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Both tree and soil carbon need to be quantified for carbon assessments of cities

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ABSTRACT

Carbon storage is a valuable ecosystem service in a world facing anthropogenic climate change. Although studies have shown that urban areas have significant carbon stocks, these areas are often neglected in carbon budgets. The majority of published studies examining urban carbon storage so far focused on carbon storage in trees, neglecting organic carbon storage soils. However, the few studies including carbon storage in soils found high values. We measured carbon stored in trees and mineral topsoils in Hamburg in a joint study design. Tree carbon was calculated with the aid of allometric equations, while soil organic carbon was analyzed with taken soil samples to a depth of 30 cm. Additionally, amounts of organic carbon in trees and mineral topsoils were compared within and between different biotope types. Subsequently, carbon storage in different degrees of urbanization was compared.

In total, about 6 Mt of organic carbon are stored within the political boundaries of Hamburg, with 2 Mt in trees and 4 Mt in mineral topsoils. Results from the city of Hamburg show an underestimation of urban carbon storage within its political boundaries in national carbon budgets. Carbon storage in trees showed no correlation to carbon storage in mineral topsoils. Further, stored amounts in both differed in analyzed biotope types. This underlines the need for quantification of both compartments independently. Comparison of the different urbanization degrees revealed that carbon storage is concentrated in the less urbanized areas. Results might be transferable to other cities via the degree of urbanization, as this classification is based on easy to compute data.

Results show a significant amount of carbon stored in a large European metropolis. Global carbon budgets will benefit from the incorporation of found values, to result in exhaustive figures for an increasingly urbanized world. To provide stakeholders with reliable data on urban carbon storage, we show the need for future quantification studies to assess carbon stored in soils as well as in trees.

Introduction

More than half of the world's population currently resides in urban areas and urban population growth is expected to exceed world population growth (United Nations, 2011), underlining the global impact of urbanization and the importance of knowledge about urban ecosystems. Estimating the extent of urban areas globally is difficult due to, e.g. differing definitions of "urban" with estimates ranging from 0.27 to 3.52 million km^2 (Potere and Schneider, 2007). While the extent of urban areas so far has not been estimated reliably, it is well known that their effects on ecosystems are reaching far beyond city limits (Grimm et al., 2008). Importance of urban ecosystems and of the ecosystem services they provide have been recently acknowledged (MA, 2005) and further assessment of urban ecosystem services has been requested by the secretaries of the environment of the G8 countries (TEEB, 2011). Despite the growing body of literature (Gómez-Baggethun et al., 2013) many aspects of urban ecosystem services have not been studied conclusively and empirical evidence is still scarce (Pataki et al., 2011). These knowledge gaps need to be filled to advise urban policy stakeholders, aiming at an ecological sustainable development (Pickett et al., 2008).

One of the ecosystem services provided by urban ecosystems is carbon storage. Atmospheric CO_2 concentration has increased significantly due to anthropogenic sources, resulting in CO_2 being the single most important driver of anthropogenic climate change (IPCC, 2. 2007) with urban areas as "hotspots" for its emission

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(Grimm et al., 2008). Terrestrial ecosystems have the ability to remove CO_2 from the atmosphere mostly by storing carbon in woody biomass and soil organic matter. In this regard, urban areas have been shown to store significant amounts of carbon (Churkina et al., 2010). So far, however, the amount of carbon stored in urban areas is often not taken into account for terrestrial carbon budgets (Janssens et al., 2005). Some studies examined proxies to account for the stored carbon in urban areas (Eigenbrod et al., 2010) or use values derived from other land-uses (Federal Environment Agency (Umweltbundesamt) 2013).

So far, soil organic carbon (SOC) is often neglected in urban carbon storage studies (e.g. Davies et al., 2011), despite studies indicating more organic carbon being stored in urban soils than in urban vegetation (Pouyat et al., 2006; Churkina et al., 2010; Edmondson et al., 2012). Carbon storage by urban forest trees has been quantified in various urban areas, mainly in US cities (e.g. Rowntree and Nowak, 1991; Nowak and Crane, 2002; Hutyra et al., 2011), but also around the globe for example in the UK (Davies et al., 2011), Germany (Strohbach and Haase, 2012), China (Liu and Li, 2012) and Australia (Brack, 2002). In contrast, fewer studies have quantified the amount of organic carbon stored in urban soils (e.g. Pouyat et al., 2002; Lorenz and Lal, 2012), producing an unbalanced level of knowledge about carbon storage in urban trees and soils. First steps have been made to jointly quantify the amount of carbon stored in trees and soils (e.g. Jo and McPherson, 1995), but so far only two studies have used a city-wide sampling regime (Pouyat et al., 2002; Edmondson et al., 2012). However to consider the heterogeneity of urban land uses, a finer spatial resolution is required than employed in the mentioned studies.

As cities differ in many aspects, the amount of carbon stored in trees (Nowak et al., 2013) and soils (Pouyat et al., 2006) differs strongly between them. Studies are needed to complement previous findings with additional carbon storage values to result in realistic estimates and improve accuracy of global carbon storage models. Up to now, no study has quantified the amount of organic carbon stored in urban forest trees and urban mineral topsoils in a large European metropolis. This study aims at quantifying organic carbon stored in urban trees and mineral topsoils of Hamburg (Germany), resulting in a city-wide carbon storage budget of both compartments. It will consider spatial heterogeneity and examine patterns of carbon storage based on land use and vegetation cover, enabling direct comparison of carbon storage in trees with organic carbon storage in mineral topsoils. Areas of special importance for this ecosystem service will be highlighted. Additionally, the political extent of the city will be divided into three degrees of different urban intensity. Carbon storage in the three degrees will then be compared. The employment of an urbanization index will enable comparisons based on an abstract measure of urbanization independent of the biotope types. Further, it will increase the ability to transfer results to other cities. Findings offer information to regional planners as well as stakeholders interested in global carbon cycle modeling.

We ask: is carbon storage in urban trees correlated to organic carbon storage in the respective urban mineral topsoils? Do biotope types and urbanization degrees differ in their amount of stored organic carbon? How much organic carbon is stored in the individual biotope types and urbanization degrees? What is the ratio of organic carbon storage in mineral topsoils to carbon storage in trees? Do some areas currently have especially high carbon stocks? Further, we will discuss, whether found relative importance of trees and mineral topsoils for urban organic carbon storage is mirrored in published studies, how urban areas are represented in national carbon budgets and how organic carbon storage values from Hamburg compare to cities around the globe.

Materials and methods

Study city

Hamburg is a metropolis in northern Germany (53°38′ N, 10°0′ E), with about 1.8 million inhabitants (Statistisches Amt für Hamburg und Schleswig-Holstein, 2013). In addition to built-up areas of housing and industry, the city's political boundaries include agricultural, grassland, leisure, ruderal, transportation and wetland areas. About 60 km^2 of the city's 755 km^2 are protected as nature reserve. About 61 km^2 are water bodies, of which the rivers Elbe (flowing from east to west) and Alster (flowing from the north into the Elbe) are the most prominent ones. Another 6 km^2 are islands located in the North Sea. Both water bodies and islands were excluded from this study. Hamburg has a temperate oceanic climate with 749 mm of precipitation annually and an average annual temperature of 8.8 °C (Hoffmann and Schlünzen, 2010).

Establishment of study plots and field measurements

To create a stratified random survey of organic carbon stored in trees and soil, the biotope type cadaster of Hamburg was used. The cadaster is based on previously existing maps, air photography and ground surveys and continuously updated, yielding a comprehensive data set of varying resolution. It is compiled on the authority of the Behörde für Stadtentwicklung und Umwelt (Office for Urban Planning and Environment) and hierarchically classifies vegetation and landscape utilization units into biotope types, accounting for the human component in landscape units as called for by Grimm et al. (2000). For this study, the cadaster's units were combined to result in ten biotope types primarily based on higher hierarchical classes of the cadaster: agriculture (e.g. fields, nurseries, orchards), densely built-up (e.g. historic center, city blocks), scattered built-up (e.g. detached houses, suburbs, terraced houses), industry and administration built-up (e.g. industrial complexes, schools, centers of commerce), dry forest (e.g. beech or pine forest), wet forest (e.g. alder or willow forests), grassland (e.g. for cattle farming), leisure area (e.g. parks, allotment gardens and cemeteries), ruderal (e.g. dry grasslands, brownfields and landfills), transportation (e.g. streets, harbor and airport) and wetland (e.g. bogs and fens).

Ten random plots per biotope type, established with the aid of ArcGIS 9.3 (ESRI Inc., Redlands, CA, USA), were sampled from June to October 2012. Digital maps were used to locate and sample determined plots in the field. If access to a plot was impossible or not granted, it was relocated to a nearby location within the same biotope type. If this proved to be impossible, the next random plot was used until ten plots per biotope type were sampled.

Each study plot consisted of a circle with a 15 m radius. To determine tree biomass, diameter at breast height (DBH) of all living trees and branches within the circle exceeding a diameter of 5 cm were measured and species determined. To determine mean SOC content, pooled soil samples of 15 individual drillings per plot were taken from 0 to 10 and 10 to 30 cm depth by a soil auger. It is important to note that the O layer was excluded from this study, yielding conservative results. To calculate fine soil mass, soil bulk density and skeleton content were determined according to BKA 2005 (AG Boden, 2005) by digging a 30 cm deep hole, noting skeleton content and taking four soil cores of 100 mL: two from 0 to 10 cm depth and two from 10 to 30 cm depth.

Under some circumstances, especially in the built-up areas, the plot design had to be modified. The goal was to keep the sampling design as unchanged as possible while being representative of the originally determined random plots features. Setting up plots on unsealed surfaces as close as possible to the originally determined random plots, i.e. on the same property, was aimed at. If properties were too small or offered not enough unsealed surface to set up a