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High carbon losses from established growing sites delay the carbon sequestration benefits of street tree plantings – A case study in Helsinki, Finland

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ABSTRACT

We assessed the net carbon (C) sequestration dynamics of street tree plantings based on 10 years of measurements at two case study sites each with different tree species in Helsinki, Finland. We assessed C loss from tree soils and tree C accumulation, tested the applicability of pre-existing growth and biomass equations against observations, and estimated the time point for the beginning of net C sequestration for the studied street tree plantings. The tree woody biomass C accumulation in the first 10 years after planting was 18–32 kg per tree. At the same time the C loss from the growth media was at least 170 kg per growth media volume (25 m^3) per tree. If this soil C loss was accounted for, the net C sequestration would begin, at best, approximately 30 years after planting. Biomass equations developed for traditional forests predicted more stem biomass and less leaf and branch biomass than measured for the species examined, but total aboveground biomass was generally well predicted.

1. Introduction

Carbon (C) sequestration is one of the ecosystem services that encourage the planting of urban trees (McPherson et al., 2005). The C sequestration effects of urban tree plantings consists of C stock change in above- and belowground tree compartments, and soil organic matter (SOM) stock changes related to tree planting and litter production by planted trees. The belowground C stock of urban trees and soils is not well known, but there are indications that urban soil C stocks can be substantial (Pataki et al., 2006). In the traditional, non-urban forests of Scandinavia, the soil C stock occurs predominantly in the superficial layers and is as large as or larger than that of the vegetation (Liski et al., 2006). In urban greening, trees are planted traditionally in limited container-like soil spaces or wider structural soil (e.g. Grabosky and Bassuk, 1995; Neal and Whitlow, 1997; Kristoffersen, 1999) volumes in which the load-bearing properties of the soil have been enhanced with stony matrices. Fine soil, suitable for tree rooting, is located in the voids of the stone matrix. In both of these methods, artificial growing media brings C-rich soil into the deep layers. Currently, Finnish municipalities use SOM contents of 10–12% (measured as loss-on-ignition, LOI) throughout the standard 1-m-deep growth media in tree plantings (Rakennustietosäätiö, 2010). A square metre of new traditional tree growth media thus typically has a C stock of approximately 40-–50 kg C m^{-2} and a structural soil of 10–20 kg C m^{-2}; about 2–10 times more than in traditional upland forest soils in Finland (Liski et al., 2006).

In contrast to natural SOM, which has substantial proportions of slowly decomposing fractions, the artificial growth media organic matter may decompose quickly and lose C to the atmosphere (Bernal et al., 1998). Soil sealing (by e.g. asphalt or pavement), common in urban environments and predominantly used in combination with structural tree soils, impairs soil heat and soil water (SW) exchange (Scalenghe and Marsan, 2009) and limits the C input from above the ground, affecting biomass accumulation and decomposition. These effects may lead to overall C loss from street tree plantings unless the C sequestered by the tree exceeds the C loss from the growing media. The organic matter in the growing media may be derived from peat, or partially or entirely from renewable C sources, such as compost. In addition to its use in growing media as such, peat is a common additive used when composting sewage sludge, kitchen and food waste etc. (e.g. Himanen and Hänninen, 2011), and consequently, also the SOM in

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Abbreviations: AB, aboveground biomass (stem, branches and leaves); ABW, aboveground woody biomass (stem and branches); BE, biomass equation (see Appendix A); C, carbon; DBH, diameter at breast height; LOI, loss-on-ignition; O_e, loss-on-ignition estimated (Eq. (6)) for the periods between LOI samplings; SOM, soil organic matter; SW, soil water; T_f, soil temperature, as measured at tree sites; WB, woody biomass; W_f, soil water content, % of weight, as measured at tree sites; α, LOI and SWC response parameter in the incubation model; β, temperature response parameter in the incubation model

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compost-derived growing media tends to contain some fraction of peat. While renewable C originating from short-term biogenic cycle is commonly considered neutral in regards to climate change, peat-derived CO_2 in energy production is currently viewed as equivalent to fossil fuel emissions (IPCC, 2006). IPCC takes no stand on other uses of peat however; thus the official C accounting status of peat in growing media is somewhat unclear. There is a general interest in finding replacements for peat in the growing media industry however, due to both wetland protection and CO_2 emissions (e.g. Defra, 2009).

In a street tree planting, growing media C emissions can be compensated and exceeded by the C sequestration of trees over time. Unfortunately, the size and C stock of urban trees of a given age are not easily predicted (Peper et al., 2014). Currently, aboveground C stocks in urban trees are estimated with allometric tree biomass equations (BEs) developed in traditional forests, if urban-based equations are not available. Root biomass may then be estimated from a set root-shoot ratio despite its large variation between ecosystems and species (e.g. IPCC, 2006). However, the accuracy of traditional forest based BEs in an urban context has been questioned (McHale et al., 2009). The particular above- and belowground environments of trees influence both the overall growth rate and biomass distribution within trees (Litton et al., 2007; Zhou et al., 2014). Consequently, the urban environment may lead to biomass distributions different from those observed in traditional forests, with consequent biomass estimation problems. In addition to biomass distribution, the tree-related C inputs into urban soil remain largely unknown. Root exudates and litter likely contribute to soil C stock while, especially in paved areas, the aboveground litter might not, because it is either removed or moves along, unable to enter the soil under the pavement.

The purpose of this study is to estimate the long term carbon dynamics of a street tree planting in the hemi-boreal city of Helsinki. We collected data from two case study street tree plantings (established according to current establishment practices in Finland) about long term C stock changes in the growth media and trees. These were combined with literature based tree growth equations that we tested with separate tree data from different aged street tree plantings in Helsinki, and literature based biomass equations. At the case study sites, we assessed the soil C stock changes occurring during the first 10 years after planting, using a LOI change-based approach. We evaluated the estimate with CO_2 production of soil samples in an incubation experiment. At these sites we estimated the tree biomass accumulation from direct measurements of the case study trees. The measurements were compared against literature-based biomass equations to find the equations corresponding best to the case study observations.

We used the data to estimate the time needed for street plantings to reach the C compensation point (the number of years after planting required for the tree C capture to reach the sum of the soil C loss in the first decade after planting) in Helsinki. Our hypothesis was that the amount of C lost from the growth media of the case study trees would offset the C uptake of the tree growth during our study period, and an improvement in average street tree life expectancy would be needed to obtain C sequestration benefits with current planting practices.

2. Materials and methods

2.1. Case study sites

We studied the tree biomass and soil C changes on two separate street sites, located 800 m apart from each other, in the Viikki suburb in Helsinki, Finland, (N60°15′, E25°03′) over 10 years after the establishment of the street. One street, 250 m in length, was planted with 15 common lime *Tilia* × *vulgaris* Hayne trees (Tilia site) and the other (200 m in length) with 22 black alder *Alnus glutinosa* (L.) Gaertn. f. *pyramidalis* Dippel 'Sakari' trees (Alnus site). The sites were established in the summer of 2002 and the trees were planted in the autumn of 2002. At both sites, three different premixed structural soil mixes were applied as a 1-m-deep, 3-m-wide continuous strip (Tilia site) or 15–20-m-long planting pockets for two to four trees (Alnus site). Cast-iron tree gratings 2.25 m^2 in size were used around the trees, and the streets outside the grates were paved over with sand-jointed block pavers. The available soil volume per tree was 45–50 m^3 at the Tilia site and 15–30 m^3 at the Alnus site.

The structural soils consisted approximately 2/3 by volume of stones ranging from 30 to 120 mm in size and 1/3 of fine soil. In soil mix 1, the fine soil was mainly sand, clay and the SOM source was peat. In soil 2, the fine soil was derived from composted sewage sludge mixed with peat, sand and pine bark, but the contribution of peat to the final soil mix SOM could not be determined. In soil 3, the components were fine gravel, sand, clay and leaf compost (peat was not used in the composting process). For soil 1, the initial LOI was 6% and for soil 2 20%, according to their respective manufacturers. For soil 3, the initial LOI was 4.4%, based on the composition and properties of the materials used (7% by volume of leaf compost, 20% of clay with LOI 8.3% and 3% bark mulch). Soils 1 and 2 were commercial mixes, while soil 3 was specially mixed for the study sites.

The transplanted *Tilia* trees were 8–11 cm in diameter-at-breast height (DBH) and *Alnus* 7–11 cm, respectively, and both were balled and burlapped. After transplanting, the trees were not pruned (except for dead and broken branches and shoots growing from rootstocks) until late 2008. Thereafter, the *Tilia* were pruned about annually to achieve the necessary crown lifting. The *Alnus* trees were not crown-lifted, and only branches that were damaged or leaned far out from the columnar crown shape were removed. Measurements performed on these sites for the study are summarized in Table 1.

2.2. Soil water content and temperature measurements

Each soil mix on both streets was instrumented during the establishment with continuously measuring soil moisture sensors (Delta T MLx2 (Delta-T Devices Ltd, Burwell, Cambridge, UK), see Riikonen et al., 2011 for installation details) at depths of 10 and 30 cm and with temperature sensors (resistor type KTY81) at depths of 10, 30 and 60 cm from the surface of the growth media.

Data loggers (DP-158; Envic Oy, Turku, Finland) read the temperature and SW sensors from July 2003 onwards at 1–30-min intervals. At the Alnus site, soil moisture sensors at 30 cm depth were installed in 2005 and data from 10 cm depth was used before that. Soil moisture and soil temperature (T_f) were averaged to 30-min means, and missing data, due mainly to periods of datalogger malfunctions, were gap-filled with linear interpolation. The SW content could only be reliably measured while the T_f was > 0 °C; periods when ground was frozen were filtered out and gap-filled linearly (Kornelsen and Coulibaly, 2012) (most missing SW values in 2003: 52%, least missing values in 2006; 7%). The measured volumetric water content was transformed to percentage of soil weight (W_f).

2.3. Soil sampling and analysis

Soil samples were collected in the autumn 2005, 2008 and 2011from two pits in each soil mix and site ($2 \times 3 \times 2$ sampling pits each year, each located in separate planting pocket at the Alnus site, and at least 10 m apart at the Tilia site). The average distance from the nearest tree was 2–3 m, depending on parked cars and other practical considerations. The pavement was removed and a pit with a diameter of 30–50 cm was dug with hand trowels. In 2005, the pits were dug down to depths of 30 cm (sampling depth 0–30 cm, altogether 12 samples), in 2008 to at least 60 cm and to 90 cm where possible (sampling depths 0–30 cm ($n = 12$), 30–60 cm ($n = 12$) and 60–90 cm ($n = 11$), altogether 35 samples), and in 2011–60 cm (sampling depths 0-–30 cm ($n = 12$) and 30–60 cm ($n = 12$), altogether 24 samples). The rocks (≥ 30 mm) in the soil mix were separated from the fine soil. All the fine soil excavated from each sampling pit was weighed, thoroughly mixed