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What can we learn from ancient fertile anthropic soil (Amazonian Dark Earths, shell mounds, Plaggen soil) for soil carbon sequestration?

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ABSTRACT

Historical land use and soil management left behind anthropic soils such as Amazonian Dark Earths (Terras Pretas de Índio - pretic Anthrosols), Anthropic shell mounds (Sambaquis - terric Anthrosols), and Plaggen soils (plaggic Anthrosols), enriched in soil organic matter and soil fertility. The objective of this study was to compare soil organic matter quantity and quality of these tropical and temperate anthropic soils among each other and against their adjacent non-anthropic soils. All anthropic soil horizons had enhanced total contents of C, N, P, K, Ca, Mg and Fe, reflecting a soil organic matter and nutrient enrichment compared to their reference soils, mostly expressed by the Sambaquis. In order to better understand the mechanisms of soil organic matter stability, besides black carbon analysis, topsoils and subsoils were incubated in the laboratory at 10 °C and 30 °C and the emitted CO_2 was recorded for 44-days. The Plaggen soil released the highest amount of CO_2 at 30 °C, being two to three times higher compared to Terra Preta de Índio and Sambaqui anthropic horizons. The highest mean residence times (MRT), between 38 and 63 years, were calculated for the subsoils of the anthropic soils incubated at 10 °C. In the artificial system of this study, the stability of anthropic soil horizons under study was not generally enhanced when compared with their reference soils. However, enhanced stability of total organic carbon (TOC) was indicated by a negative relationship between black carbon portion of TOC and the relative amount of CO_2-C released from TOC of all anthropic soils. During the incubation period of 44 days, the cumulatively mineralized amount of soil organic carbon (SOC) in the top of anthropic soils at 30 °C was three to six times as high as that at 10 °C. Consequently high temperature under tropical conditions should have stimulated the decay of organic matter, which however was not reflected by high TOC contents found in Terra Preta and Sambaqui samples, corroborating their low degradability in the long term. Therefore, we propagate that a high stability of carbon stocks exists in anthropic soil horizons, which may become a promising opportunity for the establishment of a new generation of anthropic soils with improved soil fertility and soil organic matter using the principle of soil-biochar systems.

1. Introduction

Current world population of about 7.5 billion people (www.worldometers.info/world-population) will increase to about 9.7 billion until 2050 (United Nations, 2015). Together with rising wealth especially in Asia it is estimated that food production needs to be doubled to feed the World (Hunter et al., 2017). Increasing food production can be achieved either by expanding the agricultural area e.g. by deforestation of primary forest or by intensification of existing agriculture (Glaser, 2007). The latter may lead to soil erosion, soil mineral depletion and soil organic matter mineralization resulting in soil degradation and loss of agricultural productivity (Zech et al., 1990). On the other hand, there are examples of historical land use and soil management that have increased soil organic matter stocks and soil fertility while using soils for settlement and agriculture (Glaser et al., 2001). Even today these historical anthropic soils hold large stocks of organic matter and nutrients and are sustainably fertile, centuries or millennia after their creation (Glaser et al., 2001; Wiedner et al., 2015), so that they might act as models for sustainable agriculture in the future to feed the world (Glaser, 2007; Glaser and Birk, 2012).

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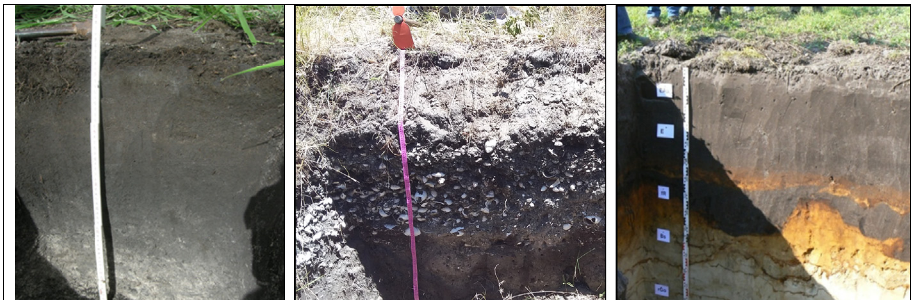

Terra Preta de Índio, Parintins, Brazil (Tropical)	Sambaqui, Arraial do Cabo, Brazil (Tropical)	Plaggen Soil, Oldenburg, Germany (Temperate)

Fig. 1. Profiles of the anthropic soils under study.

Today, anthropic soils have gained attention also in the search for strategies to counteract global climate change, since they are discussed to store a significant amount of carbon in soil (Glaser, 2007; Lal, 2009). Anthropic soils show morphological features, which have been profoundly re-worked by men. Those impacts are diverse, including i) irrigation together with mineral inputs forming irragric and puddling, ii) wet cultivation forming hydragric horizons, iii) application of earthy, earthy-mineral, organic manures, sometimes in addition with charcoal forming terric, plaggic or pretic horizons, and iv) deep cultivation plus intense fertilization with organic residues forming hortic horizons (IUSS Working Group WRB, 2015). As a result, many anthropic soil horizons are enriched in organic carbon concentrations or stocks due to stabilized organic matter and large thickness of their horizons. The best-known example of carbon-enriched and sustainably fertile anthropic soil horizons are the Amazonian Dark Earths or Terra Preta de Índio (TPI) intensively studied during the last decades (Sombroek, 1966; Glaser et al., 2001; Lehmann et al., 2003; Glaser, 2007; Woods et al., 2009; Teixeira et al., 2010; Macedo et al., 2017). It is the result of long-term human settlement, which led to addition of charred residues (black carbon or biochar) and household wastes including human excrements, and bones together with pottery sherds (Glaser and Birk, 2012). According to the World Reference Base for Soil (IUSS Working Group WRB, 2015), many of these soils with their high stocks of recalcitrant organic carbon may be classified as pretic Anthrosols.

Another anthropic formation are shell mounds (Gaspar et al., 2013; Correa et al., 2013), known as Sambaqui in Portuguese, which are marked by dark horizons with large amounts of carbon and nutrient stocks (Teixeira et al., 2012; Villagran et al., 2009). Until now they received less attention from the soil scientific community. Some of the best-known ones are located in the southeastern coastal Brazil (Gaspar et al., 2013), including our study area in the State Rio de Janeiro (Mansur et al., 2011). These prehistoric shell mounds have been built-up centuries ago and consisted primarily of mollusk shells, human burials, and hearth and housing structures (Gaspar, 2004). This was the result of managing organic residues by the indigenous population. The Sambaquis are characterized by large amounts of calcium carbonate from the shells. It is assumed that the carbonization of animal and vegetal residues was a result of human living and contributes to the larger stocks of organic carbon found in these sites (Teixeira et al., 2012; Correa et al., 2013; Villagran et al., 2009). However, there are many open questions about the mechanism of pedogenesis in Sambaqui horizons.

There is also little knowledge about soil organic matter stability of other widespread anthropic soils of temperate regions such as Anthrosols with plaggic soil horizon from Northwest-Europe (Giani et al., 2014), Russia (Hubbe et al., 2007) and Norway (Schnepel et al., 2014). Plaggen soils show a plaggic topsoil horizon exceeding 40 to 50 cm, produced by men during long-term manure management. Plaggen consist of grassy, herbal or shrub vegetation, its felted roots and soil material sticking on them (Niemeier, 1955). They were cut in communal locations, brought into the stables, enriched with animal dung and urine spread out onto the fields as a mineral-organic manure. As a consequence, thick and organic matter-rich plaggic topsoil horizons grew, reaching thicknesses of up to 70–120 cm (Blume and Leinweber, 2004). As plaggen management regularly included activities near the farm houses, waste (charcoal, rests of bricks and pottery) was disposed together with the manure and is nowadays found as artefacts confirming the anthropic genesis (Giani et al., 2014). The main aim of plaggen management, which started approximately thousand years ago was to improve soil quality, especially of nutrient-poor soils like Podzols. Plaggen management stopped about 150 years ago when mineral fertilizers were introduced.

This study focused on the comparison of three anthropic soil horizons with different physical, chemical and climatic conditions (temperate vs. tropical): i) Terra Preta de Índio (tropical), ii) Sambaqui (tropical) and iii) Plaggen soil (temperate). These anthropic soils were studied to characterize their physical and chemical soil properties and to compare soil organic matter quantity and quality among each other and against their adjacent soils, taken as reference for non-anthropic interference in its pedogenesis. Finally, the potential of the anthropic soils is discussed to be used as examples for new improved soil-biochar systems, which can help in climate change mitigation by carbon sequestration, while improving soil fertility, and thus sustainable crop production.

2. Material and methods

2.1. Study sites

Anthropic soils were sampled from two tropical locations in Brazil and from one temperate location in Germany (Fig. 1). According to a visible or traceable transition within the soil profiles, sampling was done in metric intervals and defined as "topsoil" and "subsoil".

2.1.1. Terra Preta de Índio (TPI) – pretic Anthrosol

The soil samples selected for this study were collected at two TPI sites. One TPI (TP-1) was sampled in the vicinity of the city of Parintins (Coordinates UTM centered at 2.657710 S; 56.738317 W), Amazonas State – Brazil. Samples were taken from a profile at three distinct depths (5, 15 and 48 cm) by horizontal coring. Another TPI (TP-2) soil was sampled at Embrapa Research Station of Caldeirão at depths between 0–10 cm and 100–150 cm (coordinates UTM centered at 3.246181 S; 60.243436 W) near the city of Iranduba (Amazonas State – Brazil). A reference soil for both TPI sites was a topsoil horizon (0–10 cm) from an Acrisol located 800 m from the TP-2 site. The climate is tropical rainy, Aw type (Köppen classification). Average annual temperature is 27 °C and annual precipitation is 2100 mm with a mean relative humidity of 80%. The soils at the site originated from weathering of sedimentary rocks from the Tertiary period of the Altér do Chão formation characterized by clayey sandstones, quartz sandstone, arkoses and argillites