Science of the Total Environment 563–564 (2016) 623–632

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Carbon sequestration through urban ecosystem services A case study from Finland

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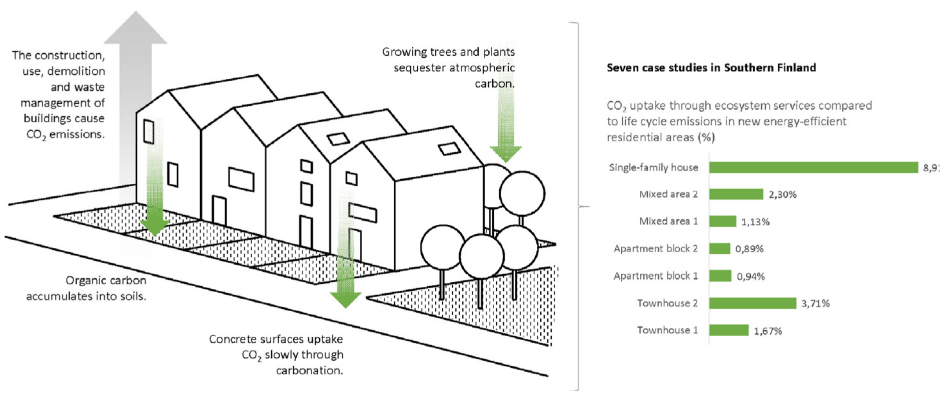
HIGHLIGHTS

- The CO_2 emissions of buildings may be regulated by the uptake of carbon in plants.
- The sequestration compensates for less than 10% of emissions over the full life cycle.
- Up to 85% of emissions may be compensated for in the production phase.
- Site efficiency and the number of trees set the potential for emission compensation.
- Several knowledge gaps were found in the quantification of the compensation potential.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form 22 March 2016
Accepted 23 March 2016
Available online xxxx

Editor: D. Barcelo

Keywords:
Ecosystem services
Greenhouse gas emissions
Residential
Life cycle
nZEB
Carbonation
Soil organic carbon
CO2 uptake

ABSTRACT

Plants and soil are natural regulators of atmospheric CO_2. Whereas plants sequester atmospheric carbon, soils deposit it for decades. As cities become increasingly more densely built, the available land area for such ecosystem services may decrease. We studied seven different housing areas in the Finnish city of Espoo to ascertain the extent to which site efficiency affects to the ecosystem services if the full life-cycle GHG emissions of these areas are taken into account. The results show that the impact of CO_2 uptake through carbon sinks in growing plants and the uptake of soil organic carbon vary greatly. Its share of all emissions varied from a marginal value of 1.2% to a more considerable value of 11.9%. The highest potential was calculated for a detached house located on a large site, while the weakest was calculated for compact apartment blocks. The study revealed that in order to quantify this potential more accurately, several knowledge gaps must first be addressed. These include impartial growth algorithms for Nordic wood species, missing accumulation factors for soil organic carbon in cold climates and statistical maintenance scenarios for gardens.

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http://dx.doi.org/10.1016/j.scitotenv.2016.03.168
0048-9697/

1. Introduction

1.1. The challenges in mitigating urban greenhouse gas emissions

Urban areas continue to expand globally. By 2050, the urban population is estimated to increase by 2.5–3 billion (Seto et al., 2014). Today cities and urban areas are accountable for 71–76% of all greenhouse gas (GHG) emissions and 67–76% of all primary energy (PE) demand (Seto et al., 2014). Urbanisation cannot continue with such consumption and emission rates if we wish to prevent the costly consequences (Stern, 2006; World Bank, 2013) and extreme risks (Hansen et al., 2013) of climate change and reach the possible co-benefits of transition into a low-carbon economy (Nelson et al., 2014).

A common solution for reducing urban GHG emissions and PE demand has been compacting cities and limiting urban sprawl (Edenhofer et al., 2014; The Global Commission on the Economy and Climate, 2014). As urban areas get denser, the amount of parks, natural forests and other green spaces within the same area decreases. Such development decreases the potential benefits of the "regulating" ecosystem services in the area of climate change mitigation. As there are less trees and soil that regulate the amount of atmospheric carbon dioxide (CO_2) by sequestering it into their biomass through photosynthesis, the lost climate change regulation will have to be met in other ways. There are possibly significant benefits from the densification of cities as well: less embodied energy and emissions from infrastructure construction and maintenance (IPCC, 2014), and denser residential areas may be more resource, energy and material efficient (Takano et al., 2014a).

However, the construction of dense and energy-efficient areas have been found to cause a peak in GHG emissions and energy demand (Heinonen et al., 2012). This peak may be large and it may take several decades before it is amortized. The payback time of these consequential GHG peaks is greatly influenced by the amount of energy that can be saved through the improved energy and carbon efficiency of buildings and areas.

1.2. The potential of ecosystem services in regulating greenhouse gas emissions

Plants and soil are natural regulators of atmospheric CO_2. Plants sequester atmospheric carbon in photosynthesis and convert it into sugar that they store in their biomass. This biomass is beneficial for humans as food or raw-material. In addition, plants grown from atmospheric carbon may provide shade and shelter from the sun, rain, wind, noise and pollution. Soil organic carbon (SOC) is a depository of the slowly decaying carbohydrate remains of plants, animals and microbes. This carbon stock is significant and vital for the regulation of a liveable climate on our planet: nearly 80% of terrestrial carbon resides in soils (Ontl and Schulte, 2012).

Urban environments also hold potential for ecosystem services. There is a growing interest in quantifying the climate benefits of ecosystem services in cities across the world. Recent scientific findings are encouraging. In Leicester, UK, it was found out that the SOC in urban areas can be much higher than in agricultural areas (Edmondson et al., 2012) and that the soils are actually the largest repository of organic carbon (OC) in urban areas, totalling 82% of all OC. Interestingly the study also showed that there is a high amount of OC lying under impervious surfaces (13%). In Leicester only 18% of urban OC was found stored in vegetation. In addition it has been found (Edmondson et al., 2013; Davies et al., 2011) that trees that grow in domestic yards greatly increase the amount of SOC. These "backyard carbon storages" should be protected to prevent the release of CO_2 into the atmosphere.

1.3. The assessment of the regulation of climate change through ecosystem services in standards

International and regional standards guide the assessment of the environmental performance of the built environment. Interestingly, no discussion about the role of ecosystem services in the environmental calculations has been found from the current versions of the international standards (ISO 14040, 14,044, 14,067) or European EN standards (EN 15643 series, EN 15978, EN 15804) for the assessment of the environmental performance of the built environment.

EN 15978 (CEN, 2011a) states that in the environmental assessment of buildings, the whole site and its full life cycle are to be included. However, there is no guidance on the inclusion or exclusion of green infrastructure within this system boundary.

The technical specification ISO/TS 14067 (ISO, 2013) briefly discusses the calculation of soil carbon change but seemingly in the context of land-use change (Section 6.4.9.5, pp. 26). The specification further mentions that "there is ongoing research to develop methodology and models, and provide data for the inclusion of soil carbon change in GHG reporting" (pp. 26). The uptake and release of GHGs in SOC, however, are not mentioned.

Standards EN 15643-1 (CEN, 2010), EN 15643-2 (CEN, 2011b) and EN 15804 (CEN, 2013) do not discuss issues that would directly relate to including the regulation of GHGs through ecosystem services into the environmental assessment of the built environment.

An overview of the current standard versions leads to the conclusion that – as there is no direct guidance for either including or excluding GHG regulation, sequestration or delayed release through ecosystem services – the environmental assessor has to make a decision on the subject based on the definition of the scope and goal of the study. This may, however, lead to biased results if the results of a life cycle assessment (LCA) are used for finding solutions to, for example, low carbon construction. The built environment in almost all cases also consists of vegetation, be it natural, cultivated, barren land or decorative gardens.

As there is no standardised method or guidance, the role of ecosystem services in the mitigation of urban GHG emissions is yet to be investigated in greater detail. We do not know how much the densification of residential areas mitigates climate change through decreasing urban emissions when compared to the lost potential of sequestering carbon in plants and soil. We do not know where the optimum between denser cities and ecosystem services lies. We lack an understanding of how to design and run a resilient city from both energy efficiency and ecosystem service viewpoints.

2. Materials and methods

2.1. Scope and objective

The aim was to investigate the potential of carbon uptake in urban yards through the processes of photosynthesis in vegetation, the accumulation of SOC and the carbonation of concrete surfaces. In addition this potential is compared to the overall GHG emissions of each building's life cycle, including the production of materials, construction work, operative energy use and at its end-of-life stage. The study period is 50 years.

The data are collected from seven residential areas in the city of Espoo, southern Finland. Choosing a Nordic example provides insight into the carbon sequestration potential of boreal urban gardens.

The study is made according to the system boundaries that are defined in the standard EN 15978 (CEN, 2011a). Thus the object of assessment is "the building, including its foundations and external works within the curtilage of the building's site, over its life cycle."(CEN, 2011a, pp.16). However, we wish to study the role of the green infrastructure if it is taken into account in the standard-based sustainability assessment of buildings. Therefore the system boundary of EN 15978 is used.

2.2. The studied areas

Seven residential areas were analysed in Espoo, Southern Finland. These areas included two townhouses, two apartment blocks, two mixed housing areas and one single-family house. For each residential area, three main land use categories have been defined: (1) *grey infrastructure*, which includes buildings, traffic areas and paved surfaces; (2) *green infrastructure*, which includes herbaceous and grass surfaces, trees and woody vegetation; and (3) *natural areas*, which includes forestland, shrub land and grassland within a residential area.

From the garden planning drawings, each residential area has been divided up according to the different subcategories mentioned above. The resulting areas for each land use have been determined in m^2 (Fig. 1) and reported in the calculation table. The areas are different in terms of site efficiency, construction materials and planted vegetation.

Fig. 1. The division of a plot into the different land use categories.

Table 1
Project information.

Number and name of the housing area		Building type	Built (year)	Floor area (m^2)	Footprint area (m^2)	Site area (m^2)	Site efficiency (e)
1	Pikku-Pietarin Piha	Townhouse 1	2005	3295	2076.68	7150.29	0.46
2	Espoon Vuorikallio	Townhouse 2	2014	3072	1930.90	10,244.2	0.30
3	Huvilinnanmäki 7	Apartment block 1	2004	2975	718.21	2924	0.82
4	Tietäjä	Apartment block 2	2007	5950	1630.70	6213.5	0.97
5	Jatuli	Mixed area 1	2008	5470	3359.83	11,099.83	0.50
6	Koukkuniemenranta	Mixed area 2	2011	5350	3765.70	18,558	0.36
7	Pikku Jonttu	Single-family house	2013	150	65.80	1168.74	0.20

Details of the studied residential areas are provided in Table 1. Floor area refers to the heated gross floor area of the building. Site efficiency is the ratio of floor area and site area. The higher the site efficiency, the more compact the area is.

2.3. Applied methods and assumptions

2.3.1. The life cycle approach

The environmental impacts in this study are assessed along the life cycle of a building. The life cycle is divided into four main phases according to the European standard EN 15643-2 (CEN, 2011b): the production stage, construction stage, use stage and end-of-life stage. Each of these phases contains several sub-stages, as shown in Table 2. An LCA can be carried out for all these stages – "cradle to grave" – or only for the construction materials of the building – "cradle to gate". In the latter, it is possible to include the parts of other modules as well; in such a case the assessment is called "cradle to gate with options" (EN 15978:2011). In this study we have chosen this approach. Dividing the environmental impacts along the life cycle illustrates the relative dominance of each phase and enables improvement of the environmental performance. (See Table 2.)

The production stage (modules A1–3) illustrates the environmental impacts caused in the production of materials for grey and green infrastructures and buildings. For the surroundings, the values were obtained from the ecoinvent Database and were multiplied by the weight of each material defined in 1 m^2 of structure type.

For the construction phase (modules A4–5) we assume that the emissions from the transportation phase (module A4) and construction phase (module A5) would be same for all of the studied buildings. Therefore workers commuting to the construction site are excluded from calculations, as this is not dependant on the building or garden type.

For the use stage (module B) of the residential areas only the modules regarding the uptake of carbon during the use of the areas (module B1) and operative energy use (B6) have been included. Other modules of the use stage (maintenance [B2], repair [B3] and replacement [B4]) are excluded because of the high uncertainty in the scenarios. Operational water use (B7) has not been taken into account as it is not in the focus of this study and because the GHG emissions related to the heating of domestic hot water are included in module B6.

For the buildings, the end-of-life stage (module C) is included.

Table 2
Life cycle stages according to EN 15643 and their inclusion in this study.

				Included
A	Production	A1	Raw material supply	●
		A2	Transport to factory	●
		A3	Manufacturing	●
	Construction	A4	Transport to site	●
		A5	Construction work	●
B	Use	B1	Use	●
		B2	Maintenance	
		B3	Repair	
		B4	Replacement	
		B5	Refurbishment	
		B6	Operational energy use	●
		B7	Operational water use	
C	End-of-Life	C1	Deconstruction	●
		C2	Transport	●
		C3	Waste processing	●
		C4	Disposal	●
D	Additional	Benefits and loads beyond system boundary		

2.3.2. Estimations for green and grey infrastructure

2.3.2.1. Trees and woody vegetation. The evaluation of the carbon sequestered in the biomass of trees required calculating their stem volume, estimating their moisture content and calculating the amount of carbon in dry mass. The stem volume equations used are from Zianis et al. (2005) and corrected with estimations of the volume of roots and branches by a correction factor of 1.24, which is based on studying the morphology of tree species in the study. The carbon sequestered in woody biomass was assessed by applying the standard EN 16449 (CEN, 2014). The carbon sink period is set to 50 years. This timeframe is a typical period used in the LCAs of buildings, and therefore using the same reference study period may be useful for other practitioners who wish to interpret our findings in their work.

The amount and species of shrubs were collected from the landscape planning drawings. As no literary data were available for the density or weight of the chosen shrubs, we chose to measure weights empirically. This was done by collecting samples of each shrub type. The chosen samples were weighed and their dry weight was calculated assuming a 30% moisture content. This moisture content is based on the following assumptions: the samples were collected during the winter season, during which their fluid circulation has not yet started, and we presume that (like in trees) the moisture content in the cambium is lower than during the growth period (Kärkkäinen, 2003). In trees the moisture content in wintertime is higher than in summertime in their stem but lower than in summertime in their cambium. Furthermore, the morphology of shrubs differs significantly from that of trees. Because the chosen shrubs consist of great number of thin branches instead predominantly being a single, thick stem, they have higher relative amount of surface and correspondingly more cambium. Thus we assume that the moisture content of an entire shrub would be lower in wintertime than that which has been measured for trees, which have typical moisture content ranging from 60% to over 99% (Kärkkäinen, 2003). We assume that because of the significantly different morphology, the moisture content of shrubs in wintertime would be in the range of one third of that of trees at the same time.

The same assessment method as for trees was used for the calculation of sequestered carbon of shrubs. The carbon sink period is 10 years. We assume that bushes are maintained so that the twigs are cut back every 10 years and removed from the site, as is very typical in Finnish residential areas. Thus the amount of accumulated carbon is the result of the last 10-year accumulation period only as we have not considered speculation on what happens to the cut twigs after they have been taken from the site. In practice, however, the twigs are usually taken to waste management sites and chipped into mulch or

Table 2
The relative share of carbon uptake when compared to the emissions of the production phase or full life cycle.

Project	Building type	Site efficiency	Carbon uptake % compared to emissions of:		
			the production phase (A1–3)	the full life cycle (A–C)	the full life cycle of an nZEB (A–C)
1 Pikku-Pietarin piha	Townhouse 1	0.46	9.49	1.67	1.76
2 Vuorikallio	Townhouse 2	0.30	33.13	3.71	4.43
3 Huvilinnanmäki	Apartment block 1	0.82	5.45	0.94	1.00
4 Tietäjä	Apartment block 2	0.97	4.86	0.89	0.94
5 Jatuli	Mixed area 1	0.50	6.47	1.13	1.20
6 Koukkuniemenranta	Mixed area 2	0.36	12.71	2.30	2.22
7 Pikku-Jonttu	Single-family house	0.20	85.45	8.91	9.92

composted into soil, depending on their size and the amount of fresh leaves. Thus, they will continue holding the sequestered carbon if chipped into mulch but they will release it if composted into soil. The needles of the coniferous bushes were included in the weighing of the samples, but we exclude the leaves of deciduous bushes, as they fall off every year for all of the included plants and decompose on site.

A list of the studied trees and shrubs with their calculated content of sequestered atmospheric carbon is shown in Table 3.

2.3.2.2. Herbaceous and grass surfaces. Above ground vegetation is considered to equally decompose and flourish throughout the winter and summer seasons and thus the net carbon sequestration over time is assumed to be zero. The potential of SOC sequestration has been considered below ground in the first 20 cm of topsoil using data given by the LUCAS Topsoil Survey Methodology (Tóth et al., 2013) for grassland. The GHG emissions from the maintenance of turf grass have been reported by Gu et al. (2015) to vary according to maintenance scenarios: 697.2 kgCO_2e/ha/a for minimum maintenance, 845.4 kgCO_2e/ha/a for medium maintenance and 2442.5 kgCO_2e/ha/a for intensive maintenance. We have used the medium maintenance scenario but apply a conservative correction factor of 0.5 to it, assuming a lesser maintenance period for a lawn in the southern Finnish climate compared to a lawn in Tennessee, USA, where the study was made.

2.3.2.3. Soil organic carbon. SOC is defined as the carbon content in the first 20 cm of topsoil, where the carbon content is highest. The LUCAS Topsoil Survey defines four main land use categories where SOC has been measured, namely cropland, shrub land, grassland and woodland (Tóth et al., 2013). The measurements are based on a sampling method on a 2 km × 2 km grid covering the territory of the EU and in Finland 1716 samples were made. The SOC values used in the present study are taken with the boreal and boreal-to-temperate climatic zones as mean values.

The soil below shrubs is considered as shrub land soil and the soil below herbaceous and grass surfaces is considered as grassland soil.

There is also SOC stored beneath streets and paving in urban areas. These values are based on the results of Edmondson et al. (2012), where the soil's organic storage beneath impervious surfaces was evaluated to be 6.7 kg/m^2 beneath vehicle load bearing surfaces and 13.5 kg/m^2 under non-vehicle load bearing surfaces in Leicester, UK. We assume that the accumulation of OC is slower in the study area than in Leicester because the studied city of Espoo is located further north. Therefore we estimate conservatively that the accumulation of SOC under impervious surfaces is 80% of that in Leicester.

2.3.2.4. Grey infrastructure and CO_2 uptake in concrete. We have estimated emissions from the production phase (A1–3) of grey infrastructure: concrete paving, wooden decking, gravel, asphalt and sand.

In addition, the carbonation of concrete is taken into account. Concrete carbonation is a process in which atmospheric CO_2 reacts with the CaO of cement. As a result, $CaCO_3$ is formed and thus a portion of the CO_2 emissions from the manufacturing phase of cement are covered. The amount of carbonated concrete is calculated according to the method of Lagerblad (2005). The carbonation has only been estimated for paving, and the concrete parts of the buildings are not assessed. The justification for this cut-off is that most of the concrete-based building parts are assumed to be either covered with paint or another medium that significantly hinders carbonation, or repaired during their service life (as carbonation may lead to the corrosion of steel reinforcement bars). Concrete paving is open to reacting with atmospheric CO_2. All concrete paving is supposed to be manufactured from ordinary Portland cement and to be exposed to weather without shelter. The carbonation

Table 4
Knowledge gaps and needs for further research.

What?	Why?	How?
Growth algorithms for Nordic tree species.	To be able to estimate the carbon sequestration of urban trees in a cold climate.	A statistical survey of the normal thinning and removal of damaged plants. Sample plants could be e.g. chipped, dried and weighed.
Biomass estimations or growth algorithms for woody vegetation and bushes.	No algorithms were found for woody vegetation or bushes.	
Field measures of the impacts of growth conditions, maintenance and fertilisation to the biomass or growth algorithm of trees.	To be able to estimate how trees grow in different urban conditions in a cold climate. To be able to optimise the carbon sink effect and minimise environmental burdens from maintenance and fertilisation.	A survey of urban trees with measurements of height and diameter at breast height (DBH) compared to temperature, precipitation levels and the hours of sunshine throughout the year. The latter also serves as mapping of the solar energy potential for different parts of the city.
Field measures for the SOC content of urban soils in a cold climate, including samples taken from under impervious surfaces.	For obtaining localised urban SOC values for more accurate climate calculations. Especially the impact of winters, gradually changing weather and snow/ice should be clarified.	Numerous samples on a grid system (similar as the LUCAS Topsoil Survey) in Nordic cities. Evaluation on a deeper level than 20 cm. Measurement would be carried out on different seasons. Samples under impervious surfaces could be gathered along with typical infrastructure maintenance work.
Maintenance and life expectancy scenarios for garden plants.	To be able to estimate the environmental impact of the maintenance in the life-cycle assessment. To get a better understanding of the role of garden plants in carbon uptake. To have closer-to-reality life scenarios.	The collection of data from botanical gardens and gardening schools.
Estimation of the environmental impacts of garden maintenance (other than lawn mowing), including the structures.		
The moisture content data of woody garden plants.	To be able to estimate dry weight more accurately and therefore the carbon content in woody vegetation.	Sampling for different species and the measurement of oven dry weight using the same methodology as for trees.

period is 50 years, again following a common study period of building level LCA.

2.3.3. Calculation, data and assumptions for buildings

2.3.3.1. The production and construction of buildings. Emissions for the production phase of buildings are based on earlier studies (Takano et al., 2014a). We have assumed an average emission factor per square metre of concrete or wood framed buildings in the calculations. The factor includes fossil GHG emissions from the manufacturing of the foundations, walls, floors, roofs, doors and windows of the buildings. The emissions from the production of building services have been excluded.

For the structure types, the emission values were estimated by calculating the weight of each material of the structure and then multiplying it with material-specific emission factors that were retrieved from the ecoinvent Database (ecoinvent Center, 2014). These values were summed up to show the impacts of each structure type. Thus the building values do not represent the exact GHG emissions of the particular buildings but represent the average emissions of typical Finnish building types that have good energy efficiency. The studied buildings are assumed to be built according to the current Finnish energy-efficiency standards (Ministry of the Environment, 2011). These standards require thermal conductivities for the different building parts of residential buildings, as follows: walls 0.17 W/m^2 K, roofs 0.09 W/m^2 K, external floors 0.17 W/m^2 K, slab-to-ground floors 0.16 W/m^2 K, and windows and external doors 1.0 W/m^2 K. The typical insulation materials include mineral wool for walls and roofs, and expanded polystyrene sheets for slab-to-ground floors.

For the construction phase we apply a generic emission value of 300 kgCO$_2$e/gross-m^2, adapted from Takano et al. (2014b). The construction phase's GHG emissions for gardens are excluded as most of the work is manual and would not cause direct emissions.

2.3.3.2. Operative energy use in buildings. For the use phase of buildings we have calculated the GHG emissions based on the energy mix of district heating and electricity in Espoo. District heating in the city of Espoo is estimated to cause emissions of 0.193 kgCO$_2$e/kWh (Holopainen et al., 2010) and grid electricity on a national level is estimated to emit 0.2216 kgCO$_2$e/kWh (Helsinki Region Environmental Services Authority and World Wildlife Fund, 2016).

We use two energy use values for the buildings. The estimated energy demand of the studied residential buildings in Espoo today is retrieved from a web-based information service "Energiatieto" (City of Espoo, 2015) and it varies between 122 and 151 kWh/m^2. For the planned energy efficiency of nearly-zero energy buildings (nZEBs) we use 141 kWh/m^2, which is calculated from the target energy-efficiency values suggested in the national roadmap report for nZEBs by Reinikainen et al. (2015).

The period of use of the buildings is 50 years in this study. During this time it is likely that the GHG emissions from energy production will decrease, as part of climate change mitigation. We follow the decarbonisation scenarios of the Finnish Energy Industries (2010) for district heating and electricity. This scenario aims at lowering GHG emissions for district heating to 0.025 kgCO$_2$e/kWh and electricity to 0.044 kgCO$_2$e/kWh. We assume that after 2050 there would be no further reductions and that the GHG intensity of energy is stable for the rest of the assessed period.

2.3.3.3. The end-of-life scenario for buildings. The emissions from the demolition, transportation and waste management of construction materials were assessed based on the reference building from Takano et al. (2014a), which gives fossil GHG emissions for each frame material element. The values for each construction material were then multiplied by the number of square metres given from the reference building. From these calculations, a value per square metre of net heated floor area was obtained and was then multiplied by the surface area of each building.

2.3.4. Uncertainties and limitations

The exact quantification of sequestered carbon in plants and soils is very challenging. Site conditions and maintenance scenarios significantly affect the growth of plants and SOC accumulation. Few Finnish examples for biomass equations or growth algorithms for urban trees were found (with the main species including birch, Norway spruce, Scots pine and Larch) and none were found for shrubs. Therefore, the available equations have been adapted to the Finnish climate. Furthermore, the amount of covered wood species in the equations is limited, while missing species have to be covered by using the equations of species of similar size and shape.

The weights of bushes are based on a few samples from each species. Growth conditions and maintenance would in practice have a major impact on the accumulation of carbon in the biomass of bushes.

In addition, the relative water content of trees, bushes and herbaceous plant is likely to have high variance. According to earlier studies (Kärkkäinen, 2003, pp. 164; Augé et al., 1990) the relative water content may vary within samples of same species depending on growth conditions, precipitation, stress levels and the genetics of the plants. No datasets for the average moisture percentages of the assessed plants were found. Therefore the calculation of dry weight and carbon sequestration, especially of bushes, is prone to errors.

The maintenance scenarios for gardens are simplified. Studying them for different areas of gardens would be important for bringing more accuracy into future estimations.

During the simulation period of 50 years there surely will be unexpected changes in the energy mixes and also renovation of the buildings. All these will increase the GHG emissions. However, we have not included the emissions from possible renovations or infrastructure improvements into our study due to high levels of uncertainty.

The construction materials of the buildings have been simplified so that all of the buildings are assessed using standardised structure types. This deviates the findings from those of real cases, but our intention has been to exemplify the potential of emissions and their compensation in general.

Furthermore, the actual realised decarbonisation of energy may differ from the scenario set by the Finnish Energy Industries. Therefore, to follow the good practice of making "conservative assumptions", we chose not to speculate on further GHG intensity reductions after 2050. This may distort the results but in a conservative direction.

3. Results

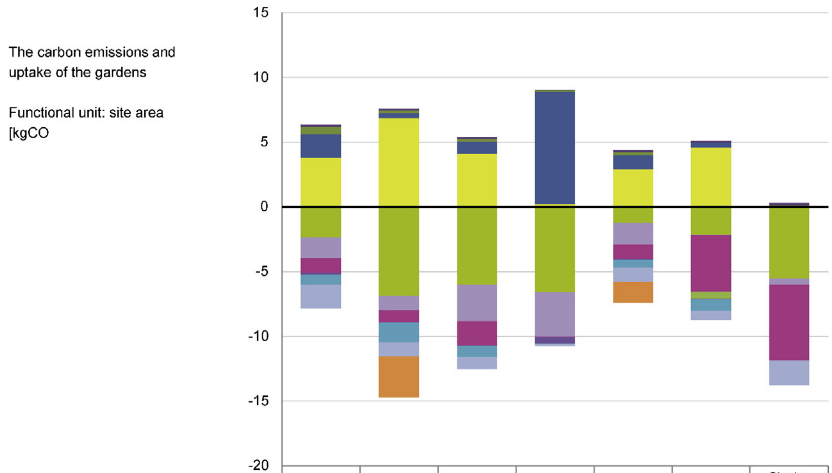
3.1. The carbon uptake and emissions of the gardens

The results of the calculation are shown in Fig. 2, which illustrates the carbon uptake and emissions of gardens, excluding buildings, divided into the site area of each residential area. The results reveal that in most cases the sinks are larger than the emissions within the study period of 50 years. The largest carbon sinks are found in the single-family house site, as the building is small and the garden large. However, even in the apartment block site the sinks are quite large.

Trees are the largest contributor to the carbon uptake of gardens. They have a dominant role in five out of seven areas. Their potential has a considerable range of variability, from 16.8% to 64.4% of the measured total sequestration.

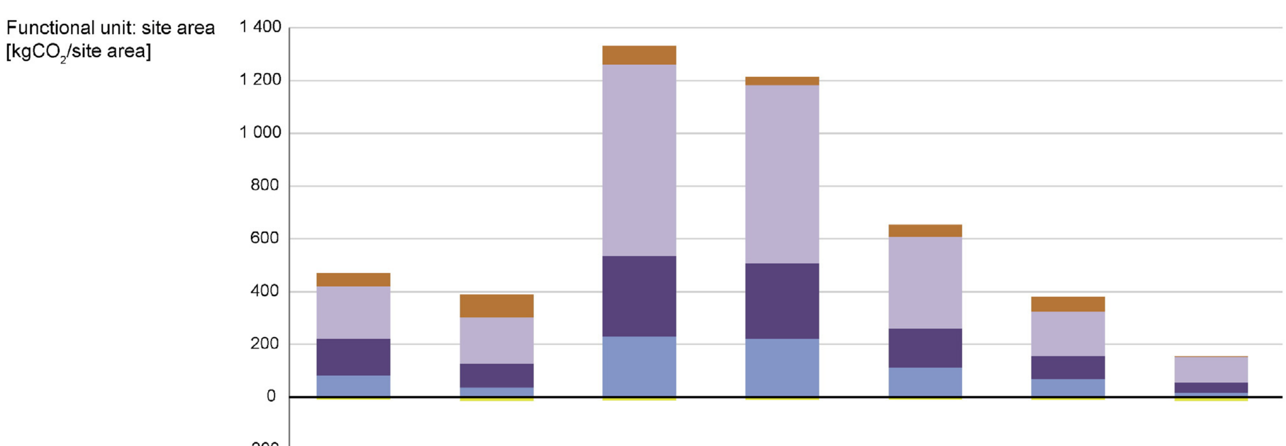
As we look at the share of soils in carbon uptake potential, the results show very volatile, case-specific variation. In some projects the uptake in soils can even reach 50.2% of the total carbon sequestered in gardens (project no. 5), whereas in others it only reaches 0.4% (project no. 4). The more grass soil there is, the larger the uptake may be.

The carbonation of concrete surfaces seems to result in only marginal carbon uptake. In all the studied cases the concrete surfaces were



		Townhouse 1	Townhouse 2	Apartment block 1	Apartment block 2	Mixed area 1	Mixed area 2	Single-family house
Uptake	Existing forests	0,00	-3,21	0,00	0,00	-1,60	0,00	0,00
Uptake	Under non-vehicle load bearing surfaces	-1,81	-1,04	-0,95	-0,15	-1,10	-0,68	-1,89
Uptake	Under vehicle load bearing surfaces	-0,78	-1,55	-0,84	-0,04	-0,60	-0,94	0,00
Uptake	Carbonation	-0,13	-0,02	-0,05	-0,49	-0,07	-0,02	0,00
Uptake	Green roof / other	0,00	0,00	0,00	0,00	0,00	-0,53	0,00
Uptake	Grass soil	-1,15	-0,93	-1,86	-0,04	-1,10	-4,38	-5,87
Uptake	Herbaceous soil	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Uptake	Woody vegetation	-1,59	-1,11	-2,82	-3,42	-1,70	-0,02	-0,49
Uptake	Trees	-2,36	-6,88	-6,02	-6,60	-1,23	-2,16	-5,52
Emissions	Open surfaces	0,20	0,14	0,12	0,01	0,15	0,10	0,20
Emissions	Semi-open surafces	0,54	0,20	0,22	0,14	0,20	0,00	0,13
Emissions	Sealed surfaces	1,83	0,41	0,95	8,70	1,12	0,38	0,00
Emissions	Traffic area	3,80	6,85	4,10	0,19	2,90	4,59	0,00

Fig. 2. The carbon emissions and uptake of gardens during their life cycle.



		Townhouse 1	Townhouse 2	Apartment block 1	Apartment block 2	Mixed area 1	Mixed area 2	Single-family house
Current energy class	Total C uptake	-7,82	-14,73	-12,54	-10,73	-7,40	-8,74	-13,77
Current energy class	End-of-life (module C)	47,16	85,99	70,24	29,23	43,57	55,34	1,86
Current energy class	Use phase energy (module B6)	201,25	176,18	726,40	675,32	347,54	169,37	98,14
Current energy class	Construction (modules A4-5)	138,25	89,96	305,23	287,28	147,84	86,49	38,50
Current energy class	Production (modules A1-3)	82,40	36,88	230,25	220,66	113,28	68,78	16,12

		Townhouse 1	Townhouse 2	Apartment block 1	Apartment block 2	Mixed area 1	Mixed area 2	Single-family house
nZEB energy class	Total C uptake	-7,82	-14,73	-12,54	-10,73	-7,40	-8,74	-13,77
nZEB energy class	End-of-life (module C)	47,16	85,99	70,24	29,23	43,57	55,34	1,86
nZEB energy class	Use phase energy (module B6)	176,36	189,71	643,65	605,78	311,75	182,37	82,42
nZEB energy class	Construction (modules A4-5)	138,25	89,96	305,23	287,28	147,84	86,49	38,50
nZEB energy class	Production (modules A1-3)	82,40	36,88	230,25	220,66	113,28	68,78	16,12

Fig. 3. The carbon balance of gardens and buildings during 50 years. The calculations made with present energy use evaluation (the chart and the topmost table) and the proposed nZEB class energy consumption (the lowermost table) are close to each other. Emissions from the use phase appear dominant for both scenarios. The uptake of carbon in vegetation, soil and concrete within this timescale becomes marginal.

exposed to weather and/or faced the ground. Neither of these solutions are favourable for carbonation. At maximum, carbonation was found to only be able to compensate for marginal shares of 0.006% (project no. 6) and 0.041% (project nr. 4) of the GHG emissions during a 50-year carbonation period.

On the emission side we find that the great majority of the GHG emissions are associated with the manufacturing of materials for traffic areas (mostly asphalt) and sealed surfaces (mostly concrete paving). Other emission sources are marginal. Depending on the landscape architectural design of the garden the dominance of these emissions compared to the uptake of carbon in green surfaces varies.

3.2. Comparison to CO_2 emissions from the construction and use of buildings

How big is the uptake of carbon in gardens if it is compared to the construction and use of buildings for 50 years? The results (Fig. 3) reveal that the gardens seem to play a rather small role in the overall emissions of most of the studied residential areas. The majority of the emissions are caused by the operative energy use of the buildings. They have far more importance in the GHG balance of the studied buildings than all the other factors together over a 50-year life cycle with the current GHG intensity of the locally available energy. The carbon uptake potential in the gardens was found to vary between 1.2% and 11.9% of the total emissions (Table 2).

For nZEB energy-class buildings we can only observe slight changes in the increase of production phase emissions and a decrease in the share of the use-phase energy emissions. Their overall life-cycle carbon footprint is smaller than in the conventional energy class, as expected. This increases the relative share of carbon uptake in gardens. In nZEB areas the carbon uptake varies from 0.94% to 9.92%. All of the studied buildings were originally built in an energy-efficient manner and thus the differences between nZEB alternatives remain small. However, when comparing the uptake of carbon to the emissions arising from the production phase of construction materials, the ratio is different: in some cases reaching 85% of the emissions of the production phase of construction materials of a single-family house (project no. 7) or 33% of the respective emissions of a townhouse (project no. 2). These can be considered very high figures.

3.3. Site efficiency and potential for carbon sequestration

What then is the impact of site density on the potential for carbon uptake? Fig. 4 shows site efficiency (the columns) and the share of carbon uptake through ecosystem services and the carbonation of full life-cycle GHG emissions (depicted as a line). As can be seen, the findings strongly indicate that the higher the site efficiency becomes, the lower the potential for carbon uptake is. This is logical, but the interesting finding is that the better the energy efficiency becomes, the stronger the difference is between site efficiency and the potential for carbon sequestration.

4. Conclusions and discussion

4.1. The relevance of ecosystem services in CO_2 balancing

The impact of carbon uptake varies according to the case. It may reach a relatively high share (13.7%) of life-cycle GHG emissions in single-family houses that have large gardens. However, the densification of the urban structure does not favour such environments. As we look at more compact examples, the projects that have room for trees have the highest potential for carbon sequestration. Thus it may be concluded that the optimal balance between denser urban environments and urban trees needs regional studying and further analysis. In addition to sequestering carbon, trees provide many other important ecosystem services.

In addition, the carbon accumulation in urban soils seems to possess significant potential. The accumulation is strong under trees and woody vegetation. Thus rows of trees should ideally be planted on open soils instead of under perforated surfaces. Practical considerations, such as the protection of roots in traffic areas, may however lead to other solutions.

If we consider the compensation of the emissions from the production phase of construction materials, then the role of carbon uptake in gardens becomes significant. While providing the residents with a recreational and restorative environment, gardens may also neutralize the emissions from the construction of the buildings over the life cycle. Naturally this assumption is subject to the uncertainties of this study and to case-specific deviation. Still, our results justify taking into account the potential of carbon compensation in the life-cycle planning of urban residential areas.

4.2. Consequences beyond the system boundary

In this study we have followed the system boundary of EN 15978. For understanding the complex GHG fluxes on an areal or city level, however, the system boundary should be extended. Emissions from traffic, infrastructure and maintenance of the city should be compared to those potential benefits that the urban ecosystem services can offer in the category of climate change mitigation. The role of ecosystem services on the larger, city-level context depends to a great extent on the structure of the city and its land use. The studied city of Espoo has

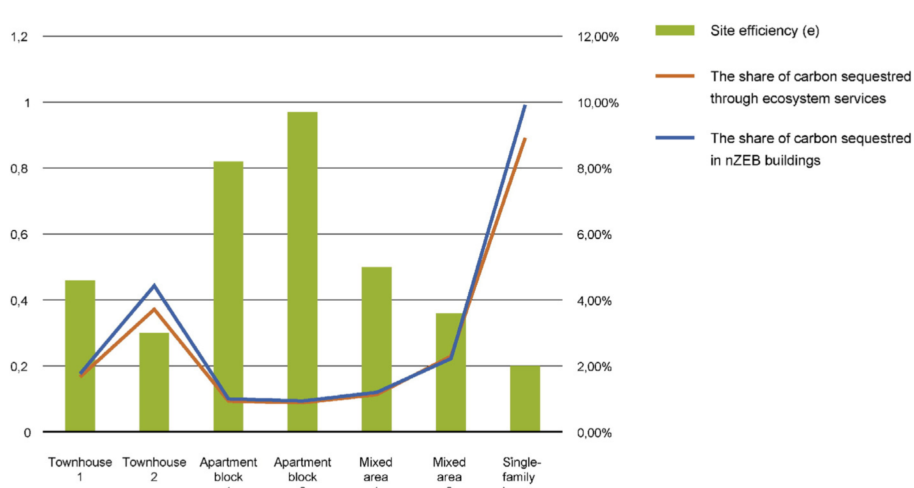


Fig. 4. The correlation of site efficiency and potential of carbon sequestration.

relatively low density (817.6 inhabitants/km^2) when compared to other cities in the Baltic Sea region: Helsinki 2932.1 inhabitants/km^2, Tallinn 2744.8 inhabitants/km^2, Stockholm 4872.5 inhabitants/km^2, Uppsala 2879.9 inhabitants/km^2, Riga 2688.9 inhabitants/km^2 and St. Petersburg 3390.94 inhabitants/km^2 (Wikipedia, 2016). The low density in the city of Espoo is a seemingly particular phenomenon that is a result of the "garden city" oriented city planning (Howard, 1902) and the slow integration of suburban areas into one single city over time. The looser the city structure becomes, the greater the transportation distances and related GHG emissions become if low-carbon public transportation is not available. To understand the potential of ecosystem services in cities that have differing densities, a comparative study of the interdependence of land use, ecosystem service potential and emissions related to urban infrastructure and energy should be carried out.

Furthermore, urban consumption trends seem to add to the GHG emissions of cities. Several studies indicate that although the denser urban settlement may bring reductions, for example to traffic-related GHG emissions, these savings can be overrun by the indirect emissions associated with an urban lifestyle and consumption habits (Edenhofer et al., 2014, pp. 78; Heinonen et al., 2013; Heinonen and Junnila, 2011). Thus a holistic evaluation of the GHG flows of a city seems to extend towards the horizon, especially when longer timescales are applied. In order to gradually improve our understanding about the potential of urban ecosystem services we therefore argue that the system boundaries of assessments should be kept tight at the beginning. The expansion of system boundaries will bring results that will only have acceptable error margins after more data becomes available.

4.3. Recommendations for city planners and designers

- Use plenty of trees on sites and along roads. Ideally trees should be positioned so that they help provide shade in summertime and wind protection in wintertime. Trees can also be used as noise barriers between residential areas and prevailing noise sources.
- Include mandatory green zones within sites in the city plan. Add a minimum number of trees into the specification text of the city plan.
- Green zones within a site boundary should be spacious enough for trees to reach their full size and thus maximize their carbon uptake potential.
- Soils possess good potential for accumulating SOC. This potential should be taken into account in urban zones. To enable SOC accumulation to reach its optimum, mowable lawns should be avoided and non-maintained herbaceous areas favored instead.
- The carbonation of yard structures does not seem to have significant potential in affecting the overall uptake of carbon. An ideal environment for carbonation can be found in sheltered outdoor spaces (e.g. car parks or non-heated storage rooms) where concrete surfaces can be favored if functional reasons require sealed surfaces or traffic areas.
- If there are needs for embankments or rocky land coverings, consider using crushed concrete rubble instead of natural stones. Concrete rubble is a feasible material for creating an effective, passive carbon sink, as the external area of concrete is multiplied compared to concrete structures and thus the impact of carbonation is increased. The visual appearance of crushed and sorted concrete is not far from the appearance of crushed natural stone.

4.4. Further research and development needs

This study has shown that there are major gaps of knowledge in the process-based carbon footprinting of urban vegetation. We have identified both the shortage of data and lack of scenarios. Without these the accuracy of studies remains moderate. The main needs for improvement and further research are listed in Table 4.

In addition to the open knowledge gaps presented in Table 4, there should be guidance for the inclusion of the potential of ecosystem services in the standards that guide the assessment of environmental performance in the built environment. Perhaps the most suitable platform for this could be the technical committee TC350 of the European Committee for Standardization whose mandate includes the development of standards for the sustainability assessment in the built environment. An update to the standards developed by TC350, in particular EN 15643-1 and EN 15643--2, should be done in order to clarify the role of ecosystem services. Furthermore, specific "product category rules" could be developed for the sustainability assessment of vegetation and garden plants. With the help of such normative documents there would be better potential for including the currently neglected role of ecosystem services into sustainability assessment.

As a final conclusion we argue that the role of urban vegetation and soils may have strategic potential in the mitigation of urban GHG emissions. It may even lead to new thinking in life-cycle models of planning of the structure and maintenance of urban regions. Therefore we recommend that field data should be gathered and analysed in various cities and disseminated to planners and designers. We may have a considerable unused potential within the green infrastructure investments that could be incorporated in the carbon balance bookkeeping of cities and regions.

Acknowledgements

This study has been funded through Aalto University's research programme "Energy-efficient Townhouse" (nr. 910021). Bush samples and measures have been provided by Dr. Henry Väre and Dr. Risto Kuittinen. The authors thank the above-mentioned for their kind help.

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