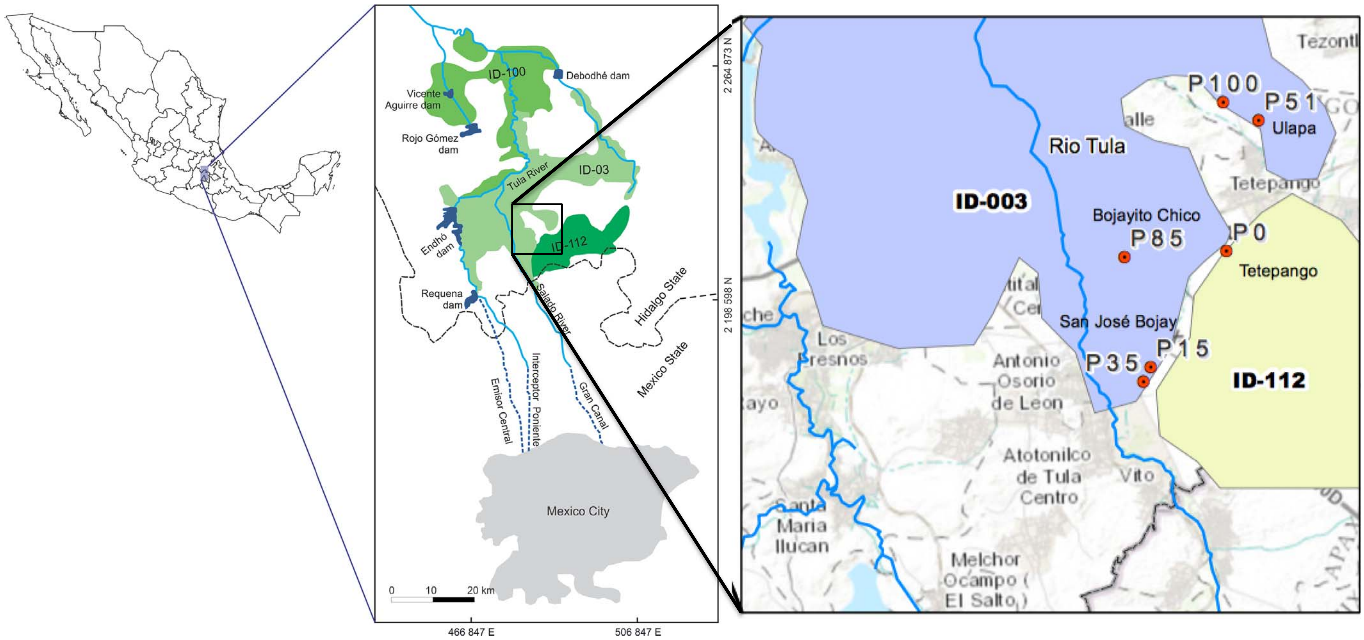

Fig. 1. Location of the study area and the specific sampling sites. Labels indicate length of irrigation.

from nearly all land uses to cropping and monocultures results in losses of SOC (Guo and Gifford, 2002). Particularly in poorly managed land use systems, which do not incorporate any kind of organic residues to compensate for the nutrient uptake by the crops, soils have lost 20 and up to 80 Mg ha $^{-1}$ C. In this agricultural system, frequent plowing and the use of mechanical tools for seed bed preparation have decreased SOM stocks, due to the enhanced oxygenation and the break down of soil aggregates, both favoring soil microbial activity (Lal, 2004).

In traditional agricultural land use systems SOC stocks are recovered by incorporating organic amendments like feedstock manure, crop residues or compost of kitchen residues. Today more than 50% of the world's population lives in cities (United-Nations, 2014) and the produced solid organic residues, sewage and sewage sludge need to be disposed of. Thus, the interest in using urban wastes as soil amendments has been increasing in the last century, with compost, biosolids and untreated wastewater increasingly used as soil amendments as a waste management strategy on the one hand, and to restore SOM stocks and thereby increase land productivity on the other (Qadir et al., 2010; Raschid-Sally, 2010; Hanjra et al., 2012). The organic fraction of urban waste materials is rich in low molecular weight compounds which are easily metabolized by soil organisms so that most of their carbon is emitted as carbon dioxide into the atmosphere shortly after deposition. For example, we have measured the emissions of CO_2 in fields irrigated with untreated wastewater in this area, and found that they are 4.66 fold larger than in rain fed maize fields. Also the emissions of CO_2 increased rapidly in response to flood irrigation with peaks up to 448 mg C m^2 h $^{-1}$ for CO_2 (González-Méndez et al., 2015). Crowther et al. (2016) found that the effects of warming are contingent on the size of the initial soil carbon stock, and they provided strong empirical support for the idea that rising temperatures will stimulate the net loss of soil carbon to the atmosphere, driving a positive land carbon–climate feedback that could accelerate climate change. Unravelling the feedback effect is particularly difficult, because the diverse soil organic compounds exhibit a wide range of kinetic properties, which determine the intrinsic temperature sensitivity of their decomposition (Davidson and Janssens, 2006).

The organic compounds present in urban waste materials generally have a small C:N ratio, like sewage (4:1), compost made out of kitchen residues (10–13:1) or biosolids (8–12:1) (Feigin et al., 1991; Hernández-Martínez et al., 2016), with only a smaller proportion of carbon contained in larger molecular weight compounds, which are more resistant to microbial decomposition and can, therefore, contribute in the medium term to increase the humidified SOM stock. The proportions between recalcitrant and labile or solid and soluble SOC in a managed agro-ecosystem should therefore depend to a large extent on the nature of the organic crop residues and the organic waste materials added to the soil. While many studies have investigated how compost, biosolids or recently also their carbonized sub product biochar change the SOM stocks and their quality (Martínez-Blanco et al., 2013; Rivero et al., 2004), very few studies exist on the effects of irrigation with either untreated or treated sewage on the SOC stocks and especially on the SOM quality (Bernier et al., 2013; Belaqziz et al., 2016). Here we present a study of a chronosequence of parcels irrigated for different lengths of time with untreated wastewater, where we sampled surface soils and soil profiles at different depths. Our aim was to analyze changes in the SOC stock under natural vegetation and under rain fed maize and alfalfa–maize rotations irrigated with wastewater. We expected the SOM quality to change due to the different composition of the organic matter input. To test this hypothesis we quantified the aerial and below ground biomass and characterized its composition by either bromatological determinations (biomass) or by infrared spectroscopy (SOM). We analyzed changes in SOM stocks over time by regression analysis, and changes in SOM quality by multivariate analyses of the infrared spectra data.

2. Materials and methods

2.1. Study area

The Mezquital Valley is located in the south-east of the state of Hidalgo, and north west of the basin of Mexico (Fig. 1), and has a mean annual temperature of 17 ° C, and a mean annual precipitation of around 600 mm. Dominant soils in the valley are Phaeozems associated either with Leptosols or Vertisols (Siebe, 1994). The natural vegetation corresponds to xerophytic shrubs with *Prosopis juliflora* (mesquite) and *Acacia* sp. as major components (Gonzalez-Quintero, 1968). Several land use changes have occurred in this area in the last millennium: the area started to be populated in the Early Classic (200–700 CE) and became the political center of the central Mexican highlands from 950 till 1250 CE, when the Toltecs dominated this area. Mastache et al.