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Urban soils as hotspots of anthropogenic carbon accumulation.

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Abstract
Urban soils and cultural layers accumulate carbon (C) over centuries, however, processes and mechanisms leading to high C accumulation in urban soils remain unknown. The processes specific for C accumulation in urban soils were analyzed and the C sequestration rates were assessed based on the data from 118 cities worldwide. For the whole range of climatic conditions, 1.5-3 times higher C content and much deeper C accumulation in urban soils resulted in 3-5 times larger C stocks compared to natural soils. Soil organic carbon (SOC) and black carbon (BC) increased with latitude, whereas soil inorganic carbon (SIC) was less affected by climate. The city size and age were the main factors controlling intra-city C stocks with higher stocks in small cities compared to megapolises, and in medieval compared to young cities, whereas the inter-city variability was dominated by functional zoning. Substantial amounts of SOC, SIC and N were sequestered for long-term in the subsoils, cultural layers and sealed soils, underlining the importance of these ‘hidden’ stocks for C assessments. Despite small city areas, urban soils are hotspots of long-term belowground C sequestration worldwide, and the importance of urban soils will increase in future with global urbanization.

Keywords: Global change, Urbanization processes, Cultural layers, Subsoil carbon, Anthropogenic processes, Pyrogenic carbon, Xeno-carbon, Carbon accumulation rate.

Introduction, scope and main objectives
Urbanization increases the importance of urban ecosystem components and raises the environmental relevance of urban soils from local to regional and global levels. Urban soils provide important functions and ecosystem services. The research clearly showed one of the ecosystem services of urban soils: the C sequestration.

Methodology
We collected data on organic (SOC), inorganic (SIC), black (pyrogenic) (BC) and N contents and stocks in urban soils from 100 papers. The database (770 values on SOC, SIC and BC stocks from 118 cities worldwide) was analyzed considering the effects of climate and urban-specific factors: city size, age and functional zoning. The processes specific for C accumulation in urban soils were analyzed and the C sequestration rates were assessed. Urban soils were compared with their natural counterparts. Natural soil types based on the Harmonized World Soil Database v 1.2 (HSWD; Fischer et al., 2008) and dominating in the 10 km buffer surrounding a city were selected as a counterpart for comparison

Results
The estimated C stocks in urban soils were 3-5 times higher than in natural soils and were based on long-term accumulation of four C forms: SOC, SIC, BC and Xeno-C. Climate was the main contributor to the variance of SOC stocks in the topsoil, whereas the city area and age mainly affected SOC stocks in subsoil and cultural layers. Topsoil urban SOC for cold and temperate

zones was higher than those in tropical and arid zones. The topsoil SIC stocks were highest in arid and cold zones. BC stocks in temperate climates were almost 10 times larger than in cold and arid zones. SOC stocks significantly increase (r = 0.61, R^2 = 0.38, p<0.05) in 0-10 cm of urban soils from tropics (~20 °) towards high latitudes (60-70 °). The pattern was similar to the SOC distribution in upper 10 cm in natural soils for the same range of latitudes (ISRIC-WISE Dataset, Batjes, 2008), but the correlation for the natural soils was weaker (r = 0.46, R^2 = 0.21, p<0.05). Thus urban topsoil in tropics and arid climates (20-30 ° latitudes) contained less SOC, whereas in temperate and cold climate SOC contents and stocks were substantially higher compared to natural soils (Fig. 1)

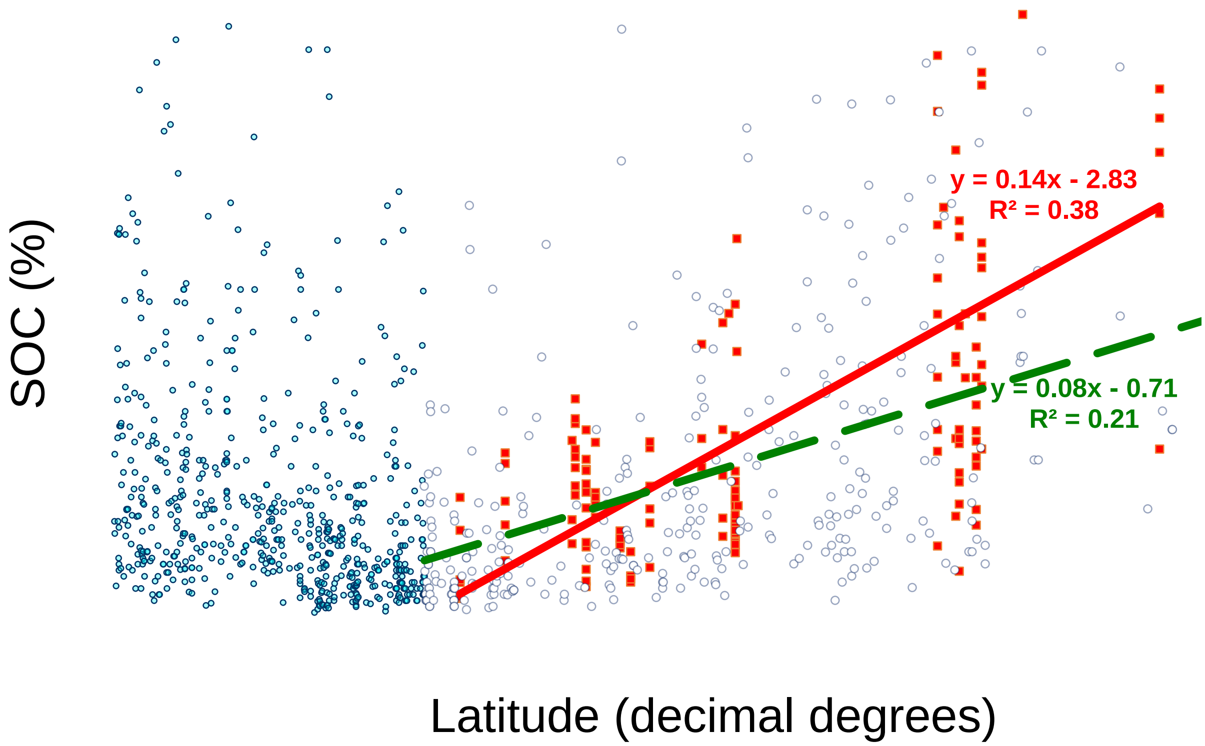

Fig. 1: Zonal patterns in SOC content in urban and natural topsoil (0-10 cm).

The inter-city variability of C stocks was dominated by functional zoning: large SOC and N stocks in residential areas and large SIC and BC stocks in industrial zones and roadsides were similar for all climates and for cities of various size and age. Substantial amounts of SOC, SIC and N were sequestered for long-term in the subsoils, cultural layers and sealed soils, underlining the importance of these ‘hidden’ stocks for C assessments. Long-term C inputs from outside the cities and C accumulation coincided by upward soil growing of 50 cm per century result in continuous accumulation of 15-30 kg C m^{-2} per century in urban soils and cultural layers.

Discussion

Much higher C stocks in urban compared to natural soils are explained by the specific anthropogenic and natural processes and mechanisms, contributing to fast C accumulation in urban areas. These mechanisms include 1) C inputs from suburban-areas (e.g. transfer of food, wood and raw materials), 2) C provisioning and redistribution inside the city (e.g. xenobiotics, soot and charcoal) and 3) *in situ* transformations (e.g. sealing, over-compaction and water-logging). Upward growth of urban soils over a long period results in very deep cultural layers with very high C accumulation. Urban soils grow upward for about 50 cm per century corresponding to C accumulation rate of 20-30 kg C m^{-2} per century. This results in SOC stocks in 200 cm depth in soils of medieval cities which are higher than the maximal SOC stocks in Chernozems and Phaeozems - natural soils with highest C stocks. Such high rates of C accumulation in urban soils highlight their potential to mitigate climate change despite their comparatively small area.

Conclusions

Urbanization is one of the most important components of Global Change and its rates are faster than of the other components. Consequently, the importance of urban soils as omnipresent part of the cities will increase in future. Therefore, urban soils should be considered not only as the stocks of waste and pollutant accumulations (as in the most studies), but having a broad range of ecosystem function, one of them - long term C sequestration, which is much higher than in natural soils.