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A more complete accounting of greenhouse gas emissions and sequestration in urban landscapes

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ABSTRACT

Understanding interactions between complex human and natural systems involved in urban carbon cycling is important when balancing the dual goals of urban development to accommodate a growing population, while also achieving urban carbon neutrality. This study develops a systems breakdown accounting method to assess the urban carbon cycle. The method facilitates greater understanding of the complex interactions within and between systems involved in this cycle, in order to identify ways in which humans can adapt their interactions to reduce net greenhouse gas emissions from urban regions. Testing the systems breakdown accounting method in Stockholm County, Sweden, we find that it provides new insights into the carbon interactions with urban green-blue areas in the region. Results show how Stockholm County can reduce its emissions and achieve its goal of local carbon net-neutrality, if the green areas protect its carbon sequestration potential and maintain it to offset projected remaining active emissions. Results also show that the inland surface waters and inner archipelago waters within Stockholm County are a considerable source of greenhouse gases to the atmosphere. A better understanding of these water emissions is necessary to formulate effective planning and policy measures that can reduce urban emissions. The insights gained from this study can also be applied in other regions. In particular, water bodies could play a significant role in the urban carbon cycle and using this knowledge for more complete carbon accounting, and a better understanding of green-blue interactions could help to reduce net urban emissions in many places.

1. Introduction

To meet the dual challenges of a growing global population and mitigating climate change, considering how urban areas can sustainably grow while minimising impacts on the environment is necessary. Climate change mitigation requires primarily a reduction in global greenhouse gas (GHG) emissions. Many countries and cities have committed to becoming ‘carbon-neutral’ within the coming decades, e.g. as part of the Paris Agreement (United Nations, 2015). Achieving carbon neutrality in urban systems, however, is complex and challenging. It requires understanding carbon dynamics in urban ecosystems, including process-level identification and distinction of natural and human-perturbed carbon exchanges and their interactions. ‘Carbon neutrality’ is itself a complex concept at the scale of a city or region. It is definable in several ways according to the emission scope included in calculations. This study considers land use-related carbon emissions and therefore uses a geographically determined “internal emissions” definition of carbon neutrality. This definition includes only the emissions within a geographical boundary and a very few “core” external emissions, which are directly related to land use choices (Kennedy and Sgouridis, 2011).

Consideration of land use-related GHG emissions and sequestration in urban and regional planning and policy-making is needed for achieving carbon-neutral cities in the future (Fang et al., 2015; Pan et al., 2020). To do this effectively, however, requires further understanding of urban carbon cycles. Much research has focused on parts of these cycles. Studies include emissions from various sources and how to reduce them (Pichler et al., 2017; Xu et al., 2019), carbon sequestration by vegetation (Christen et al., 2011; Vaccari et al., 2013), reduction of net emissions using nature-based solutions (Baró and Gómez-Baggethun, 2017; Kalantari et al.,

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2019b), and carbon emissions and sequestration in water and soils (Cole et al., 2007; Edmondson et al., 2012; Guo and Gifford, 2002; Raymond et al., 2013; Smith, 2008). Human activities have impacted many of the components of the urban carbon cycle (and vice versa), with consequences for both human and natural systems that must be considered together, to understand and model the cycle in helpful ways in making cities more sustainable (Churkina, 2008).

Assessments of the GHG emissions of cities or regions usually take the form of either 'bottom-up' accounting or inventories, or 'top-down' emissions measurements (Marcotullio et al., 2014). The former combines contributions of various sources (and sometimes sequestration) to obtain a total. The latter involves measurements or calculations of net GHG fluxes over the study area, which can vary in scale from directly measurable fluxes in local neighbourhoods to the use of global data from satellite observations for large-scale calculations (Andrade et al., 2018; Christen et al., 2011; Duren and Miller, 2012). While top-down assessments can give an overarching picture of net emissions in a study area, they do not necessarily provide insights into where these emissions derive from, and how to effectively reduce them. Accounting and inventory (bottom-up) methods can provide such insights.

In a bid to reduce contributions to global GHG emissions, many cities, regions and countries have performed bottom-up carbon accounting. These efforts often follow methodologies similar to that published by the Intergovernmental Panel on Climate Change (IPCC) in its Guidelines for National Greenhouse Inventories or the World Resources Institute in its Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC). While these types of inventories can be useful in identifying areas where cities can make changes to reduce their emissions, they usually do not include sequestration or potential sources of GHG emissions influenced by local human activity. Carbon accounting often also excludes water as a potential source of GHG emissions in the calculations. For example, water is only mentioned in GPC in relation to emissions from wastewater and its treatment; emissions from water-based travel; and emissions related to pumping and otherwise supplying water to people and industries (Fong et al., 2014; IPCC - The Intergovernmental Panel on Climate Change, 2006; Kennedy and Sgouridis, 2011; Marcotullio et al., 2014).

The IPCC guidelines for carbon accounting do not include calculations for water-covered land (e.g. lakes and rivers), despite considerable evidence that inland waters are a source of large amounts of GHG to the atmosphere and that human activities have significantly affected this contribution (Cole et al., 2007; Raymond et al., 2013; Tranvik et al., 2009). Such water-covered areas are under ongoing change (increasing in recent decades) across the world (Borja et al., 2020). Oceans, on the other hand, are accounted for as a large carbon sink globally (Landschützer et al., 2014; Le Quéré et al., 2014), but locally, the coastal waters located in or next to urban areas can be sources of GHGs to the atmosphere ignored in accounting (Melaku Canu et al., 2015). In general, inland and coastal waters also integrate and reflect the net waterborne inputs to these water resulting from multiple sources, sinks and processes occurring in their hydrological catchments, which extend over much greater areas than the water bodies themselves (Cvetkovic et al., 2012; Destouni et al., 2010).

Since local inland and coastal water bodies can contribute GHGs significantly to the atmosphere, and since many cities, urban regions and countries encompass such water bodies, carbon inventories must include the carbon implications of these waters for a more complete picture of actual emissions. Considering and understanding the role of inland and coastal waters and their catchments in the urban carbon cycle, and associated impacts on net results of carbon inventories, can suggest new or modified actions and policies to move towards carbon neutrality. At the very least, this could help to ensure that plans striving for net carbon neutrality are not derailed by neglecting a major portion of the cycle.

The overarching goal of this work is to promote reduction of net urban GHG emissions by improving understanding of the complex interactions between land-use changes associated with urban growth and GHG emissions. The objectives are as follows. First, we develop a systems breakdown accounting (SBA) methodology for a more comprehensive inventory of GHG emissions and sequestration in urban regions (including water-covered land and coastal water areas, which are not typically included, for example in IPCC methodologies). Second, we test the methodology in an urban region case (Stockholm County). Third, we use results of the test case to increase understanding of the emission and sequestration roles of blue-green areas in the urban carbon cycle, with an eye toward better management of these natural systems including with nature-based solutions.

To address these objectives, this study sought to answer the following specific research questions: i) What role (if any) do freshwater bodies play in the urban carbon cycle?; ii) What role (if any) do coastal waters play in the urban carbon cycle in a coastal region?; and iii) How significant are these roles to warrant inclusion of water bodies in urban carbon accounting? For the first question, the hypothesis was that freshwaters contribute significantly to GHG emissions in urban regions where there are many lakes or rivers, since globally these are a significant source of GHGs to the atmosphere (Raymond et al., 2013). The second hypothesis was that, although oceans are globally carbon sinks, locally coastal waters can be a source of GHGs in urban regions. For the third question, we hypothesised that water bodies (and particularly freshwaters) play a sufficiently significant role in the urban carbon cycle to warrant their inclusion in carbon accounting, although their role will likely vary greatly according to how much water is included in the accounting area.

2. Methodology - systems breakdown accounting approach

The SBA approach helps to understand carbon cycles in urban regions by investigating various system components and the GHG emissions and sequestration processes within and between them in a regional system. Investigating these system components before performing carbon accounting for the whole system can help distinguish local sources and sinks (such as water bodies and green areas) that are frequently overlooked in carbon accounting. Fig. 1 illustrates the natural and social systems considered in this study and the links between components within and between these systems. The numbered arrows show the links investigated, whereas arrows with dashed grey lines indicate probable links that were not investigated within the scope of this study. The methodology that follows describes investigations of the various processes and interactions depicted in Fig. 1, following the numbering shown.

2.1. Urban greenhouse gas emissions to the atmosphere

The arrows marked '1' in Fig. 1 indicate the contributions of human land use, transportation and industry to urban GHG emissions to the atmosphere. The transport and industry emissions are direct emissions of GHGs, whereas those from land use are mostly indirect and refer to how the use of a piece of land in a particular way causes emission of GHGs to the atmosphere. For example, although residential buildings themselves do not directly emit significant amounts of GHGs to the atmosphere beyond the construction phase, their existence nonetheless causes emissions throughout their useful lifetime, due to the demand for electricity

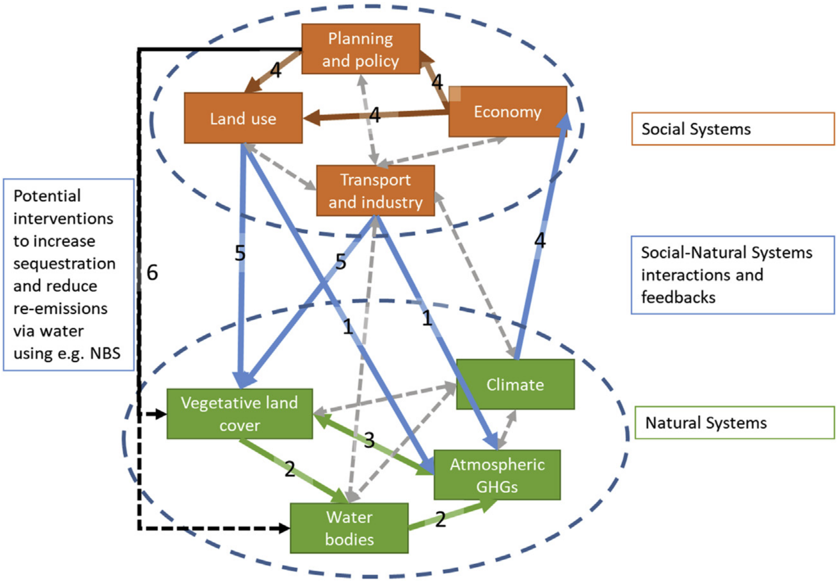

Fig. 1. Conceptual basis of the systems breakdown accounting methodology - a diagram of the natural and social systems contributing to the carbon cycle in an urban region and the links between these systems and their components. Potential intervention points for nature-based solutions (NBS) in this cycle are also shown.

and heating in these buildings. Together, these sources account for the GHG emissions to the atmosphere regularly included in urban and regional carbon accounting, as suggested in the carbon accounting guidelines (Fong et al., 2014; IPCC - The Intergovernmental Panel on Climate Change, 2006). The SBA methodology considers emissions on a regional scale, and the scale of input data is the total emissions energy use by all residential, commercial and industrial buildings in the study area. Direct calculation is possible by relating emissions to the recorded total energy used annually by buildings in the study area. Traffic emissions are considered at the scale of total emissions from average annual traffic volumes by the various transportation types within the area.

2.2. Greenhouse gas emissions and sequestration in water bodies

The arrows marked ‘2’ in Fig. 1 indicate GHG sequestration in urban water bodies and emissions to the atmosphere, and the link between vegetative sequestration in and carbon loading from the respective hydrological catchments into the water bodies. The latter link is important for understanding the urban carbon cycle, as it reflects the fact that vegetative sequestration is not simply an endless sink. Some portion of the carbon removed from the atmosphere by vegetation is cycled to hydrological transport of dissolved carbon from the land surface, largely through subsurface water, into the nearest surface water (Jantze et al., 2013; Lyon et al., 2010). Ultimately, all these waterborne transport components are integrated through catchment outlets to recipient surface and coastal waters (Cvetkovic et al., 2012; Destouni et al., 2010), and from these back to the atmosphere.

To calculate GHG emissions or sequestration by water bodies in a region, identifying the water-atmosphere interfaces that exist within the region and their total surface areas is first necessary. These interfaces include the areas of freshwater lakes, rivers and reservoirs, parts of seas, oceans and lagoons, and various other permanent or seasonal water bodies. In this SBA methodology, we do not include marshes and other vegetated wetland areas as water bodies, but as part of vegetative land cover. It is important to distinguish between different types of surface water bodies in a region on the finest scale possible, as different types of water bodies can have vastly different emission or sequestration potential. In general, studies have found freshwater bodies to emit GHGs to the atmosphere, with rivers emitting significantly more per unit area than lakes (Cole et al., 2007; Raymond et al., 2013; Tranvik et al., 2009). Seas and oceans can be GHG sources or sinks, with large variations even within the same water body, but on a global scale, salt waters are a significant carbon sink (Kuliński and Pempkowiak, 2011; Landschützer et al., 2014; Le Quéré et al., 2014).

2.3. Vegetative greenhouse gas sequestration

The arrow marked ‘3’ in Fig. 1 indicates removal of carbon from the atmosphere via vegetative sequestration. Carbon sequestration is an important ecosystem service provided by green and green-blue (marsh, wetland) spaces in urban regions. Thus, protection, expansion and proper management of such areas can be an effective nature-based solution to help offset urban GHG emissions as cities strive to reach net-zero emissions (Cohen-Shacham et al., 2016). Forests are perhaps the most common type of vegetation that springs to mind concerning terrestrial carbon sinks, but their carbon storage potential can vary greatly with type, location, age of the trees and even biodiversity (Díaz et al., 2009; Dybala et al., 2019; Luyssaert et al., 2007; Ťupek et al., 2010; Zhu et al., 2019). Agricultural land and grasslands can be a carbon source or sink, depending on what is grown and farming practices such as soil tillage and fertilisation (Freibauer et al., 2004; Luo et al., 2010; Smith, 2014; West and Marland, 2002). Other vegetation in urban regions (i.e. nature reserves, parks, gardens and vegetated wetlands) also has carbon sequestration potential, although again, such potential is dependent on how the management of these areas (Zirkle et al., 2011).

Calculation of the areas of each type of vegetation in a study region is possible from a land cover map. The vegetation in these maps, however, often appears as categories according to a general standard, so it is important to identify exactly the type of vegetation represented by each category in the study region. For example, the tree species present in broad-leaf forest in Europe may completely differ from those in corresponding forest in North America, but both would still appear as ‘broad-leaf forest’ in the standard classification.

2.4. Impacts of climate, the economy, planning and policy on future land use

Climate change has impacts on many aspects of cities, including their economic and social systems. These impacts in turn drive planning and policy decisions and eventually affect future land use in urban regions, as illustrated by the arrows marked '4' in Fig. 1. Various planning support systems and other technologies are available to help assess these impacts and how they may shape urban regions in the future (Page et al., 2020; Pan et al., 2018). Modelling tools can show how land use in the future will likely change, given what is known now about the drivers pushing the change (Kalantari et al., 2019a). In this proposed methodology, we suggest using modelling results of future land use change for the study region to assess how such changes can likely impact GHG emissions and sequestration in the future.

2.5. Extrapolation of land use change impacts on future emissions and sequestration

The arrows marked '5' in Fig. 1 indicates the impact of changes in land use on the GHG cycle of vegetated areas in the future. The most obvious impact is possible loss of vegetative carbon sinks due to urban expansion, implying decreased ability to remove GHGs from the atmosphere if these sinks are unprotected. Conversely, policies and plans that encourage protection, expansion and rehabilitation of areas with high vegetative sequestration potential will increase regional capacity to remove GHGs from the atmosphere in the future. In this proposed methodology, we perform the calculations under points 1, 2 and 3 above using modelled future land use maps (from point 4). Additional available emissions plans, predictions and policies support these calculations resulting in future emissions and sequestration in the urban carbon cycle for a study region.

2.6. Assessment of planning and policy impacts and identification of other potential interventions

The arrows marked '6' in Fig. 1 indicate the next steps in the proposed methodology, after completing carbon cycle assessments for both the present and future scenarios. These steps create a better understanding of the components in an urban carbon cycle and how they interact. They provide guidance for *using this understanding to identify places where effective action is possible through planning and policy* to reduce future net GHG emissions and meet climate change goals. The results also provide a basis for assessing existing plans and policies to guide future predictions. They can inform policymakers the likelihood of achieving goals for climate change, as well as improvements to increase the likelihood of success.

3. Application of methodology to a test case

In line with the second stated goal of this work, we apply the SBA methodology to the case region of Stockholm County, Sweden. Stockholm County is an urban region on Sweden's east coast (Fig. 2). It includes two cities (the Swedish capital Stockholm and Södertälje to the south), as well as smaller towns, industrial areas and farmland. The county includes many islands that are part of the Stockholm archipelago in the Baltic Sea. The county also contains many large forested areas, lakes and streams. Vast blue-green areas surround and extend into the urban centres, making the area ideal

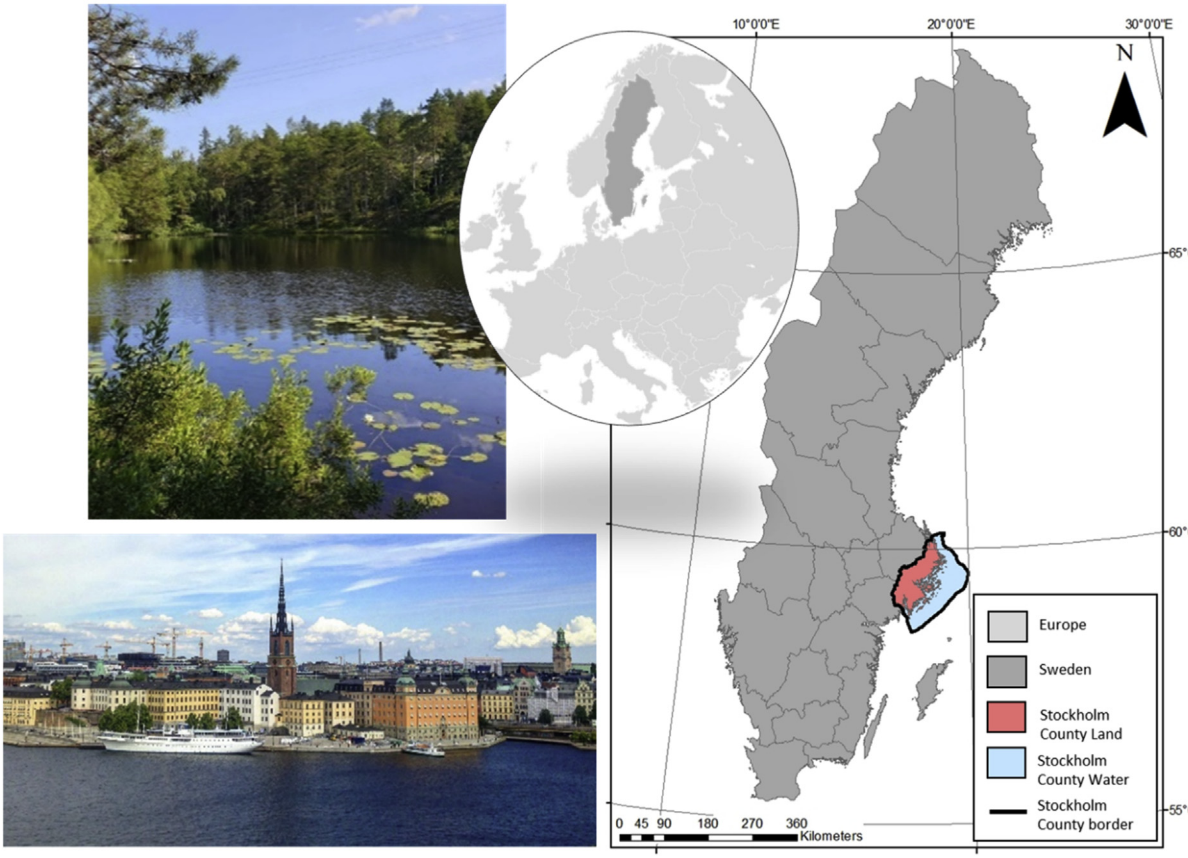

Fig. 2. Images of a lake in Stockholm County (top left) and the urban centre of Stockholm City, where Lake Mälaren and the Baltic Sea meet (bottom left), and map showing the location of Stockholm County in Sweden (right). The central inset map shows the location of Sweden in Europe (Jose, 2006).

considering the roles of blue-green areas in the urban carbon cycle. The population is growing rapidly, from 2.35 million in 2019 to a predicted 3.4 million by 2050.

3.1. System boundaries

Since this study focuses on land use-related emissions, we chose the primary geographical system boundary as the border of Stockholm County. The emissions included mostly fall within the “internal emissions” category (i.e. occurring within the physical system boundary) and some “core external emissions” (see Kennedy and Sgouridis, 2011). This category includes, for example, ‘urban’ emissions from electricity generation and transportation associated with various land uses in the area, as well as emissions from and sequestration by natural systems such as water bodies. A very limited number of “core” external emissions are included (namely those related to electricity generated outside county borders, but used **within),** but not emissions from other activities, such as consumption within the study area of food and goods produced elsewhere. This last exclusion enables a focus on the natural and social systems related to land use within an urban region. It provides insights into how alterations in planning and policy can reduce the associated emissions. Emissions related to production and transportation of goods produced outside the study area and consumed within it, however, comprise a significant proportion of the overall carbon emissions associated with the Stockholm region and Sweden as a whole (Schmidt et al., 2019). Section 5.1 discusses the implications of this exclusion for truly declaring Stockholm County as achieving carbon neutrality in the. Calculations for all emissions and sequestration in the study area are on a per-year basis.

3.2. Data collection and description

3.2.1. Urban greenhouse gas emissions

The annual emissions considered in the case study are from Stockholm County authority, including emissions from transportation, everyday functioning of buildings, and industrial activities taking place within the county. We calculated the building emissions on an annual basis, according to the amount of electricity used in (residential and commercial) buildings and carbon released (measured in 10^9kg $C0_{2\text{-eq}}$) in generation of this electricity, together with any emissions associated with supplying these buildings with energy, such as from heating. Calculations of industrial emissions are from the sum of emissions associated with energy supply to industries, as well as the direct emissions released. We calculated transport emissions according to annual average traffic volumes for internal goods and passenger transport via road, rail and water, plus take-off and landing emissions from the airports within the county (also reported in 10^9kg $C0_{2\text{-eq}}$). (TRF - Tillväxt- och Regionplaneförvaltningen, 2016).

In its 2016 report on climate efforts in Stockholm County, the county planning department also provided predictions on planned urban emissions from these sources in the future, up to the year 2045 (TRF - Tillväxt- och Regionplaneförvaltningen, 2016). These predicted emissions are considerably lower than those from 2014, despite the growing population in the county. The report detailed measures for reducing emissions to the predicted levels. These measures include stricter building energy standards for both new and existing buildings, a continuing shift towards electric vehicles for transportation of people and goods, a further shift away from fossil fuels in electricity generation, and other strategies (Stockholms Stad, 2016; TRF - Tillväxt- och Regionplaneförvaltningen, 2016). The recorded urban emissions in 2014 and the predicted 2045 emissions for Stockholm County are shown in Table 1.

3.2.2. Emissions from water

The water bodies considered in Stockholm County include lakes, stream networks and a coastal portion of the Baltic Sea. All of these are sources of varying strength of GHG emissions to the atmosphere. Table 2 shows the surface area of each type of water body in the county, together with the annual GHG emissions.

Stockholm County contains a large number of freshwater lakes occupying a total area of 627 km^2, or 9.6 % of the total land area. These lakes range in size from small ponds to Lake Mälaren, which is the third largest lake in Sweden, with a total area of 1140 km^2 (Lantmäteriet, 2021). Based on measurements of the properties of water in the lake, Alin and Johnson (2007) estimated emissions from Lake Mälaren to the atmosphere as 0.602 kg CO_2-eq m^{-2} yr^{-1}.

Stockholm County also contains many small rivers and watercourses. We calculated the total area of these stream networks based on national survey maps (Lantmäteriet, 2021). Their total length is 4460 km, and a reported average width of rivers and streams in Stockholm County is 3.5 m (Sers and Degerman, 2016). A previous study found that rivers and streams in Sweden emit between 1.73 and 11.11 kgCO_2-eq m^{-2} yr^{-1}, depending on stream order (Humborg et al., 2010). Studies have shown that streams with Strahler order 1 (classified by Strahler (1957) as streams with no tributaries, often the first streams flowing into a river network) have the highest rates of carbon dioxide emissions to the atmosphere, with emissions per area of stream surface decreasing as stream order increases (Humborg et al., 2010). For the watercourses in Stockholm County, we calculate and used a weight-average value (based on the recorded area of watercourses of each stream order in Sweden) of 6.203 kg CO_2-eq m^{-2} yr^{-1}.

A portion of the Baltic Sea lies within the boundaries of Stockholm County. Reported net annual carbon emissions of 0.010 (+-0.016) kg CO_2-eq m^{-2} yr^{-1} derive from the Baltic Sea. This indicates that this coastal portion is a relatively weak source of carbon to the atmosphere (Kuliński and Pempkowiak, 2011).

3.2.3. Vegetative sequestration

For identifying the various land uses in Stockholm County, we used a land-cover map of the county classified according to the CORINE Land Cover (CLC) system (Kosztra et al., 2019). We assigned each terrestrial land use a carbon sink potential value based on the vegetative land cover (Goldenberg et al., 2018). The carbon sequestration potential values (Table 3) were selected after a search of the available literature. In general, the carbon sequestration potential of vegetation is highly variable and is both time- and region-dependent (Baldocchi et al., 2001; Rayment and Jarvis, 2000). The values in this study (see citations in Table 3) are from studies of vegetation types and growing conditions (such as climate and daylight hours) that are as close as possible to those

Table 1
Stockholm County urban emissions recorded in 2014 and predicted emissions for the year 2045 (TRF - Tillväxt- och Regionplaneförvaltningen, 2016).

Emission source	2014 emissions (10^9 kg CO_2-eq)	2045 emissions (10^9 kg CO_2-eq)
Buildings	2.49	0.5
Transport	2.9	0.25
Industry	0.48	0.2
Total	5.87	0.95

Table 2
Surface area and greenhouse gas (GHG) emissions potential of the various water bodies in Stockholm County.

Water body type	Emissions(kgCO$_2$-eq m^{-2} yr^{-1})	Source
Lakes	0.602	(Alin and Johnson, 2007)
Stream networks	6.203	(Humborg et al., 2010)
Baltic Sea	0.010	(Kuliński and Pempkowiak, 2011)

Table 3
Vegetative carbon sequestration potential of different terrestrial land cover types found in Stockholm County.

Land cover type	Carbon sequestration potential (kgCO$_2$-eq m^{-2} yr^{-1})	Source
Urban fabric – discontinuous structures[a]	0.586	(Christen et al., 2011)
Continuous urban fabric	0	N/A
Other built-on land	0	N/A
Sports and leisure facilities	0.110	(Tidåker et al., 2017)
Non-irrigated arable land	0.088	(Miljömål.se, 2018; Smith et al., 2005)
Pastures	0.183	(Kätterer et al., 2012)
Fruit trees and berry plantations	1.026	(Wu et al., 2012)
Broad-leaf forest	0.652	(Luyssaert et al., 2007)
Mixed forest	0.399	(Luyssaert et al., 2007)
Coniferous forest	0.147	(Luyssaert et al., 2007)
Transitional woodland-shrub	0.022	(Kätterer et al., 2012)
Grassland and sparsely vegetated areas	0.022	(Kätterer et al., 2012)
Inland marshes	1.246	(Nag et al., 2017)
Peat bogs	0.073	(Antle et al., 2001)
Salt marshes	0.769	(Charpentier et al., 2010)

[a] This value is used for areas with only isolated structures; i.e. the land cover is at least 95 % vegetation. The same value was reduced according to the percentage of built-on land for very low-density; low-density; medium-density; and dense discontinuous urban fabric.

prevailing in Stockholm County (for which site-specific vegetation values are not available). All of the values used represent net ecosystem carbon uptake, which includes soil carbon sequestration and the effects of prevailing land management actions for that land use (such as fertilisation and tillage of agricultural land and maintenance of sports grounds).

3.2.4. Modelled future land use changes and sequestration impacts

Since the population in Stockholm County is expected to grow in coming decades, considerable urban development in the future is also likely (SCB, 2016; TRF - Tillväxt- och Regionplaneförvaltningen, 2017). Stockholm County planning department has plans and policies intended to ensure that the necessary development has minimal negative impacts on the environment. In particular, these plans include zoning to encourage compact development and limit sprawl, and protection for many green areas (TRF - Tillväxt- och Regionplaneförvaltningen, 2017). Based on these plans and policies, a previous study modelled probable locations and extent of new development, finding a likely loss of 2.4 % of the total carbon sequestration potential existing in Stockholm County by 2040 (Pan et al., 2020). This value is used here to reduce the 2014 sequestration potential for 2045, proportionally from 2040 (using linear regression), resulting in a predicted loss of 2.86 % of the 2014 carbon sequestration potential by 2045.

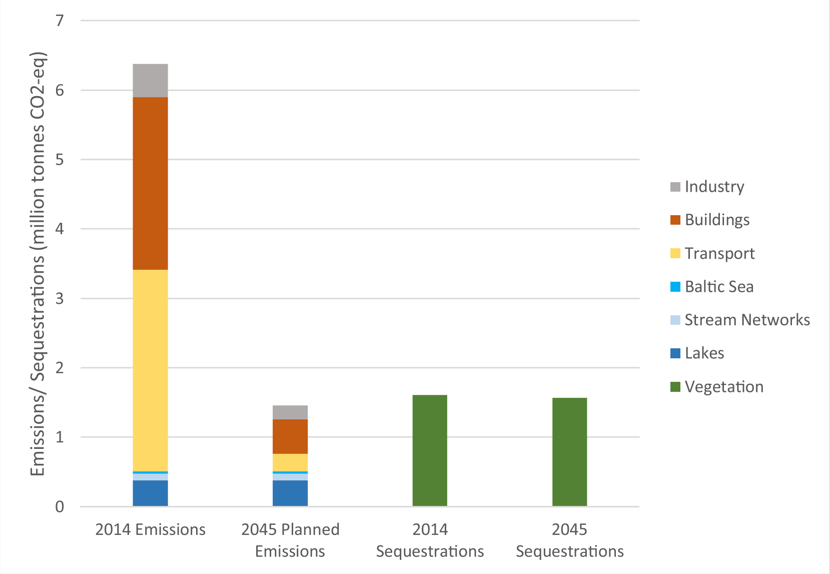

Fig. 3. Measured greenhouse gas emissions and sequestration in Stockholm County in 2014 and predicted values for2045.

4. Results

Fig. 3 shows total emissions and sequestration in Stockholm County in 2014 and in summary, the calculated sequestration for 2014 is 1.61 million tonnes CO_2-eq, whereas the urban emissions are 5.87 million tonnes CO_2-eq, and the combined water emissions are 0.47 million tonnes CO_2-eq. The water emissions are comparable to the 2014 industrial and commercial energy emissions of 0.48 million tonnes CO_2-eq. The predicted urban emissions for 2045 are considerably lower than those in 2014, with a total of just 0.95 million tonnes CO_2-eq. The calculated water emissions remain at 0.47 million tonnes CO_2-eq, and the calculated 2045 sequestration of 1.57 million tonnes CO_2-eq would then suffice to completely offset the expected combined total urban and water emissions in 2045.

4.1. Urban emissions

In 2014, urban emissions amounted to 5.87 million tonnes CO_2-eq, or 2.7 tonnes CO_2-eq per capita, divided as shown in Fig. 3 between the three urban emissions categories (industry, buildings, transport). Stockholm City Council and Stockholm County authorities are committed to reducing emissions in the county to a total of 0.95 million tonnes CO_2-eq by 2045, which is less than 0.5 tonnes CO_2-eq per capita (TRF - Tillväxt- och Regionplaneförvaltningen, 2016). These emissions correspond to the solid arrows labelled “1” in Fig. 1, and represent 92 % of the total in-boundary emissions in 2014, reduced to 65 % in 2045.

4.2. Emissions from inland waters

In total, we estimate that stream networks in Stockholm County emit 96,822 tonnes CO_2-eq to the atmosphere annually, whereas lakes emit 377,538 tonnes CO_2-eq annually (Fig. 3). These water emissions represent 7% of the total in-county emissions in 2014 (see Fig. 1, arrows labelled “2”.) By 2045, these emissions represent a much more significant 32 % of the total in-county emissions, due to the planned reduction of total local urban emissions.

4.3. Emissions from coastal waters

Based on CO_2 emissions values calculated for the entire Baltic Sea (Kuliński and Pempkowiak, 2011), the area of the sea included in Stockholm County emits 36,959 tonnes of CO_2-eq annually to the atmosphere. Despite the large area of seawater contained within county borders, this emission represented only 1% of the total in-county emissions in 2014, and 3% in 2045. Fig. 1 shows these emissions in their systems context, represented by the arrows labelled “2”. Although this value is low compared with emissions from freshwater bodies in the county, the outflow of carbon into the Baltic Sea and subsequent emissions from the sea to the atmosphere should be further investigated.

4.4. Vegetative sequestration

We estimate that vegetation in Stockholm County sequestered 1.61 million tonnes CO_2-eq in 2014 (see Fig. 3). The majority of this sequestration potential (1.18 million tonnes CO_2-eq) came from the large areas of boreo-nemoral forest (containing both deciduous and evergreen trees) in the county. Open urban and suburban green spaces (including gardens, parks, and sports facilities) had a sequestration potential of 0.32 million tonnes CO_2-eq, and the remaining potential came from many different land uses, including agriculture and wetlands. Fig. 4 shows the spatial distribution of the vegetative carbon sequestration potential across Stockholm County and Stockholm City. Based on current plans and policy for

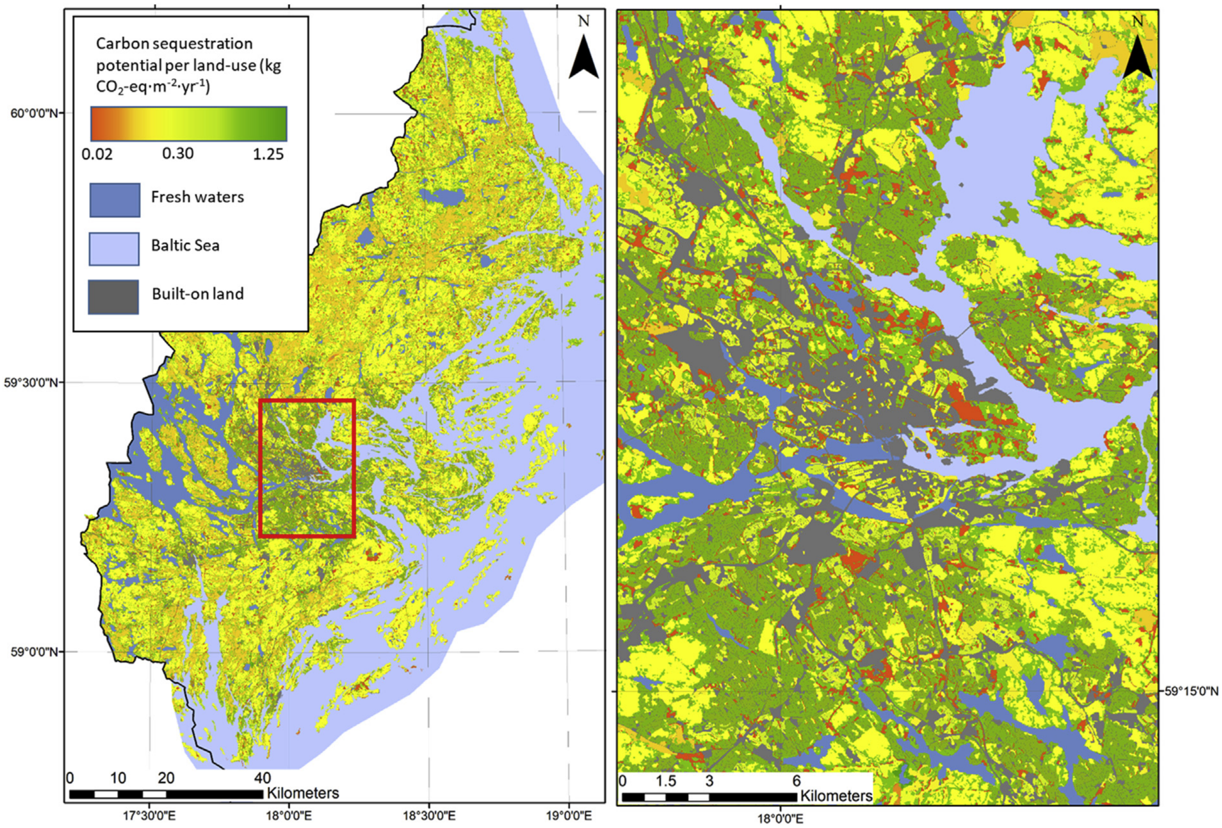

Fig. 4. Maps showing the carbon sequestration potential of terrestrial land cover in Stockholm County (left) and in Stockholm City (right).

urban expansion in Stockholm to house a growing population, a land use model has shown that 2.86 % of sequestration capacity will be lost, resulting in vegetative sequestration of 1.57 million tonnes CO_2-eq by 2045 (Pan et al., 2020).

5. Discussion

5.1. Urban emissions

Although many of the plans to reduce emissions in the county are under implementation, whether the planned reductions in local emissions can actually be achieved is unclear (Länstyrelsen Stockholm, 2020). In fact, a recent report on the GHG budget for Stockholm County from 2020 up to 2040 showed an increase of about 12 % in estimated direct GHG emissions in the county from 2014 to 2019 (Anderson et al., 2018). Of course, this does not mean that the emissions reduction goals is unachievable by 2045.Many of the measures will take years to implement and, while the population in the county has been increasing, per-capita emissions have decreased. It is also possible, however, that other measures beyond those in the County's plan will be necessary to reach local net-neutrality in Stockholm by 2045.

As mentioned above (Section 3.1), these urban emissions are limited almost entirely to the carbon physically emitted within Stockholm County, and exclude emissions associated with goods produced outside county borders. Sweden is a net importer of consumer goods, particularly food and clothing, from outside the country (World Intergrated Trade Solution, 2018). The Swedish Environmental Protection Agency found the 2014 average global and local consumption-based emissions per Swedish resident to be 8.99 tonnes CO_2-eq per capita, compared to the local urban emissions of 2.7 tonnes CO_2-eq per capita found in this study when excluding the consumption of goods (Naturvårdsverket, 2021). The emissions associated with production and transportation of imported goods consumed in Stockholm represent a proportion of the total global emissions caused by the region, and for which its residents are reasonably accountable (Schmidt et al., 2019). Thus, while achievement of the worthy goal of *local* carbon neutrality is possible for Stockholm County by 2045 with current policies, achieving true *global* carbon neutrality for the region will require considerable additional policy, socio-economic and behavioural changes by government, businesses and inhabitants of Stockholm County. This could take place on many levels, from a reduction in consumption by individuals and businesses to changes of consumption behaviours to choose lower-emissions options. Consumption emissions could also be offset through cultivation of increased carbon sinks, both within the region and through international carbon-offset schemes.

5.2. Emissions from inland waters

A global study of large freshwater lakes (>500 km^2) found GHG emissions to range from -0.11 to +2.63 kg CO_2-eq m^{-2} yr^{-1}, with an average of 0.26 kg CO_2-eq m^{-2} yr^{-1} (Alin and Johnson, 2007). A study of lakes in Sweden found that the smallest Swedish lakes (0.01–0.1 km^2) emit 0.32 kg CO_2-eq m^{-2} yr^{-1}, whereas the largest (>100 km^2) emit on average 0.12 kg CO_2-eq m^{-2} yr^{-1} (Humborg et al., 2010). In the global study of large lakes, emissions from Lake Mälaren to the atmosphere were calculated (based on measurements taken in the lake) as 0.60 kg CO_2-eq m^{-2} yr^{-1} (Alin and Johnson, 2007). This emission is considerably higher than the average reported for large (>100 km^2) Swedish lakes (Humborg et al., 2010), and also larger than the values calculated for the other two largest lakes in Sweden, Vättern (0.26 kg CO_2-eq m^{-2} yr^{-1}) and Vänern (0.32 kg CO_2-eq m^{-2} yr^{-1}) (Alin and Johnson, 2007).

The higher emissions from all three large lakes (Mälaren, Vättern and Vänern) than the average for large lakes in Sweden are attributable to their location in the southern half of the country. The vegetation differs from that in northern Sweden and the milder climate in the south means that the lakes are frozen for shorter periods. This difference would be consistent with a global trend of higher emissions from lakes located closer to the equator (Alin and Johnson, 2007; Raymond et al., 2013). Latitude, however, does not explain why the carbon saturation levels, and consequently the emissions from Lake Mälaren, are approximately double those in Lakes Vättern and Vänern, both of which lie (slightly) to the south of Mälaren. The most notable differences between the lakes are that Lake Mälaren is directly connected to the Baltic Sea, with intrusion of salt water occasionally possible (although prevented by sluices), and that it lies in the most populous and urban part of Sweden, while the other two lakes are located in more rural inland parts of the country (Stockholms Stad, 2017). It is unlikely that the connection with the Baltic is the reason for higher carbon levels in Lake Mälaren. In fact, approximately 41 000 tonnes of total organic carbon flow from the lake into the Baltic annually (Institutionen för vatten och miljö, 2018; SMHI, 2020; Stockholms Stad, 2019). Tranvik et al. (2009) showed that human activities significantly influence the contributions of freshwaters to the global carbon cycle. In a recent study of Uppsala County (which neighbours Stockholm County to the north-west and contains a small portion of Lake Mälaren), Wallin et al. (2020) also found that the carbon levels in agricultural streams were higher than expected. Thus, the intensive human activity in and around Lake Mälaren was likely responsible for the elevated levels of carbon in this lake relative to other comparable lakes in Sweden. Consequently, human interactions in the lake's catchment would be a useful intervention point, e.g. for implementing nature-based solutions to better manage urban runoff and other factors contributing to the high levels of carbon in the lake.

5.3. Emissions from coastal waters

A large part of Stockholm County comprises the Stockholm archipelago, with thousands of islands in the Baltic Sea. The Baltic Sea extends inland to the centre of Stockholm City, where it meets Lake Mälaren, with a large flow of freshwater going from the lake to the sea across several sluices. A canal in Södertälje also connects the two water bodies in the south of Stockholm County. The total flow rate from Lake Mälaren to the Baltic Sea can reach 800 m^3 s^{-1}, with an average outflow of about 5000 Mm^3 yr^{-1} (SMHI, 2020; Stockholms Stad, 2019). This outflow and other freshwater runoff throughout the county significantly affect both salinity and nutrient loading (including carbon) to the inner archipelago waters of the Baltic Sea (Engqvist and Andrejev, 2003), i.e. the coastal area included in the system boundaries of this study. During the period 1996–2018, the load of total organic carbon in the outflow from Lake Mälaren to the Baltic, measured at a station in the city centre (Centralbron), was on average 8.2 mg L^{-1} (Institutionen för vatten och miljö, 2018). It is estimated that only around 4% of the total organic carbon is trapped and eventually accumulated in the sediments of the inner Stockholm archipelago. The rest is either re-mineralised (and partly re-released back into the atmosphere) or exported to other parts of the Baltic Sea and eventually the North Sea (Jönsson et al., 2005; Wesslander, 2011).

Wide spatial and temporal variation existis in recorded and calculated GHG emissions from the Baltic Sea. The sea is therefore a sink or a source of GHGs, depending on location, and sometimes in the same place in different years (Wesslander, 2011). Given the evidence of significant carbon outflow into the waters of the

Stockholm archipelago, these waters are potentially significant local sources of GHG to the atmosphere, if the emissions rate in the archipelago is higher than in the rest of the sea. Thus, long-term monitoring of Stockholm archipelago emissions is worthwhile for bridging knowledge gaps and gaining an improved understanding of carbon dynamics in the area.

5.4. The land-water carbon cycle

Applying the SBA approach to quantifying GHG emissions and sequestration in Stockholm County provides new insights into the relationship between vegetative carbon sequestration and carbon emissions from water bodies. A large proportion of the carbon found in water bodies and emitted to the atmosphere as GHGs arrives in the water from the associated hydrological catchment area and its vegetation. Plants use atmospheric CO_2 to build aboveground tissues and roots. A proportion of this plant material falls on the land surface of each hydrological catchment and is decomposed, with dissolved organic carbon eventually transported by subsurface and surface water flow through the catchment outlets into recipient water bodies (Cvetkovic et al., 2012; Destouni et al., 2010; Jantze et al., 2013; Lyon et al., 2010). There, some of it is further re-mineralised and released back into the atmosphere (Cole et al., 2007; Humborg et al., 2010). These waterborne transport and transformation processes can lower the efficiency of vegetative sequestration. In Stockholm County, $\sim 32\,\%$ of the carbon fixed by plants is re-emitted via various water bodies. Improved understanding of these green-blue catchment-water body interactions of carbon is important to achieving net-zero emissions, as a 32 % reduction in efficiency of vegetative sequestration is considerable.

The per-area emissions values used for water bodies in this study are net water-atmosphere GHG fluxes. These fluxes implicitly include the results of internal processes such as the activities of aquatic fauna and flora, and soil-water carbon exchange. A possible future improvement of this methodology lies in including soil explicitly as a separate component in SBA accounting. Although this inclusion may not change the overall net results, further insights may be possible into the land-water carbon cycle, and in understanding how to reduce these re-emissions via water.

5.5. Impact of land use planning and policy on future carbon sinks

The current plans for development in Stockholm County prioritises protection and inclusion of green spaces within and around urban areas. This prioritisation explains why the modelled loss of vegetation is quite small (only 2.86 % of the 2014 sequestration capacity lost by 2045), despite considerable planned development and urban expansion (Pan et al., 2020; TRF - Tillväxt- och Regionplaneförvaltningen, 2017). In other regions, a much greater loss of vegetative sequestration potential might be expected if land use planning policies do not sufficiently protect existing green spaces (Pan et al., 2019).

The SBA analysis evidently shows that Stockholm will be reliant on its forested areas in order to reach carbon-neutrality in the future. Based on the current plans, this goal is achievable. A recent study shows, however, that Europe is losing forest area to harvesting in recent years, with particularly high losses in Sweden (Ceccherini et al., 2020). If this trend prevails in Stockholm County, it will be unable to reduce emissions as far as intended. It will need to consider and include further nature-based solutions to increase carbon sequestration in the county. A strong theme throughout the literature on vegetative carbon sequestration is that the carbon sink potential of green spaces is highly dependent on critical factors, particularly weather conditions and land management (Luyssaert et al., 2007; Mudge et al., 2011; Smith, 2014). Although one cannot control weather, land management such as fertilisation regimes and methods are adjustable to increase carbon sequestration capacity in some green spaces (Guo and Gong, 2017). Changing weather patterns due to climate change is also predictable and planned for to some degree. Studies have shown how changes in mean temperature or precipitation can severely affect forests and their sequestration capacity. Increasing the resilience of forests to changing climate conditions, however, is possible through strategies to increase their biodiversity, which may also lead to increased carbon sequestration capacity (Newton and Cantarello, 2015; Thompson et al., 2009). In the future, vegetative sequestration will play an important role in offsetting emissions to achieve net-zero levels. Therefore, policies and planning for carbon-neutral cities, countries and regions, including Stockholm, should include measures to prevent loss of green areas, and nature-based solutions to increase carbon sink resilience and capacity.

Although Stockholm County's report on climate action planning acknowledges the importance of forests as a carbon sink, the plans for forest areas simply include “afforestation and sustainable forest management” (TRF - Tillväxt- och Regionplaneförvaltningen, 2016). The study by Kaczorowska et al. (2016) of planning for ecosystem services in Stockholm found that, while highly valued by l stakeholders involved in developing the region, a knowledge gap exists specifically on how to plan and make policies to protect and increase ecosystem services in urban areas. Practical knowledge is also lacking in where and how to apply nature-based solutions. Researchers should support policy-makers and planners in overcoming this knowledge gap. They should clearly communicate information about where and how such solutions are implementable to ensure their inclusion toward positive climate action.

5.6. Broader significance of case findings

The application of Stockholm for the SBA methodology yields broader insights into the urban carbon cycle that are globally relevant. The first of these is that water bodies (and particularly inland water bodies) and their integration of carbon from their catchment areas can contribute significantly to GHG emissions. Urban carbon accounting should therefore consider them in places where large water bodies exist in the area, in Stockholm and elsewhere around the world. Furthermore, the test case showed that water emissions become especially significant when striving for net-zero emissions. Carbon re-emissions via water bodies amount to an effective reduction in total vegetative sequestration potential in an accounting area. As many cities globally are striving to reach carbon neutrality in coming decades (Alvarez, 2020; Carbon Neutral Cities Alliance, 2021), consideration of emissions from water is therefore increasingly relevant.

Beyond the accounting questions of “reaching neutrality”, better understanding of urban carbon cycles is important to ultimately reduce the contributions of cities to climate change through GHG emissions to the atmosphere. A better understanding of urban carbon cycles is important in achieving this, as it allows actions better suited to reducing these contributions. In particular, this study reveals several areas in which inclusion of nature-based solutions in planning and policy will facilitate reduction of overall urban GHG emissions. The study shows that, even in famously forested places like Sweden, targeted use of nature-based solutions is important to maintain and improve vegetative sequestration potential to offset those GHG emissions that cannot reduce to absolute zero. It also identifies a need for further studies of GHG emissions from waters specifically in urban regions, and for development of nature-based solutions to reduce anthropogenic emission-related activities.

6. Conclusions

The SBA approach developed and applied to the case of Stockholm County in this paper considers and accounts for human-nature interactions in conducting an inventory of urban GHG emissions and sequestration. The application process and results provide new insights into urban carbon cycling. In particular, they clarify how human activities interact with natural systems in this cycle, and how improvements in planning and policy can help ensure that the urban region will achieve its goal of net-neutrality by 2045.

The answers to the specific research questions posed are as follows. First, inland waters play a very significant role in urban carbon accounting for the Stockholm region. The SBA results show that ~ 29 % of the carbon sequestered by vegetation in the county is re-emitted to the atmosphere via inland water bodies fed by their respective hydrological catchments within the county's boundaries. Second, coastal waters in Stockholm County play a smaller role in the urban carbon cycle, as 3% of the carbon sequestered by vegetation is re-emitted to the atmosphere via coastal waters. Third, the contributions of water bodies to the urban carbon cycle are significant, especially when striving for net-zero emissions. They warrant inclusion in urban carbon accounting in regions that encompass large water bodies, such as Stockholm County.

Stockholm County can achieve its goal of net-zero *local* emissions by 2045 if it succeeds in reducing urban emissions in line with current plans and ensures protection for existing carbon sinks. Since achieving this goal will heavily rely on vegetative sequestration, particularly in forests, ensuring that forests are not lost to harvesting is especially important, as in recent trends, and that they remain resilient to climate change. Maintaining their carbon sequestration capacities through relevant planning and policies is also important, using strategies such as nature-based solutionsto maintain biodiversity. To achieve true global carbon neutrality, Stockholm will also need to consider the emissions related to residents' consumption of goods produced elsewhere and how to reduce and offset these emissions too.

The higher rate of GHG emissions from waters in Stockholm County (particularly Lake Mälaren) suggests further investigations. is The higher rate may be explainable by the large extent of human activity in the catchment of Lake Mälaren and other water bodies in Stockholm, affecting regional green-blue areas and resulting in decreased vegetative sequestration efficiency and increased water emissions. Identifying underlying mechanisms and determining modifications in human interactions with green-blue areas in regional catchments is important to minimise the negative impacts.

The findings of the study further suggest a need for more comprehensive evaluations of the carbon cycling implications of green-blue urban areas in general. Neglecting or underestimating re-emission of vegetative carbon sequestration by recipient water bodies to their catchments may render city-level carbon emissions accounts inaccurate, for example, leading to insufficient planned actions for achievement of carbon neutrality. At the same time, these green-blue areas offer various ecosystem services and opportunities for nature-based solutions in urban areas to mitigate their greenhouse gas emissions, such as greenways and lakeshores used to promote cycling and walking. An important next step in research, therefore, is to evaluate effects of human behaviour on green-blue urban areas and related nature-based potential for mitigating greenhouse gas emissions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Alin, S.R., Johnson, T.C., 2007. Carbon cycling in large lakes of the world: a synthesis of production, burial, and lake-atmosphere exchange estimates. Glob. Biogeochem. Cycles 21 (3) doi:http://dx.doi.org/10.1029/2006GB002881.

Alvarez, D.G., 2020. Mission 100 Climate Neutral Cities by 2030. Available at: https://ec.europa.eu/jrc/communities/en/community/city-science-initiative/document/mission-100-climate-neutral-cities-2030 (accessed 6 November 2020). .

Anderson, K., Schrage, J., Stoddard, I., et al., 2018. Koldioxidbudget för Stockholms län 2020-2040: Del I. Klimatledarskapsnoden, Uppsala University, Sweden Available at: https://www.lansstyrelsen.se/stockholm/tjanster/publikationer/2018/koldioxidbudget-2020-2040-stockholms-lan.html (accessed 22 June 2020).

Andrade, J.C.S., Dameno, A., Pérez, J., et al., 2018. Implementing city-level carbon accounting: a comparison between Madrid and London. J. Clean. Prod. 172, 795–804. doi:http://dx.doi.org/10.1016/j.jclepro.2017.10.163.

Antle, J.M., Apps, M., Beamish, R.J., et al., 2001. Ecosystems and their goods and services. In: McCarthy, J.J., Canziani, O.F., Leary, N.A. (Eds.), Climate Change 2001: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK, pp. 235–342 Available at: https://library.harvard.edu/collections/ipcc/docs/27_WGIITAR_FINAL.pdf (accessed 18 June 2020).

Baldocchi, D., Falge, E., Gu, L., et al., 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull. Am. Meteorol. Soc. 82 (11), 2415–2434. doi:http://dx.doi.org/10.1175/1520-0477(2001)082<2415:FANTTS>2.3.CO;2.

Baró, F., Gómez-Baggethun, E., et al., 2017. Assessing the potential of regulating ecosystem services as nature-based solutions in urban areas. In: Kabisch, N., Korn, H., Stadler, J. (Eds.), Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice. Theory and Practice of Urban Sustainability Transitions. Springer International Publishing, Cham, pp. 139–158. doi:http://dx.doi.org/10.1007/978-3-319-56091-5_9.

Borja, S., Kalantari, Z., Destouni, G., 2020. Global wetting by seasonal surface water over the last decades. Earth's Future 8 (3) e2019EF001449 doi:http://dx.doi.org/10.1029/2019EF001449.

Carbon Neutral Cities Alliance, 2021. Carbon Neutral Cities Alliance Members. (n.d.) Available at: https://carbonneutralcities.org/cities/ (accessed 6 November 2020). .

Ceccherini, G., Duveiller, G., Grassi, G., et al., 2020. Abrupt increase in harvested forest area over Europe after 2015. Nature 583 (7814), 72–77. doi:http://dx.doi.org/10.1038/s41586-020-2438-y.

Charpentier, M., Wigand, C., Hyman, J., 2010. Estimates of Carbon Sequestration in Tidal Coastal Wetlands along the US East Coast. Available at: https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NHEERL&dirEntryId=230134 (accessed 18 June 2020). .

Christen, A., Coops, N.C., Crawford, B.R., et al., 2011. Validation of modeled carbon-dioxide emissions from an urban neighborhood with direct eddy-covariance measurements. Atmos. Environ. 45 (33), 6057–6069. doi:http://dx.doi.org/10.1016/j.atmosenv.2011.07.040.

Churkina, G., 2008. Modeling the carbon cycle of urban systems. Ecol. Modell. 216 (2), 107–113. doi:http://dx.doi.org/10.1016/j.ecolmodel.2008.03.006 Special Issue dedicated to the memory of Yuri Svirezhev.

Cohen-Shacham, E., Walters, G., Janzen, C., et al. (Eds.), 2016. Nature-Based Solutions to Address Global Societal Challenges. IUCN International Union for Conservation of Nature doi:http://dx.doi.org/10.2305/IUCN.CH.2016.13.en.

Cole, J.J., Priarie, Y.T., Caraco, N.F., et al., 2007. Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget | SpringerLink. Ecosystems 10 (1), 172–185. doi:http://dx.doi.org/10.1007/s10021-006-9013-8.

Cvetkovic, V., Carstens, C., Selroos, J.-O., et al., 2012. Water and solute transport along hydrological pathways. Water Resour. Res. 48 (6) doi:http://dx.doi.org/10.1029/2011WR011367.

Destouni, G., Persson, K., Prieto, C., et al., 2010. General quantification of catchment-scale nutrient and pollutant transport through the subsurface to surface and coastal waters. Environ. Sci. Technol. 44 (6), 2048–2055. doi:http://dx.doi.org/10.1021/es902338y.

Díaz, S., Hector, A., Wardle, D.A., 2009. Biodiversity in forest carbon sequestration initiatives: not just a side benefit. Curr. Opin. Environ. Sustain. 1 (1), 55–60. doi:http://dx.doi.org/10.1016/j.cosust.2009.08.001.

Duren, R.M., Miller, C.E., 2012. Measuring the carbon emissions of megacities. Nat. Clim. Change 2 (8), 560–562. doi:http://dx.doi.org/10.1038/nclimate1629.

Dybala, K.E., Matzek, V., Gardali, T., et al., 2019. Carbon sequestration in riparian forests: a global synthesis and meta-analysis. Glob. Change Biol. 25 (1), 57–67. doi:http://dx.doi.org/10.1111/gcb.14475.

Edmondson, J.L., Davies, Z.G., McHugh, N., et al., 2012. Organic carbon hidden in urban ecosystems. Sci. Rep. 2 (1), 1–7. doi:http://dx.doi.org/10.1038/srep00963.

Engqvist, A., Andrejev, O., 2003. Water exchange of the Stockholm archipelago—a cascade framework modelling approach. J. Sea Res. 49 (4), 275–294. doi:http://dx.doi.org/10.1016/S1385-1101(03)00023-6 Proceedings of the 22nd Conference of the Baltic Oceanographers (CBO), Stockholm 2001.

Fang, C., Wang, S., Li, G., 2015. Changing urban forms and carbon dioxide emissions in China: a case study of 30 provincial capital cities. Appl. Energy 158, 519–531. doi:http://dx.doi.org/10.1016/j.apenergy.2015.08.095.

Fong, W.K., Sotos, M., Doust, M., et al., 2014. Global Protocol for Community-Scale Greenhouse Gas Emission Inventories. World Resources Institute, USA Available at: https://ghgprotocol.org/greenhouse-gas-protocol-accounting-reporting-standard-cities (accessed 14 June 2020).

Freibauer, A., Rounsevell, M.D.A., Smith, P., et al., 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122 (1), 1–23. doi:http://dx.doi.org/10.1016/j.geoderma.2004.01.021.

Goldenberg, R., Kalantari, Z., Destouni, G., 2018. Increased access to nearby green–blue areas associated with greater metropolitan population well-being. Land Degrad. Dev. 29 (10), 3607–3616. doi:http://dx.doi.org/10.1002/ldr.3083.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Glob. Change Biol. 8 (4), 345–360. doi:http://dx.doi.org/10.1046/j.1354-1013.2002.00486.x.

Guo, J., Gong, P., 2017. The potential and cost of increasing forest carbon sequestration in Sweden. J. For. Econ. 29, 78–86. doi:http://dx.doi.org/10.1016/j.jfe.2017.09.001.

Humborg, C., Mörth, C.-M., Sundbom, M., et al., 2010. CO2 supersaturation along the aquatic conduit in Swedish watersheds as constrained by terrestrial respiration, aquatic respiration and weathering. Glob. Change Biol. 16 (7), 1966–1978. doi:http://dx.doi.org/10.1111/j.1365-2486.2009.02092.x.

Institutionen för vatten och miljö, 2018. Station vattenkemi. Available at: http://info1.ma.slu.se/ma/www_ma.acgi$Station?ID=Intro&S=1447 (accessed 16 April 2020). .

IPCC - The Intergovernmental Panel on Climate Change, 2006. In: Eggelston, S., Buendia, L., Miwa, K. (Eds.), 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies (IGES), Japan Available at: https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ (accessed 15 June 2020).

Jantze, E.J., Lyon, S.W., Destouni, G., 2013. Subsurface release and transport of dissolved carbon in a discontinuous permafrost region. Hydrol. Earth Syst. Sci. 17 (10), 3827–3839. doi:http://dx.doi.org/10.5194/hess-17-3827-2013.

Jönsson, A., Lindström, M., Carman, R., et al., 2005. Evaluation of the Stockholm Archipelago sediments, northwestern Baltic Sea Proper, as a trap for freshwater runoff organic carbon. J. Mar. Syst. 56 (1), 167–178. doi:http://dx.doi.org/10.1016/j.jmarsys.2004.11.001.

Kaczorowska, A., Kain, J.-H., Kronenberg, J., et al., 2016. Ecosystem services in urban land use planning: integration challenges in complex urban settings—case of Stockholm. Ecosyst. Serv. 22, 204–212. doi:http://dx.doi.org/10.1016/j.ecoser.2015.04.006.

Kalantari, Z., Santos Ferreira, C.S., Page, J., et al., 2019a. Meeting sustainable development challenges in growing cities: coupled social-ecological systems modeling of land use and water changes. J. Environ. Manage. 245, 471–480. doi:http://dx.doi.org/10.1016/j.jenvman.2019.05.086.

Kalantari, Z., Ferreira, C.S.S., Deal, B., et al., 2019b. Nature-based solutions for meeting environmental and socio-economic challenges in land management and development. Land Degrad. Dev. 1–4 doi:http://dx.doi.org/10.1002/ldr.3264 (n/a).

Kätterer, T., Bolinder, M.A., Berglund, K., et al., 2012. Strategies for carbon sequestration in agricultural soils in northern Europe. Acta Agriculturae Scandinavica Sect. A Anim. Sci. 62 (4), 181–198. doi:http://dx.doi.org/10.1080/09064702.2013.779316.

Kennedy, S., Sgouridis, S., 2011. Rigorous classification and carbon accounting principles for low and Zero Carbon Cities. Energy Policy 39 (9), 5259–5268. doi:http://dx.doi.org/10.1016/j.enpol.2011.05.038.

Kosztra, B., Büttner, G., Hazeu, G., et al., 2019. Updated CLC Illustrated Nomenclature Guidelines. European Environment Agency, Austria 10 May. Available at: https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/docs/pdf/CLC2018_Nomenclature_illustrated_guide_20190510.pdf (accessed 22 June 2020).

Kuliński, K., Pempkowiak, J., 2011. The carbon budget of the Baltic Sea. Biogeosciences 8 (11), 3219–3230. doi:http://dx.doi.org/10.5194/bg-8-3219-2011.

Landschützer, P., Gruber, N., Bakker, D.C.E., et al., 2014. Recent variability of the global ocean carbon sink. Glob. Biogeochem. Cycles 28 (9), 927–949. doi:http://dx.doi.org/10.1002/2014GB004853.

Länstyrelsen Stockholm, 2020. När vi miljömålen? Available at: https://www.lansstyrelsen.se/stockholm/miljo-och-vatten/energi-och-klimat.html (accessed 22 June 2020). .

Lantmäteriet, 2021. Öppna Data. (n.d.) Available at: https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/oppna-data (accessed 4 February 2020). .

Le Quéré, C., Peters, G.P., Andres, R.J., et al., 2014. Global carbon budget 2013. Earth Syst. Sci. Data 6 (1), 235–263. doi:http://dx.doi.org/10.5194/essd-6-235-2014.

Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric. Ecosyst. Environ. 139 (1), 224–231. doi:http://dx.doi.org/10.1016/j.agee.2010.08.006.

Luyssaert, S., Inglima, I., Jung, M., et al., 2007. CO2 balance of boreal, temperate, and tropical forests derived from a global database. Glob. Change Biol. 13 (12), 2509–2537. doi:http://dx.doi.org/10.1111/j.1365-2486.2007.01439.x.

Lyon, S.W., Mörth, M., Humborg, C., et al., 2010. The relationship between subsurface hydrology and dissolved carbon fluxes for a sub-arctic catchment. Hydrol. Earth Syst. Sci. 14 (6), 941–950. doi:http://dx.doi.org/10.5194/hess-14-941-2010.

Marcotullio, P.J., Sarzynski, A., Albrecht, J., et al., 2014. A top-down regional assessment of urban greenhouse gas emissions in Europe. AMBIO 43 (7), 957–968. doi:http://dx.doi.org/10.1007/s13280-013-0467-6.

Melaku Canu, D., Ghermandi, A., Nunes, P.A.L.D., et al., 2015. Estimating the value of carbon sequestration ecosystem services in the Mediterranean Sea: an ecological economics approach. Glob. Environ. Change 32, 87–95. doi:http://dx.doi.org/10.1016/j.gloenvcha.2015.02.008.

Miljömål.se, 2018. Dataunderlag – Åkermark. Available at: http://www.miljomal.se/Miljomalen/Alla-indikatorer/Indikatorsida/Dataunderlag-for-indikator/?iid=1&pl=2&t=Lan&l=1 (accessed 22 October 2018). .

Mudge, P.L., Wallace, D.F., Rutledge, S., et al., 2011. Carbon balance of an intensively grazed temperate pasture in two climatically contrasting years. Agric. Ecosyst. Environ. 144 (1), 271–280. doi:http://dx.doi.org/10.1016/j.agee.2011.09.003.

Nag, S.K., Liu, R., Lal, R., 2017. Emission of greenhouse gases and soil carbon sequestration in a riparian marsh wetland in central Ohio. Environ. Monit. Assess. 189 (11), 580. doi:http://dx.doi.org/10.1007/s10661-017-6276-9.

Naturvårdsverket, 2021. Konsumtionsbaserade växthusgasutsläpp per person och år. Available at: https://www.naturvardsverket.se/Sa-mar-miljon/Statistik-A-O/Vaxthusgaser-konsumtionsbaserade-utslapp-per-person/ (accessed 26 March 2021). .

Newton, A.C., Cantarello, E., 2015. Restoration of forest resilience: an achievable goal? New For. 46 (5), 645–668. doi:http://dx.doi.org/10.1007/s11056-015-9489-1.

Page, J., Mörtberg, U., Destouni, G., et al., 2020. Open-source Planning Support System for Sustainable Regional Planning: a Case Study of Stockholm County. Environment and Planning B: Urban Analytics and City Science, Sweden.

Pan, H., Deal, B., Destouni, G., et al., 2018. Sociohydrology modeling for complex urban environments in support of integrated land and water resource management practices. Land Degrad. Dev. 29 (10), 3639–3652. doi:http://dx.doi.org/10.1002/ldr.3106.

Pan, H., Page, J., Zhang, L., et al., 2019. Using comparative socio-ecological modeling to support Climate Action Planning (CAP). J. Clean. Prod. 232, 30–42. doi:http://dx.doi.org/10.1016/j.jclepro.2019.05.274.

Pan, H., Page, J., Zhang, L., et al., 2020. Understanding interactions between urban development policies and GHG emissions: a case study in Stockholm Region. Ambio 49 (7), 1313–1327. doi:http://dx.doi.org/10.1007/s13280-019-01290-y.

Pichler, P.-P., Zwickel, T., Chavez, A., et al., 2017. Reducing urban greenhouse gas footprints. Sci. Rep. 7 (1), 14659. doi:http://dx.doi.org/10.1038/s41598-017-15303-x.

Rayment, M.B., Jarvis, P.G., 2000. Temporal and spatial variation of soil CO2 efflux in a Canadian boreal forest. Soil Biol. Biochem. 32 (1), 35–45. doi:http://dx.doi.org/10.1016/S0038-0717(99)00110-8.

Raymond, P.A., Hartmann, J., Lauerwald, R., et al., 2013. Global carbon dioxide emissions from inland waters. Nature 503 (7476), 355–359. doi:http://dx.doi.org/10.1038/nature12760.

SCB, 2016. The Future Population of Sweden 2016–2060. Available at: http://www.scb.se/en/finding-statistics/statistics-by-subject-area/population/population-projections/population-projections/pong/publications/the-future-population-of-sweden-20162060/ (accessed 4 February 2020). .

Schmidt, S., Södersten, C.-J., Wiebe, K., et al., 2019. Understanding GHG emissions from Swedish consumption - Current challenges in reaching the generational goal. J. Clean. Prod. 212, 428–437. doi:http://dx.doi.org/10.1016/j.jclepro.2018.11.060.

Sers, B., Degerman, E., 2016. Elfiske i Stockholms län 2002-2014 Utvärdering av elfiske i 25 kustmynnande vattendrag. Länsstyrelsen i Stockholm, Stockholm Available at: www.lansstyrelsen.se/stockholm/publikationer (accessed 22 June 2020).

SMHI, 2020. Fakta om Mälaren. SMHI Available at: https://www.smhi.se/kunskapsbanken/hydrologi/fakta-om-malaren-1.5089 (accessed 16 April 2020).

Smith, P., 2008. Land use change and soil organic carbon dynamics. Nutr. Cycl. Agroecosyst. 81 (2), 169–178. doi:http://dx.doi.org/10.1007/s10705-007-9138-y.

Smith, P., 2014. Do grasslands act as a perpetual sink for carbon? Glob. Change Biol. 20 (9), 2708–2711. doi:http://dx.doi.org/10.1111/gcb.12561.

Smith, P., Andrén, O., Karlsson, T., et al., 2005. Carbon sequestration potential in European croplands has been overestimated. Glob. Change Biol. 11 (12), 2153–2163. doi:http://dx.doi.org/10.1111/j.1365-2486.2005.01052.x.

Stockholms Stad, 2016. Strategy for a Fossil-fuel Free Stockholm by 2040 Available at:. City Executive Office, Stockholm. https://international.stockholm.se/globalassets/rapporter/strategy-for-a-fossil-fuel-free-stockholm-by-2040.pdf.

Stockholms Stad, 2017. Översvämningsriskerna i Mälaren - Stockholm växer. Available at: https://vaxer.stockholm/projekt/slussen/slussen-klimatanpassas/ (accessed 15 June 2020). .

Stockholms Stad, 2019. Utflödet från Mälaren - Stockholms miljöbarometer. Available at: http://miljobarometern.stockholm.se/klimat/klimat-och-vaderstatistik/utflodet-fran-malaren/linjar-trend/ (accessed 16 April 2020). .

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Eos Trans. Am. Geophys. Union 38 (6), 913–920. doi:http://dx.doi.org/10.1029/TR038i006p00913.

Thompson, I., Mackey, B., McNulty, S., et al., 2009. Forest Resilience, Biodiversity, and Climate Change. Secretariat of the Convention on Biological Diversity, Montreal, pp. 1–67 Technical Series no. 43. 1-67. 43.

Tidåker, P., Wesström, T., Kätterer, T., 2017. Energy use and greenhouse gas emissions from turf management of two Swedish golf courses. Urban For. Urban Green. 21, 80–87. doi:http://dx.doi.org/10.1016/j.ufug.2016.11.009.

Tranvik, L.J., Downing, J.A., Cotner, J.B., et al., 2009. Lakes and reservoirs as regulators of carbon cycling and climate. Limnol. Oceanogr. 54 (6part2), 2298–2314. doi:http://dx.doi.org/10.4319/lo.2009.54.6_part_2.2298.

TRF - Tillväxt- och Regionplaneförvaltningen, 2016. Klimatarbetet i Stockholmsregionen. TRN 2016-0082. Stockholms Läns Landsting, Stockholm Available at: http://www.rufs.se/globalassets/h.-publikationer/2018/klimatarbetet-i-stockholmsregionen.pdf/ (accessed 11 June 2020).

TRF - Tillväxt- och Regionplaneförvaltningen, 2017. Regional Utvecklingsplan För Stockholmsregionen (RUFS) 2050. Available at: http://www.rufs.se/publikationer/2018/rufs-2050/ (accessed 4 February 2020). .

Ťupek, B., Zanchi, G., Verkerk, P.J., et al., 2010. A comparison of alternative modelling approaches to evaluate the European forest carbon fluxes. For. Ecol. Manage. 260 (3), 241–251. doi:http://dx.doi.org/10.1016/j.foreco.2010.01.045.

United Nations, 2015. The Paris Agreement. Available at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed 1 July 2020). .

Vaccari, F.P., Gioli, B., Toscano, P., et al., 2013. Carbon dioxide balance assessment of the city of Florence (Italy), and implications for urban planning. Landsc. Urban Plan. 120, 138–146. doi:http://dx.doi.org/10.1016/j.landurbplan.2013.08.004.

Wesslander, K., 2011. The Carbon Dioxide System in the Baltic Sea Surface Waters Available at:. . https://www.baltex-research.eu/baltic-c/downloads/Karin%20Wesslander%20Ph%20D%20summary%202011.pdf.

West, T.O., Marland, G., 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91 (1), 217–232. doi:http://dx.doi.org/10.1016/S0167-8809(01)00233-X.

World Intergrated Trade Solution, 2018. Sweden Product Exports and Imports 2018. WITS Data. Available at: https://wits.worldbank.org/CountryProfile/en/Country/SWE/Year/LTST/TradeFlow/EXPIMP/Partner/WLD/Product/All-Groups (accessed 28 October 2020). .

Wu, T., Wang, Y., Yu, C., et al., 2012. Carbon sequestration by fruit trees - chinese apple orchards as an example. PLoS One 7 (6) e38883 doi:http://dx.doi.org/10.1371/journal.pone.0038883.

Xu, C., Haase, D., Su, M., et al., 2019. The impact of urban compactness on energy-related greenhouse gas emissions across EU member states: population density vs physical compactness. Appl. Energy 254, 113671 doi:http://dx.doi.org/10.1016/j.apenergy.2019.113671.

Zhu, K., Song, Y., Qin, C., 2019. Forest age improves understanding of the global carbon sink. Proc. Natl. Acad. Sci. 116 (10), 3962. doi:http://dx.doi.org/10.1073/pnas.1900797116.

Zirkle, G., Lal, R., Augustin, B., 2011. Modeling carbon sequestration in home lawns. HortScience 46 (5), 808–814. doi:http://dx.doi.org/10.21273/HORTSCI.46.5.808.