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Carbon sequestration and storage potential of urban green in residential yards: A case study from Helsinki

Mari Ariluoma [a,1], Juudit Ottelin [b], Ranja Hautamäki [a,*], Eeva-Maria Tuhkanen [c], Miia Mänttäri [d]

[a] Aalto University, Department of Architecture, Otakaari 1X, PO Box 11000, Finland
[b] Aalto University, Department of Built Environment, Otakaari4, 02150, Espoo, Finland
[c] Natural Resources Institute Finland, Itäinen Pitkäkatu 4 A, 20520, Turku, Finland
[d] Natural Resources Institute Finland, Latokartanonkaari 9, 00790, Helsinki, Finland

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ABSTRACT

Cities have been identified as key actors in climate change mitigation. Nature based carbon sinks have been suggested as a means of mitigating the greenhouse gas emissions of cities. Although there are several studies on the carbon storage and sequestration (CSS) of urban green, the role of residential sites is not fully understood. In addition, the carbon storage of soils is often excluded. Also the implications for planning require more attention. This study estimates the CSS potential of trees and biochar in urban residential yards and identifies effective means to enhance it. Moreover, the study discusses the results at the city scale. The research is based on a case study in Helsinki, Finland, and applies i-Tree planting tool to assess the current and potential life cycle CSS of the case area. The results reveal that trees and the mixing of biochar into growing medium can increase the CSS considerably. The CSS potential of the case area is 520 kg CO_2 per resident during 50 years. The added biochar accounts for 65 % of the capacity and the biomass of trees accounts for 35 %. At the city scale, it would lead to 330 000 t CO_2 being stored during 50 years. The findings suggest that green planning could contribute more strongly to climate change mitigation by encouraging the use of biochar and the planting of trees, in addition to ensuring favourable growing conditions.

1. Introduction

1.1. Background

The urban population and the built-up area are increasing steadily in Europe and rapidly globally. The investments in new infrastructure and buildings, and the residents' demand for goods and services are major drivers of global greenhouse gas (GHG) emissions and other environmental burdens (see e.g. a review by Ottelin et al., 2019). However, cities are the drivers of human development and sustainable innovations as well (Joss, 2015). In addition, urban areas are part of the global carbon cycle and provide ecosystem services for their residents and visitors (Niemelä et al., 2010; IPBES, 2019).

Carbon sinks inside and outside city boundaries have been suggested as a means of mitigating the global GHG impacts of cities (Dhakal, 2010; Shigeto et al., 2012; Lazarus et al., 2013; Paloheimo and Salmi, 2013). The importance of urban green has been highlighted in previous literature. Urban green infrastructure includes all the natural, semi-natural and artificial networks of ecological systems in urban and peri-urban areas, such as forests, parks, community gardens, private yards and street trees (Tzoulas et al., 2007; Gómez-Baggethun and Barton, 2013; Lähde and Di Marino, 2019). While the carbon sequestration of urban green has been found to be small compared to the anthropogenic emissions of cities (Nowak et al., 2013; Velasco et al., 2016), in small rural municipalities with large forest areas, the carbon sequestration of trees within the municipal boundaries can actually exceed the total carbon footprint of the residents (Paloheimo and Salmi, 2013).

Urban green provides multiple ecosystem services, such as carbon sequestration and storage (CSS) (Nowak and Crane, 2002) and climate change adaptation (Keeley et al., 2013). It has also been recognised in national and international policies. The EU has adopted a Strategy on Green Infrastructure in order to preserve biodiversity and ecosystem

* Corresponding author.
E-mail addresses: mari.ariluoma@aalto.fi (M. Ariluoma), juudit.ottelin@aalto.fi (J. Ottelin), ranja.hautamaki@aalto.fi (R. Hautamäki), eeva-maria.tuhkanen@luke.fi (E.-M. Tuhkanen), miia.manttari@luke.fi (M. Mänttäri).
[1] First author.

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services in both rural and urban settings (EC, 2013) and is currently promoting *Nature-Based Solutions and Re-Naturing Cities* (EC, 2018; IUCN, 2019). Accordingly, several countries and cities have developed strategies and applications to support urban green infrastructure and nature-based solutions (NBSs), especially related to biodiversity and climate change adaptation (Faivre et al., 2017; Urban Nature Atlas, 2020) Urban Nature Atlas //naturvation.eu/atlas). NBSs are defined as solutions to societal challenges, inspired and supported by nature, which simultaneously provide environmental, social and economic benefits (EC, 2018; Faivre et al., 2017). In the urban context, NBSs mean solutions that bring nature, and natural features and processes into cities.

Residential yards are an important part of urban green, and an increasing amount of studies highlight the importance of private residential greenery for the provision urban ecosystem services (Tahvonen and Airaksinen, 2018; Haase et al., 2019). Though still rarely analysed and mapped as part of the urban green, some studies have indicated that more than one third of the urban green space consists of private residential green in a typical European city (Haase et al., 2019). Yet there are limited tools for steering the planning process of the private lot and thus the quality of the green infrastructure of courtyards. Common neighbourhood sustainability standards, such as LEED, BREEAM and DGNB systems include criteria for green infrastructure and landscape, but they are only partly mandatory and focus on specific aspects (Pedro et al., 2019). One tool specifically created to address green infrastructure elements in the courtyards is Green Factor (Juhola, 2018). Green Factor is a planning tool and a sustainability metric that is used for increasing both the quality and quantity of green elements on private properties. It has previously been applied in several cities at least in Finland, Sweden, Norway, Germany and USA and many new cities are planning to start using the tool in the near future. However, none of these planning tools address specifically carbon sequestration and storage but instead, focus on other benefits of urban green.

1.2. Urban green as carbon sinks

Several studies have assessed the current carbon storage and annual carbon sequestration of urban forests within case cities in temperate climates (Nowak and Crane, 2002; Davies et al., 2011; Strohbach and Haase, 2012; Muñoz-Vallés et al., 2013; Nowak et al., 2013). Urban forests include all trees in urban areas (i.e. urban trees), and most studies are not differentiating between forest trees and planted urban trees (see e.g. Roy et al., 2012; Nowak et al., 2013). These studies have found that cities provide important carbon storages and also carbon sinks. The net carbon sequestration of urban forests is positive for growing forests but slows down as the forest matures (Nowak et al., 2013). However, the maintenance of urban trees also cause emissions and thus, forest-like areas with less intensive maintenance are more effective than park-like trees or street trees (McPherson and Simpson, 2002; Strohbach et al., 2012; Riikonen et al., 2017). Several scholars have discussed the possibility of increasing the carbon sequestration of urban vegetation through policy initiatives (Davies et al., 2011; Muñoz-Vallés et al., 2013) or careful planning (Niemelä et al., 2013).

It should be noted that the CSS of urban trees is temporary in the long term, since the sequestration and storage process is reversible. The carbon storage of urban forests may decrease if, for example, the trees are cut or die. The effectiveness of using temporary CSS to mitigate climate change has been questioned as well (Korhonen et al., 2002; Kirschbaum, 2006). In both carbon footprinting (Levasseur et al., 2011) and life cycle assessment (LCA) (Brandão et al., 2013) contexts, it has been highlighted that the benefits of temporary carbon storage depend on the chosen time horizon. Levasseur et al. (2011) emphasised that temporary mitigation activities should not be favoured over the permanent avoidance of fossil fuel emissions.

Research on the carbon sequestration of urban trees usually excludes the carbon storage of urban soils. Only a few studies on urban soil carbon dynamics have been published and data on urban soil carbon is scanty (Lorenz and Lal, 2015). However, soil has a significant impact: Churkina et al. (2010) demonstrated that 64 % of the carbon storage in the human settlements is attributed to soil, 20 % to vegetation, 11 % to landfills and 5% to buildings. Moreover, other scholars (Kaye et al., 2005; Golubiewski, 2006; Lindén et al., 2020) have pointed out that soils in urban parks and lawns can store large amounts of carbon, which could highly exceed the amount stored in native grasslands, agricultural fields and boreal forests. In particular, long-term terrestrial carbon storage occurs in soils (Lorenz and Lal, 2015). In order to efficiently mitigate climate change, carbon must remain stored for a much longer time than it can be stored in certain materials, for example, in wood material. Thus, as soil has a high capacity and potential for carbon storage, this needs to be addressed in the planning and design of urban green.

The carbon storage of urban soils can be further increased by adding biochar in the growing medium (Ghosh et al., 2012; Scharenbroch et al., 2013). Biochar is highly stable organic carbon residue that is produced during biomass pyrolysis, meaning a process of temperature decomposition of organic material in the absence of oxygen. In soil, biochar may improve water holding capacity and physical structure, absorb nutrients and affect microbial activity and mycorrhizal growth positively, which have benefits for plant growth (Atkinson et al., 2010). In urban or engineered soils, the effects of biochar on soil processes depend, however, on the properties of biochar, soil, climate and soil fauna (Hagner et al., 2016) and the effects on plant growth may vary with experimental conditions and plant species (Jeffery et al., 2011; Liu et al., 2013). Biochar represents a potentially valuable sink for carbon as it is highly stable in soil environments (Gaunt and Lehmann, 2008; Meschewski et al., 2019). Due to the multiple benefits, the use of biochar is growing in popularity for managing urban soils, especially for urban trees (Scharenbroch et al., 2013). For example, the city of Stockholm has started to use park and garden waste to produce biochar that is applied to urban growing media and structural soils for tree plantings ((City of Stockholm, 2016)

1.3. Aims

As described above, the CSS potential of residential yards has not been studied separately before. The carbon sequestration and storage of trees have been identified as the main contributor to the CSS of green infrastructure in previous studies. The carbon binding capacity and storage are directly dependant on the leaf area and biomass of a plant, and thus over the different vegetation types, trees contribute to carbon storage highest. In addition, biochar amendment has been identified as an effective means of adding the carbon storage of urban soils. Therefore, the aim of the study is to estimate the CSS potential of trees and biochar amended in growing medium (or top soil) in residential yards, and to identify effective means to increase carbon sink and storage potential of yards. Moreover, the study discusses the significance of the results at the city scale. In addition, the study discusses how to support sustainability planning tools for urban green in general, from the perspective of climate change mitigation.

The research is based on a case study in Helsinki, Finland and combines a simple screening life cycle assessment (LCA), a publicly available i-Tree planting tool developed by the USDA Forest Service, and scenario modelling. First, the cumulative CSS of urban trees during fifty years was assessed in the case area. Then, an optimal scenario was created for the CSS potential of the case yards. The scenario was based on optimising the CSS by both increasing the amount of trees and the carbon stored in the soil. Finally, the implications of the findings at the city scale were roughly estimated and discussed.

2. Materials and methods

2.1. The case area and research material

The case area is located in a new residential area called

Fig. 1. The location of the case area Kuninkaantammi in Helsinki, Finland (© OpenStreetMap contributors).

Kuninkaantammi in northern Helsinki, Finland, (Fig. 1) and it is close to large urban green areas (Central Park in Helsinki). The case area represents a relatively high density new development with 3–6-storey apartment buildings and about 200 dwellings per hectare. It is a typical new housing area and exemplifies a common housing typology in Finland. In Helsinki, overall, 85,6% of the population live in apartment buildings (Helsinki Region Trends, 2017). The aim in the planning of the area has been to create a green urban housing area and special effort has been put on the sustainable stormwater management.

The case area covers three sites and their yards (see Fig. 2 and Table 1), which were planned in 2016 and have been built in 2019. The total area of the case area is 1.2 ha, total floor space is 16 000 m^2 and the estimated population will be 400 residents. The yards are relatively large, 1700 m^2, 1900 m^2 and 2800 m^2 in size (see Table 1 for more details). Two of the yards are partly podium courtyards, (i.e. there is underground parking below the yard) the podium covering approximately 1000 m^2 of the total yard area (see appendix A1). The Green Factor tool, developed for the city of Helsinki, was applied in their planning. The background documents of the Green Factor tool, particularly plant lists and landscape construction drawings were used as the main research material.

2.2. Research design and system boundary selection

A simple screening LCA was used to assess the CSS potential of the residential yards of the case area. In screening LCA, the main processes causing environmental impacts during the life cycle of a product or service are identified, and then the environmental impacts are

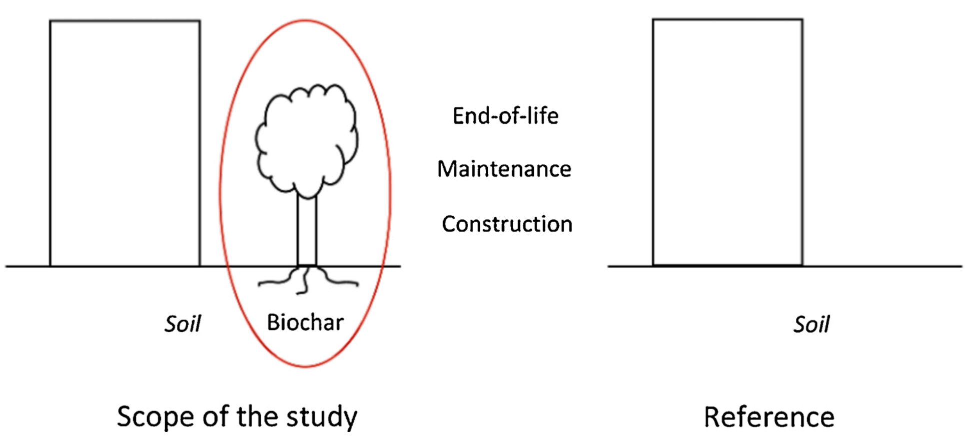

Fig. 2. The case area in Kuninkaantammi and the three yards: 1= Fannynkallio, 2= Sienakuja and 3= Taidemaalarinkatu (City of Helsinki, 2013).

Table 1
A description of the case area and its three sites. The figures in the table are based on the construction drawings and the Green Factor calculation documents of the yards.

Site	1) Fannynkallio	2) Sienakuja	3)Taidemaa-larinkatu	Total or average
Area (ha)	0.49	0.31	0.38	1.2
Area covered by buildings (ha)	0.21	0.12	0.21	0.54
Size of the yard (ha)	0.28	0.19	0.17	064
Size of the podium yard (ha)	0.06	0.04	0	0.1
Yard area of the total area (%)	57	61	45	54
Space available for planting (m^2)	1024	1113	610	2747
Floor space (m^2)	7000	3800	5200	16,000
Number of trees	22	24	13	59
Number of trees per hectare	47	80	34	51

estimated. The study focuses only on one environmental impact category: climate change, which is measured as sequestered and stored CO_2.

Based on previous literature, it was assumed that trees (Davies et al., 2011; Strohbach and Haase, 2012; Nowak et al., 2013) and soil (Churkina 2010; Lorenz 2015) are the most important components in the CSS of green infrastructure. The CO_2 emissions caused by the construction, maintenance and the end-of-life of the green infrastructure were excluded. These emissions have been found to be low compared to the carbon sequestration ability of urban trees in the long term (Strohbach et al., 2012). However, it should be noted that several factors, such as maintenance practices, soil and growth media type and planting type, may affect the carbon emissions caused by the construction and maintenance phases. During the first ten to twenty years from planting, when the carbon sequestration of urban trees is relatively low, the emissions caused by construction and maintenance may offset the CSS benefits. For example, a recent case study from Finland highlights that the carbon losses from typically used growth media for street trees are higher than the CSS of young street trees during the first decades (Riikonen et al., 2017). However, the growing conditions for street and yard trees usually differ, yards typically resembling more a situation in parks. Another study, made in USA, found that maintenance, especially pruning of trees and irrigation, resulted remarkable emissions that can be reduced by changing maintenance practices (McPherson et al., 2015). However, usually pruning and irrigation are done in very limited amount in Finnish green space maintenance, especially in yards. These impacts were not considered here because of the selected scope, see below, a relatively low impact in the long term and the variation in practices that can differ a lot in different countries and even between different yards. The selected time span of the study is 50 years.

The aim of the study is to assess the CSS potential of trees and added biochar alone, keeping all other things equal. Thus, the scope of the study reflects a simple comparative situation: a) an urban yard with vegetation (specified later) or b) an urban yard without vegetation (e.g. stone pavement or similar) (Fig. 3). However, no actual reference case was modelled, as a relevant reference case would have been difficult to define. Instead, it was assumed that the construction, maintenance and end-of-life related emissions are similar in size in all cases and were excluded from the assessment. In reality, the amount of emissions would depend on the selected construction materials and methods, and maintenance and waste management practices, which can vary a lot in an urban context (see the limitations section for further discussion).

Regarding vegetation, only the biomass of trees was included and the biomass of other vegetation, such as shrubs, lawns, perennials and green roofs were not considered. Previous literature has revealed that trees have the highest ability for carbon sequestration because of the large biomass whereas the impact of other urban greenery is small (Davies et al., 2011; Muñoz-Vallés et al., 2013). However, the quality and the depth of the growing medium of other vegetation types still plays role and therefore all vegetation types impact on the overall carbon storage potential. In particular, a significant increase in the carbon storage is achieved by adding biochar to the growing media of all planting types. This was taken into account in the scenario models of the study (see Table 5 for details).The quality of the growth media would affect especially the potential carbon loss from the growing media in the beginning (after the construction), compost being a better solution than peat (Riikonen et al., 2017). However, we assumed that in the long term this loss would be compensated by the carbon accumulation in the soil (Setälä et al., 2016, Linden at al. 2020). Due to uncertainties and lack of data the soil carbon sequestration was not taken into account in the scenario modeling, but estimation of the potential long term impact of soils have been presented in discussion. The system boundary selection of the study is illustrated in Fig. 3, and the overall research design in Fig. 4.

2.3. *Assessment of the CSS of the trees of the case area*

The freely available i-Tree planting tool (v.1.1.3; https://planting.itreetools.org/), created by the USDA Forest Service, was used to assess the amount of carbon (kg CO_2) sequestered by the trees of the case area during 50 years. The 50-year time span was selected because it is common in the LCA of buildings and has been used by e.g. Strohbach et al. (2012) for an urban park.

The purpose of the study is not to offer a detailed case study of the CSS of the trees but rather to capture the lowest and highest limits of the possible CSS of the case area both as it is now and as it could be with the optimal number of trees and added biochar. Thus, only a simple screening method was needed for the assessment of the CSS. For this purpose, the i-Tree planting tool was selected (the USDA Forest Service, 2019). However, i-Tree planting is currently only adjusted to the climate conditions of US. Thus, the city of Augusta in Maine, in the US, was used to represent the weather conditions in Helsinki, Finland.

The climate of Augusta is similar to that of Helsinki, but there are differences as well (Fig. 5). In particular, the annual precipitation is higher in Augusta. Thus, the model is likely to overestimate the biomass growth and the carbon sequestration in the case area in Helsinki to a minor extent. This was taken into account in the interpretation of the results.

The i-Tree planting tool includes both the above- and below-ground biomass of trees. The user enters the number of the different tree species, the sizes of the trees at planting, information on the distance of the trees to the nearest building and its direction in relation to them, the condition of the trees, the amount of sun and shade, estimated mortality and the project lifetime. In addition, it is possible to enter information related to the energy consumption of the buildings in order to estimate the GHG emissions avoided due to energy savings. This was not included since the energy saving modelling is not adjusted to the Nordic conditions.

In the designs for the case area, there are 59 trees in total, mainly Scots pines (*Pinus sylvestris* L.), apple trees (*Malus domestica* Borkh.) and European mountain ashes (*Sorbus aucuparia* L.) (Table 2). The species proposed for the case area are typical planted urban trees in Finland. Most of the species are included in the i-Tree planting tool as well. When the exact species were not found, the nearest taxon was used (see Table 2 for details). It was assumed that the trees to be planted will be in good condition. The recommendations of the city of Helsinki to define the size of the trees at the time of planting were applied: the diameter at breast height (DBH) was 3.5 cm for *Malus domestica*, *Acer tataricum* L. and *Sorbus aucuparia*; DBH was 4 cm for *Pinus sylvestris*; DBH was 4.1 cm for *Prunus pensylvanica* L. f.; and DBH was 4.7 cm for *Betula pendula* Roth. The possible range of the carbon sequestration of the area was estimated by changing the growing conditions (the direction of the nearest

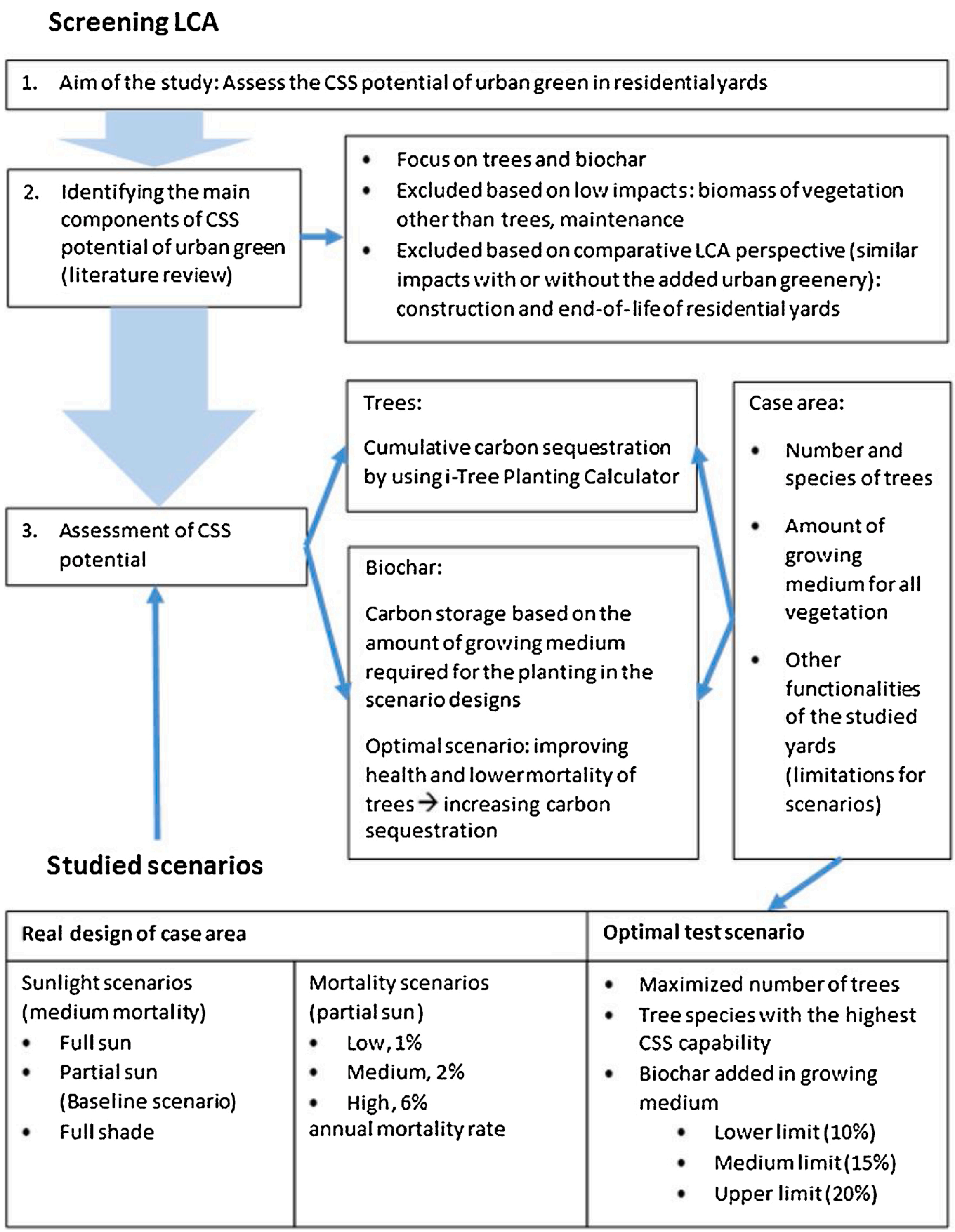

Fig. 3. System boundary selection.

building, the amount of sun and shade) and the mortality rate in the i-Tree planting tool.

Previous studies have revealed that the mortality rate of the trees significantly affects carbon sequestration (Morani et al., 2011; Strohbach et al., 2012). It has also been found that the mortality rate of urban trees varies a lot. Young and small trees have been found to have particularly high mortality among urban trees (Nowak et al., 2004), especially street trees (Roman et al., 2014). In the conditions of the case sites, the mortality rate of public trees maintained by the city is probably lower than in these previous studies, because in public plantings there is two years' guarantee for maintenance and replacement if needed in the contracts. There is, however, no data available on mortality rates in Finland. The case study by Nowak et al. (2004) from Baltimore, in the US, revealed that in addition to the tree species, size and condition, land use also affects the mortality. In their study, trees in transportation, commercial and industrial areas had the highest annual mortality rates (10–20 %) whereas trees in medium- to low-density residential areas had a low annual mortality rate (2.2 %).

In the i-Tree planting tool, it is possible to adjust the mortality rate of the planting project. Based on previous literature on urban tree

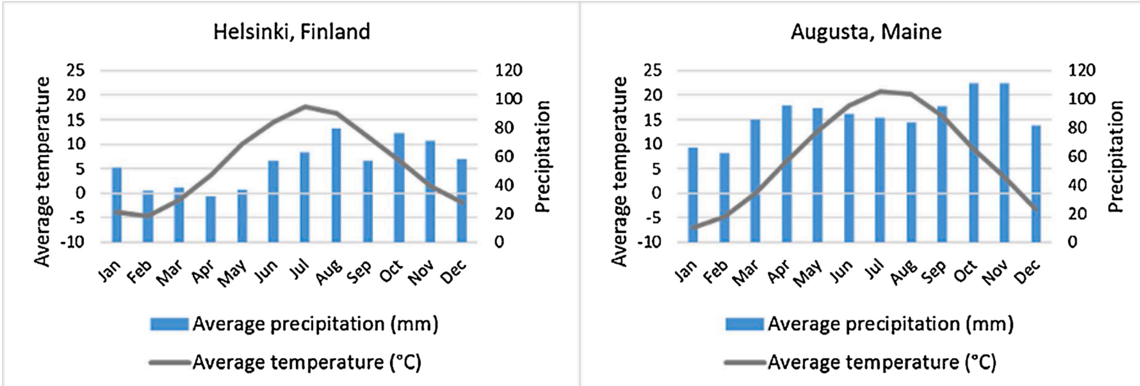

Fig. 4. Research design.

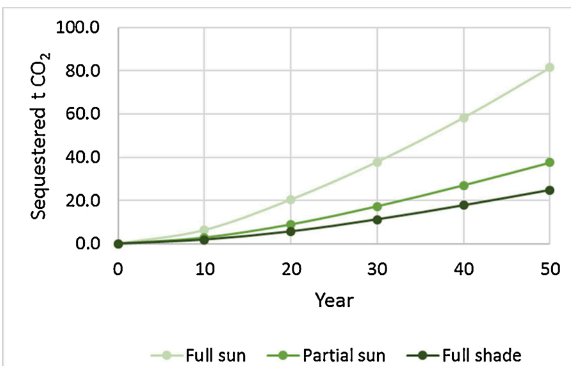

Fig. 5. The monthly average temperatures and average precipitation (1981-2010) of Helsinki (source: the Finnish Meteorological Institute) and Augusta (source: US Climate Data).

Table 2
The trees of the case area entered in the i-Tree planting tool.

Species scientific name	Species	Number of trees
Acer tataricum L. subsp. *ginnala*	Amur maple	1
Malus domestica Borkh.	Apple tree	16
Sorbus aucuparia L.**	European mountain ash	12
Prunus pensylvanica L.f. ***	Pin cherry	8
Pinus sylvestris L.	Scots pine	18
Betula pendula Roth	Silver birch	4
Total		**59**

** Includes 3 Swedish whitebeams, Sorbus intermedia.
*** Includes 2 sour cherries, Prunus cerasus.

mortality, three annual mortality rates were selected to test their impact on carbon sequestration: low (1%), medium (2%) and high (6%). In other words, during the 50-year life cycle of the case area, 39 %, 64 % and 95 % of the originally planted trees will die respectively. The dead trees are replaced with saplings in all scenarios. In reality, the trees planted in the case area have a maintenance guarantee for their first two years.

2.4. The creation of the optimal test scenario

In order to explore the potential maximum CSS, an *optimal test scenario* was created. Alternative plans for the three case yards were produced to test how much the landscape design affects the CSS potential. In the scenario designs the aim was to maximize the number of trees since previous literature has suggested that the role of other urban vegetation is small in carbon sequestration (Davies et al., 2011). In order to select the tree species with the highest sequestration ability, the i-Tree planting tool was used to compare the different tree species growing in the site area (Table 3). Lime trees (*Tilia* spp.) were included in the comparison since they are a common urban tree species group in Finland, although not planted in the case area. Based on the comparison, three species to be used in the optimal carbon sequestration scenario were selected: the apple tree, the Scots pine and the European mountain ash (which particularly excels in partial sun and full shade).

Table 3
The carbon sequestration ability of different urban tree species (t CO_2 sequestered by one tree in good condition during 50 years, i-Tree planting, location: Augusta, Maine). The compass points refer to the direction of the tree in relation to the nearest building.

Species scientific name	Species	South, full sun	East or West, partial sun	North, full shade	Average
Acer tataricum subsp. *ginnala*	Amur maple	1.6	0.9	0.5	1.0
Malus domestica	Apple tree	**2.7**	0.9	0.5	**1.2**
Sorbus aucuparia	European mountain ash	1.3	**1.1**	**0.8**	**1.1**
Prunus pensylvanica	Pin cherry	0.5	0.4	0.3	0.4
Pinus sylvestris	Scots pine	**2.5**	0.9	0.5	**1.2**
Betula pendula	Silver birch	1.2	0.7	0.5	0.8
Tilia spp.	Lime	1.4	0.5	0.3	0.7

In the scenario modelling, the aim was to create feasible landscape designs that correspond to the requirements of the area. The designs took into consideration the limitations of the sites for planting trees, for example, underground car parking, the growing conditions (sun and shade) and the recommendations for the planting distances of urban trees (the distance from buildings and other trees). Trees were not placed in the podium yard area, where the limited soil space would limit the lifetime and size of the trees and thus their carbon sequestration potential. Moreover, other functions of the yards (such as offering routes, use as playgrounds and use for urban farming) were taken into consideration, including their spatial requirements and maintained the

Table 4
The trees of the optimal test scenario entered in the i-Tree planting tool.

Species scientific name	Species	Number of trees
Malus domestica	Apple tree	16
Sorbus aucuparia	European mountain ash	22
Pinus sylvestris	Scots pine	44
Total		**82**

Table 5
The biochar added in the growing medium in the optimal test scenario. The classification of vegetation types is based on the elements used in the Green Factor tool (The city of Helsinki, 2018) and the depth of growing medium in the Finnish green planning guidelines. The figures include all the three case yards.

Vegetation type	planting area (m^2)	depth of growing medium	growing medium (m3)	biochar 10 % (kg)*	biochar 15 % (kg)*	biochar 20 % (kg)*
large trees	44	0.8	35.2	1,056	1,584	2,112
small trees	38	0.6	22.8	684	1,026	1,368
shrubs	932	0.4	372.8	11,184	16,776	22,368
perennials	525	0.4	210	6,300	9,450	12,600
meadow	478	0.2	95.6	2,868	4,302	5,736
lawn	812	0.2	162.4	4,872	7,308	9,744
green roof ***	565	0.1	56.5	1,695	25,42.5	3,390
TOTAL			955.3	28,659	429,88.5	57,318
kg C (biochar) **				24,360	36,540	48,720
kg CO_2				90,223	135,334	180,446

* specific density 300 kg/m3.
** the carbon content of biochar 85 %.
*** green roofs are located mainly on the small single-storey buildings, see appendix A1.

functions of the original designs (see appendix A1). Based on the scenario designs, 36 % of the total yard area is available for green planting in the yards 1 and 2 and 58 % in the yard 3 (see Table 1). These boundary conditions significantly limited the number of trees, increasing them by only 1–6 big trees and 1–5 small trees per yard (Table 4). The definition of big and small trees is based on the Finnish planning guidelines (InfraRYL, 2010), in which big trees are taller than 10 m at maturity. Illustrations of the scenario designs are presented in the appendix.

Considering the potential of biochar to increase the carbon storage of urban soils, it was decided to test a scenario of adding biochar to the topsoil and exploring how that would affect the carbon storage potential of the yards (compared to the impact of the number of trees). As the starting point, the amount of topsoil required for the planting in the scenario designs was calculated, following the general quality specifications for infrastructure construction in Finland (InfraRYL, 2010), which give recommendations for the depth of the growing medium for different planting types. According to the recommendation of a Finnish producer of garden biochar, approximately 15 % of the total volume of the topsoil could be biochar if it would be mixed into the soil during construction. In the scenario modelling, three concentrations of biochar were tested: the lower limit (10 %), the medium limit (15 %) and the upper limit (20 %) (Table 5). It was assumed that biochar can be used in all vegetated areas, including green roofs. In addition, it was assumed, on the basis of previous research (Ghosh et al., 2012; Scharenbroch et al., 2013), that the biochar improves the condition of the trees from *good* to *excellent*, and reduces the annual tree mortality rate from *medium* (2%) to low (1%). Biochar has been found to improve soil quality (Ghosh et al., 2012) and to improve the water holding capacity of the soil, which may increase the survival of the planted trees in limited soil volume.

3. Results

3.1. The CSS of the trees in the case area

The trees of the case area would sequester a total of 38 t CO_2 during 50 years if the trees were located in partial sun and if the mortality rate was medium, which is a realistic scenario (Fig. 6). This equals 95 kg CO_2 sequestered per resident and 2.4 kg CO_2/ m^2 of floor space during the whole 50 years. If the trees were in full sun, the carbon sequestration would be more than doubled, reaching up 81 t CO_2 during the 50 years. However, this is an unlikely scenario in the urban context. In practice, the buildings surrounding urban trees usually cast shade on them for at least some part of the day. If the trees were in full shade, the total sequestration would drop to 25 t CO_2.

In the above scenarios, a medium annual tree mortality (2%) was used. The mortality rate affects the carbon sequestration significantly as well (Fig. 7). With low tree mortality (1%), the carbon sequestration increases to 44 t CO_2 during 50 years (in partial sun). Respectively, high tree mortality (6%) decreases it to 31 t CO_2.

3.2. The optimal CSS potential of the case area

Optimising the number of trees and the tree species (see the methods section for details) would increase the total carbon sequestration of the trees in the case area by 95 % during 50 years (Fig. 8). It should be noted that in the optimal test scenario, it is assumed that the added biochar in growing medium improves the condition of the trees from *good* to *excellent* and reduces the annual tree mortality rate from *medium* (2%) to *low* (1%). However, the sun and shade conditions are difficult to change in urban settings, and thus the trees are assumed to be in partial sun even in the optimal test scenario.

Adding biochar to growing medium increases the carbon storage significantly (Fig. 9). In the optimal test scenario of the study, 15 % of

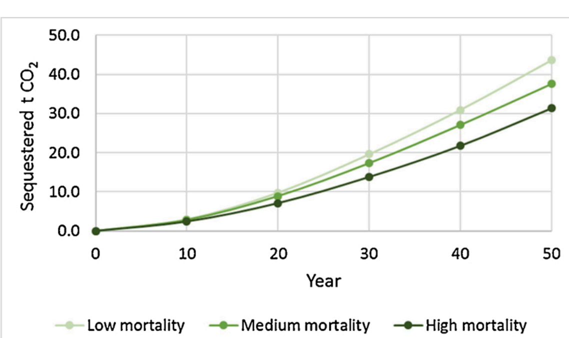

Fig. 6. The cumulative carbon sequestration (t CO_2) of the trees in the case area during 50 years in sunlit conditions (with a medium mortality rate).

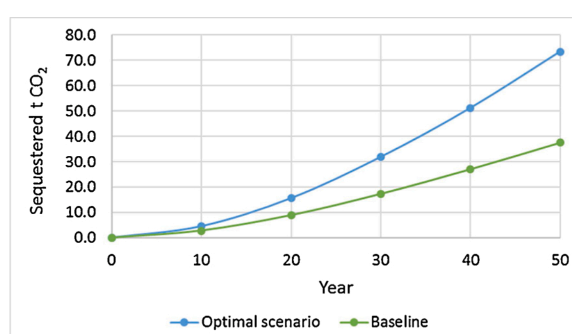

Fig. 7. The cumulative carbon sequestration (t CO_2) of the trees in the case area during 50 years according to the mortality rate (in partial sun).

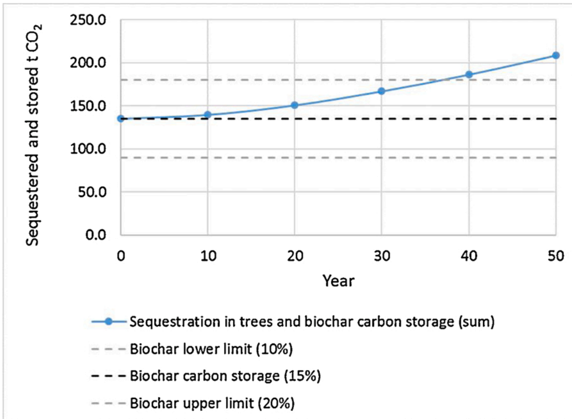

Fig. 8. The cumulative carbon sequestration (CO_2 t) of the trees of the case area during 50 years in the optimal test scenario compared to the baseline.

the total volume of growing medium was biochar. In addition, the impact of 10 % (lower limit) and 20 % (upper limit) biochar concentrations was tested. When the added biochar was taken into account, the full amount of sequestered and stored carbon was 208 t CO_2 after 50 years in the optimal test scenario, composed of 73 t CO_2 sequestered by trees and 135 t CO_2 stored as biochar in soil. The amount is equal to 520 kg CO_2 per resident.

The result demonstrates that, in addition to the number of trees, the amount of topsoil in the yard, which results from the planting type, has a major impact on the carbon storage potential of the yard. Though the total number of trees in the scenario designs was not radically larger than in the original designs, there were more planting areas, which resulted in a larger amount of productive topsoil and thus a potentially larger amount of added biochar.

4. Discussion and conclusion

4.1. The implications of the findings at the city level

In the baseline scenario, the trees of the case area would sequester a total of 38 t CO_2 in 50 years, which equals 95 kg CO_2 sequestered per resident and 2.4 kg CO_2/ m^2 of floor space during the whole 50 years. For comparison, the average carbon footprint of the residents in the Helsinki metropolitan area is 10 t CO_2-eq/year per capita (Ottelin et al., 2018a), and the construction of a typical apartment building can cause 730 kg CO_2-eq/ m^2 when the embodied emissions of construction materials are taken into account (Säynäjoki et al., 2017). Although the CSS potential of residential yards is low compared to the annual carbon footprints of the residents (even in the optimal test scenario of the study), it might be significant at the city level. To illustrate, if all residents of Helsinki had (on average) a similar carbon sink and storage in their yards as the residents of the case area in the optimal test scenario (meaning 520 kg CO_2 per capita during 50 years), it would come to 330 000 t CO_2.

Of course in practice, there are several limitations. The residential density of the case area does not necessarily reflect the average density in Helsinki, and the amount of residents varies also with time. Furthermore, the amount of biochar that can be added and the number of trees that can be planted on the existing yards are limited. However, particularly in new residential areas, the full potential could be achieved. With some caution, the result is also generalizable to other European cities.

4.2. Additional impacts of soil carbon release and sequestration

In the scenarios, the natural flows of soil carbon were excluded. Urban soils can be a remarkable carbon storage, but the long term sequestration in urban soils is difficult to estimate, especially in private yards. However, studies made in urban parks in cold climates might give a good reference. Setälä et al. (2016) found that in cold climates carbon

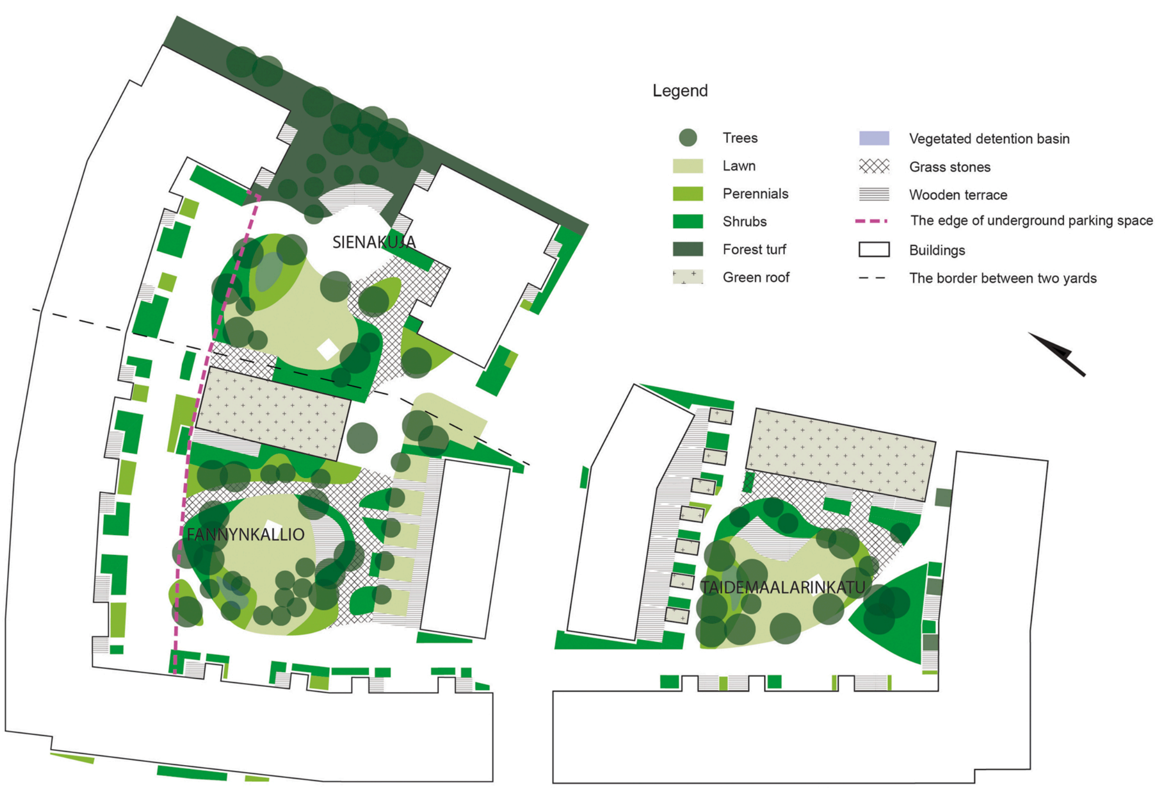

Fig. 9. The cumulative CSS (t CO_2) of the case area during 50 years in the optimal test scenario.

storage of young parks is 18,9 – 21,4 kg C / m^2, depending on the vegetation type, and for the old parks the figures are 23,4 – 35,5 kg C / m^2 (the higher figures are for parks with evergreen trees). This means an increase of 4,5 – 14,1 kg C / m^2. For the 2747 m^2 of planted area in the case sites a total increase of 12,3 – 38,7 t C (51,9 – 146,4 t CO_2) would be reached. Respectively, Linden et al. (2020) reports the soil carbon storage of urban parks in Helsinki to be 10,4 kg C / m^2 (all soil types) and 15,5 kg C/ m^2 in average for vegetated soils. Based on these figures the soil carbon storage of case sites would be 42,6 t C (156,3 t CO_2) in total, which is more than double the sequestration by the planted trees during 50 years in the optimal scenario situation (73 t CO_2). Furthermore, according to Riikonen et al. (2017), the potential carbon loss during the first decades for street trees was ~170 kg C / tree. For the 61 trees in the case sites that would count for 10,4 t C (38 t CO_2). In Riikonen's study the trees were planted in sealed soils, which prevents the organic matter accumulation in the soil, which is typical for street trees, but not common in yards. The results illustrate that the impact of urban soils is potentially large, but depends on several variables. However, we did not find any studies made of urban soils in residential yards.

Furthermore, if the yard would be covered with concrete or granite pavers, there would be virtually no C stocks in soil, due to the Finnish standard construction practices (Linden at al. 2020). The carbon release of the pavement construction would be about 12 kg CO_2 / m^2 with granite pavers (Finnish granite) (Finnish Natural Stone Association, 2018). For the whole vegetated area of the scenario designs the carbon release would be about 33,9 t CO_2 (9,2 t C). Assumed that the carbon release of the construction phase of the vegetation would be compensated in the long term, this would further highlight the impact of vegetated areas.

4.3. Policy and practical implications

The purpose of this study was to demonstrate the CSS potential of residential yards. The findings highlight that the potential can be significantly enhanced by three measures: (1) increasing the number of trees, (2) selecting tree species with a high ability to sequester carbon and to grow large on the spots and (3) maximising the vegetated areas in the yards and (4) adding biochar in the planting beds. Since practical aspects in planning (such as the functionalities of yards) cause limitations to how much and what sort of trees can be planted, the study suggests that the carbon storage can be most effectively increased by adding biochar to the growing medium. Moreover, considering that urban soils are a major contributor to urban carbon storage, even without added biochar, the study concludes that the most effective way to increase urban carbon storage in new residential yards is to focus on the quality and quantity of the topsoil that functions as a productive growing medium for the plants.

Considering that biochar has the potential to improve soil quality and thus to reduce the use of other planting soil materials, such as peat, in planting soil mixtures, the true impact of biochar use could be even higher (Kern et al., 2017). Biochar may improve the growing conditions of soil microbes (Chan et al., 2008) and have other effects on soil processes (Cheng et al., 2017) which may lead to increases in carbon bound to organic matter in growing medium. On the other hand, trees exude organic compounds from roots to soil (Scharenbroch et al., 2013), which in turn affects microbial community and soil flora and fauna. Thus, the interplay of trees, biochar and soil in carbon sequestration might increase soil carbon more than their separate effects considered in this study. However, some studies report that pyrolyses biochar is a highly stabilized form of carbon and has negligible effects on soil biology (Meschewski et al., 2019). Further research is needed on the long term effects of biochar in urban soils.

The method of biochar production can affect its climate impacts. At the city scale, it would be possible to collect the dead biomass generated by urban green and produce biochar from it, thus creating a circular system. The Stockholm Biochar Project provides a pioneering example of such a system in practice (City of Stockholm, 2016: Jonsson, 2016). With the biochar project, the city aims at generating the first urban carbon sink in the world. The process produces energy that becomes heat for the city's district heating network. In Finland garden biochar is produced commercially from broad leaved species, mainly birches, and to a minor extent by cultivating willows on peatlands that have formerly been used for turf production. The production will be growing in the near future, and thus the availability and cost–benefit ratio of the product will improve. Also, different types of biochar products are being developed for different purposes.

The study concludes that CSS requires more attention in sustainability planning tools, such as green factor and LEED. For example, more weighting could be given for planting trees, especially tree species with high carbon sequestration capability (in local conditions). In addition, growing conditions should be considered to guarantee that the planted trees can grow large. Moreover, using biochar to increase the carbon storages of yards could function as an effective means. The results of the study suggest the current CSS of residential sites could be increased as much as 450 % by developing green planning so that it takes these aspects better into account. Moreover, the results illustrate that although the impact of a single yard may be small, the scalability of the result has the potential to amplify this impact.

In addition to the direct impacts on urban carbon sinks and storages, increasing urban greenery may contribute to climate change mitigation in indirect ways. Increased time use and economic activities in the green infrastructure sector can potentially decrease highly carbon-intensive activities such as the construction of grey infrastructure – assuming constant time and monetary budgets. This can cause additional emission reductions (the so-called negative rebound effect of green investments; see Ottelin et al., 2018b).

The increasing of urban greenery is also likely to enhance the perceived residential environmental quality (Kyttä et al., 2013). This could possibly decrease the number of so-called escape trips from dense urban areas to more natural environments and the related GHG emissions (Reichert et al., 2016). Long-distance leisure travel is an increasing source of emissions particularly in cities (see a review by Czepkiewicz et al., 2018).

4.4. The limitations of the study

The study is based on modelling and thus includes high uncertainties regarding the range that the results illustrate. The main uncertainties relate to the used methods and the subjectivity of the scenario modelling. First, a screening LCA was used to find the most important life cycle phases of urban greenery in private yards from the carbon storage perspective. It is possible that the boundary selection excluded some important carbon sources or storages (Brandão et al., 2013). For example, the long-term interactions between soil and urban trees may increase the carbon storage (Scharenbroch et al., 2013; Setälä et al., 2016; Lindén et al., 2020), while the carbon losses of growth media during the first decades after planting and intensive maintenance practices may decrease it (Riikonen et al., 2017; McPherson et al., 2015).

Second, a specific reference case was not modelled in the study. It was assumed that the emissions from the construction and maintenance of urban yards would be similar with or without vegetation, but this is in fact unknown, and would require further research. For example, typical urban pavement materials, such as stone and concrete, are highly carbon intensive, suggesting that any alternatives for them could potentially lead to emission savings. There are also big differences in the carbon footprint of different materials, which means that comparison would require modeling of several different cases.

Third, the i-Tree planting tool used in the study is developed for the US, and thus Augusta, Maine, was applied as an approximation of the weather conditions in Helsinki. As mentioned in the methods section, this is likely to mildly overestimate the carbon sequestration ability of

Fig. A1. Scenario design for Sienakuja, Fannynkallio ja Taidemaalarinkatu.

urban trees in Helsinki. In addition, i-Tree equations do not have specific equations for certain subspecies (such as an apple tree) of the case yards and it uses approximations of species groups. Furthermore, the true sun and shade conditions, as well as the true mortality rate of the trees, are unknown. The selected 50-year time horizon affects the results as well. Fourth, an expert opinion was used to estimate the possible amount of biochar that could be added in growing medium. However, it was not tested in practice. Similarly, the impact of biochar on both the condition of the trees and tree mortality rate were not tested in practice. Fifth, the scenario designs were based on subjective choices, although all the relevant aspects and limitations were taken into account. While the above-mentioned uncertainties exist, they are unlikely to affect the scale of CSS assessed in the study or undermine the main conclusions.

4.5. Conclusions

Green infrastructure planning can improve ecosystem service provision and regulation, including carbon sequestration (Tratalos et al., 2007; Niemelä et al., 2010). This study highlights the importance of urban green yards and their role in CSS. In particular, soil with added biochar can be an effective method for increasing the carbon storage potential. Moreover, urban trees can significantly contribute to the carbon sequestration in the long run. The long lifespan of urban trees should be guaranteed as the carbon sequestration capacity increases as trees mature. This requires space for trees both in soil and on the ground and favourable growing conditions which, in turn, accentuate the quality and quantity of the topsoil. The quantity of topsoil correlates with the potential for carbon sinkage, both in terms of trees and biochar, and thus yards with a thick soil layer should be preferred.

Even though climate change adaptation and mitigation have been addressed in green infrastructure planning, urban carbon storage potential has remained largely understudied. Therefore, further research is required to assess the CSS potential of urban green, including vegetation and soil and their mutual interaction, as well as different materials and production processes. Additionally, more efficient planning tools and policies are needed in order to enhance the green infrastructure with the maximum CSS potential. The study recommends that sustainability planning tools should be developed in order to better address CSS potential, with a special emphasis on the soil. This would lead to a multiple-win situation as high-quality soil improves the quality of the green infrastructure, which in turn has the capacity to provide several ecosystem services. Even if single yards have a quite limited impact on carbon storage, up-scaling to the city level would certainly significantly increase the impact. Therefore, the study highlights the importance of the mainstreaming of urban green infrastructure with a high CSS capacity.

Author statement

Mari Ariluoma, as the first author, had the main responsibility for writing and finalizing the manuscript and especially designed and performed the scenario designs and analyzed results concerning them.

Juudit Ottelin, as the second author, created the research design together with Ariluoma and performed the LCA study, conducted the i-Tree analysis and analyzed results concerning them, in addition to contributed to writing the manuscript.

Ranja Hautamäki, as the corresponding author, supervised the research and contributed to writing and commenting the manuscript.

Eeva-Maria Tuhkanen and Miia Mänttäri reviewed and commented on the manuscript

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A

Fig. A1

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