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Sustainable Urban and Regional Development and Related Ecosystem Services and Water-Climate Interactions

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Doctoral Thesis in Physical Geography at Stockholm University, Sweden 2023

Sustainable Urban and Regional Development and Related Ecosystem Services and Water-Climate Interactions

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Abstract

To accommodate a growing global population while mitigating climate change, urban areas must grow while minimising environmental impacts. To achieve this, a city must be treated as a complex socio-ecological system in which many actors and subsystems act in unclear and unpredictable ways. This thesis explores the workings and interactions of this complex socio-ecological system by assessing how urban and regional planning and policy decisions affect the contributions of cities to climate change, and whether appropriate planning and policy tools can minimise these contributions. Computer models were developed to investigate and couple planning and policy decisions and their potential impacts on the environment, particularly in terms of greenhouse gas (GHG) emissions to the atmosphere. The models were then employed for generation of scientific knowledge and for converting this knowledge into practical planning tools and recommendations.

Methods used in developing models that reflect complex urban systems included cooperation with experienced county planners to improve model accuracy; coupling of sub-system models in a socio-ecological framework for scenario analysis of the outcomes of planning and policy decisions in terms of GHG emissions; systems breakdown analysis of green-blue contributions to the urban carbon cycle; and modelling to identify how these contributions could be harnessed to reduce net urban emissions. The main study area was Stockholm County, Sweden, with later extension of the modelling approach to 54 major European cities.

Cooperation with Stockholm County planners during model development resulted in an improved tool for scientific research that was also suited to practical planning, increasing the potential for knowledge developed through scientific research to be applied in reality. Scenario analysis of policies for Stockholm County revealed that zoning reduced the extra GHG emissions associated with necessary urban growth by 72% compared with a baseline scenario. Analysis of the urban carbon cycle in Stockholm County showed that vegetative carbon sequestration helped offset GHG emissions locally, but that re-emissions via surface waters compromised the potential to reach ‘net-zero’ emissions from Stockholm County. However, climate action goals for Stockholm could still be achieved if its ambitious emissions reduction plans are realised and if the current sequestration capacity of Stockholm County’s many green areas can be maintained in coming decades.

Extensive modelling of urban emissions in multiple European cities showed potential for green-space sequestration and revealed that nature-based solutions (NbS) applied at city scale could help reduce urban emissions. Incorporation of NbS into climate action plans for these cities would maximise the associated GHG emissions reduction and increase the likelihood of the cities achieving their climate action goals.

In conclusion, the climate change impacts of future urban expansion could be mitigated by incorporating planning and policy tools such as zoning, protection of green-blue spaces and NbS into whole-system urban and regional development plans. This could bring cities closer to achieving truly sustainable urban development.

Keywords: *urban planning, regional planning, sustainable cities, nature-based solutions, climate change, planning support systems, sustainable development.*

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In conclusion, the climate change impacts of future urban expansion could be mitigated by incorporating planning and policy tools such as zoning, protection of green-blue spaces and NbS into whole-system urban and regional development plans. This could bring cities closer to achieving truly sustainable urban development.

Sammanfattning

För att göra plats för en växande befolkning och samtidigt hantera klimatförändringarnas utmaningar måste stadsområden växa hållbart samtidigt som miljöpåverkan minimeras. För att uppnå detta måste en stad behandlas som ett komplext socioekologiskt system där många aktörer och delsystem agerar på oklara och oförutsägbara sätt. I denna avhandling undersökte vi hur detta komplexa socio-ekologiska system fungerar och interagerar genom att bedöma hur stads- och regional planering och politiska beslut påverkar städernas bidrag till klimatförändringen, och om lämpliga planerings- och policyverktyg kan minimera dessa bidrag. Datormodeller utvecklades för att undersöka och koppla samman planering och politiska beslut och deras potentiella påverkan på miljön, särskilt när det gäller utsläpp av växthusgaser till atmosfären. Modellerna användes sedan för att generera vetenskaplig kunskap och omvandla denna kunskap till praktiska planeringsverktyg och rekommendationer.

Följande metoder användes för att utveckla modeller av komplexa stadssystem i samarbete med erfarna stads- och regionsplanerare för att förbättra modellens noggrannhet; koppling av delsystemsmodeller i ett socioekologiskt ramverk för scenarioanalys av resultaten av planering och policybeslut i termer av växthusgasutsläpp; systemnedbrytningsanalys av grön-blå bidrag till den urbana kolcykeln; och modellering för att identifiera hur grön-blå bidrag kan utnyttjas för att minska nettoutsläppen från städer. Det huvudsakliga studieområdet var Stockholms län, Sverige, och senare utvidgades modelleringsmetoden till 54 europeiska städer.

Samarbetet med Stockholms läns planerare under modellutvecklingen resulterade i ett förbättrat verktyg för vetenskaplig forskning som också lämpade sig för praktisk planering, vilket ökade potentialen för att den vetenskapliga kunskap som utvecklats kommer att tillämpas i verkligheten. Scenarieanalys av policyer för Stockholms län visade att zonindelning minskade de extra växthusgasutsläppen i samband med nödvändig stadstillväxt med 72 % jämfört med ett basscenario. Analys av den urbana kolcykeln i Stockholms län visade att vegetativ kolbindning hjälpte till att kompensera för växthusgasutsläpp lokalt, medan kolet frigörs igen via vatten vilket minskade potentialen att nå "netto-noll"-utsläpp från Stockholms stad. Klimatmålen för Stockholm skulle fortfarande kunna uppnås om dessa ambitiösa utsläppsminskningsplaner förverkligas och om den nuvarande kollagringskapaciteten av Stockholms läns många grönområden kan bibehållas under kommande decennier.

Omfattande modellering av utsläpp från städer i flera europeiska städer visade på potential för kolinlagring i grönområden och visade att naturbaserade lösningar (NbS) som tillämpas på stadsnivå kan bidra till att minska utsläppen från städer. Att integrera NbS i klimatplaner för dessa städer skulle kunna maximera minskningen av växthusgasutsläppen och öka sannolikheten för att städerna når sina klimatåtgärdsmål.

Sammanfattningsvis skulle klimatförändringarnas effekter av framtida stadsexpansion kunna minskas genom att integrera planerings- och policyverktyg som zonindelning, skydd av grön-blå områden och NbS i stads- och regionalutvecklingsplaner. Detta skulle kunna föra städer närmare att uppnå en verkligt hållbar stadsutveckling.

Dissertation content

This doctoral compilation dissertation consists of a summarising text and the four articles listed below.

I **Page J**, Mörtberg U, Destouni G, Ferreira CSS, Näsström H, Kalantari Z. 2020. Open-source planning support systems for sustainable regional planning: A case study of Stockholm County, Sweden. *Environment and Planning B: Urban Analytics and City Science*, 47(8), pp. 1508–1523. doi: 10.1177/2399808320919769.

II Pan H, **Page J**, Zhang L, Cong C, Ferreira CSS, Kåresdotter E, Näsström H, Destouni G, Kalantari Z. 2020. Understanding interactions between urban development policies and GHG emissions: A case study in Stockholm Region. *Ambio*, 49, pp. 1313–1327. doi: 10.1007/s13280-019-01290-y.

III **Page J**, Kåresdotter E, Destouni G, Pan H, Kalantari Z. 2021. A more complete accounting of greenhouse gas emissions and sequestration in urban landscapes. *Anthropocene*, 34, 100296. doi: 10.1016/j.ancene.2021.100296.

IV Pan H, **Page J**, Shi R, Cong C, Cai Z, Barthel S, Thollander P, Colding J, Kalantari Z, 2023. Potential contribution of prioritized spatial allocation of nature-based solutions to climate neutrality in major EU cities. *[Manuscript]*. doi: 10.21203/rs.3.rs-2399348/v1

Supplementary material to Paper IV

Author contributions

The contributions from listed authors are divided as follows for each article.

I JP led the review of the literature; acquired data from the planning department at Region Stockholm with help from HN; processed the data for the model update; led the update of the LEAM model with help from the LEAM team at the University of Illinois (including HP); led the presentation and discussions on the LEAM model with planners at Stockholm County before, during and after the update, together with ZK and UM; produced the model results, performed comparisons with the official regional development plan for Stockholm (Regional Utvecklingsplan För Stockholm, RUFS 2050) and the analysis; and prepared all diagrams for the paper. All co-authors assisted in writing the final version of the manuscript.

II JP acquired and processed all data used in modelling, with assistance from EK for the carbon sequestration mapping; HP produced the model results together with CC; JP analysed the model results together with HP; JP provided, translated and interpreted all policy and planning documents for the case study with help from HN. HP led the writing of the paper and coordinated contributions from co-authors. JP led the writing for portions of the paper; assisted with the writing throughout; and produced Figure 1. The study and related methods were designed by HP, JP, ZK and CC. All co-authors assisted in writing the final version of the manuscript.

III JP led the modelling and analysis of results; led data acquisition and processing, assisted by EK for the carbon sequestration mapping; reviewed the literature; and led the writing. The study and related methods were designed by JP, ZK and GD. All co-authors assisted in writing the final version of the manuscript.

IV JP identified the research gap and proposed the study; acquired and processed all data used in land use and greenhouse gas (GHG) modelling with help from RS; led the data and methodology research and literature review for the land use and GHG portions of the study and assisted with the nature-based solutions (NbS) portion; and led the implementation of GHG distribution modelling with help from CC. CC and ZC led the NbS and climate action contribution portions, respectively. HP led the writing and coordinated contributions from the co-authors. JP led the writing for portions of the paper and assisted with the writing throughout. All co-authors assisted in writing the final version of the manuscript. The idea was developed and related methods were designed by JP, HP, ZK, SB and CC.

Contents

Abbreviations

CO_2-eq	Carbon dioxide equivalents
EU	European Union
FUA	Functional urban area
GHG	Greenhouse gas
GID	Global Infrastructure Emissions Database
LEAM	The Land-use Evolution and impact Assessment Model
LUC	Land use change
Mt	Megatonne (1 million tonnes = 10^9 kilograms)
MZ	Mitigation zoning
NbS	Nature-based solutions
PSS	Planning Support System
RUFS 2050	*Regional Utvecklingsplan För Stockholmsregionen* (Regional development plan for Stockholm for 2050)
SDG	Sustainable development goal

1 Introduction

Cities are complex socio-ecological systems in which many actors and subsystems act in ways that are not always easy to understand or predict Bettencourt (2021).To meet the dual challenges of accommodating a growing global population and mitigating climate change, urban areas must grow sustainably, which includes minimising impacts on the environment. This duality is apparent in efforts to achieve the United Nations Sustainable Development Goals (SDGs), as conflicts often arise when multiple SDGs are pursued simultaneously. In a growing city, there is a pressing need to provide people with clean water, energy and infrastructure, and decent work opportunities and economic growth (SDGs 6, 7, 9 and 8, respectively), while also seeking to reduce the negative impacts of the city on the natural environment (SDGs 14 and 15) and its contributions to climate change (SDG 13) (United Nations Development Programme, 2023). In order to balance these goals so that growth and development of a city can occur with minimal negative environmental impacts, it is first necessary to understand how urban social systems operate, how various ecological systems function and how they all interact with one another.

The aim in this thesis was to learn more about the workings and interactions of these systems, in particular regarding how urban socio-ecological systems contribute to climate change and how cities can maintain human wellbeing and provide for growing populations while minimising current and future contributions to global warming and other climate change. Climate change mitigation primarily requires a reduction in global greenhouse gas (GHG) emissions and many countries and cities have committed to becoming ‘carbon-neutral’ in coming decades, e.g. as part of the Paris Agreement (United Nations, 2015). However, achieving carbon neutrality in urban systems is complex and challenging. For example, it requires a good understanding of carbon dynamics in urban ecosystems, including process-level identification and distinction of natural and human-perturbed carbon exchanges and their interactions, and of how cities grow and develop. Both sides of this complex socio-ecological problem are addressed in this thesis by examining how a city grows and can be shaped with planning and policy tools, by analysing the urban carbon cycle and by assessing how knowledge in these two areas can be combined and applied to devise strategies for use in urban and regional planning.

1.1 Research Questions, Aims, and Objectives

In this thesis, we investigated a number of research questions. These questions and their accompanying hypotheses are summarised here:

- Can the participation of the intended users in the development and adaptation of a planning support system (PSS) help overcome barriers to its use in planning practice? The hypothesis for this question was that the participatory model development process will result in a tool which is better suited for use in practical planning, and therefore more likely to be used in that context (Paper I).

- What are the impacts of the land use changes associated with building and transport development on net GHG emissions in an urban region? The hypothesis here was that urban development will lead to increased GHG emissions, but the degree of this eventual increase will be linked to the location and form of that development (Paper II).
- Can socio-ecological modelling be used to design a policy strategy which is likely to result in reduced future GHG emissions from an urban region? For this question, the hypothesis was that using scenario modelling to test the impacts of different zoning policies on GHG emissions will reveal the policy strategy which will result in the smallest possible increase in GHG emissions through urban development (Paper II).
- What is the role of fresh- and coastal water bodies in urban carbon cycles, and is this significant enough to warrant their inclusion in carbon accounting for urban regions? Here, the hypothesis was that fresh waters will play a significant role in the urban carbon cycle as sources of GHGs to the atmosphere, while coastal waters could also play a smaller role locally. The degree of significance of these roles, and therefore whether or not they should be included in carbon accounting will depend on the extent of the various water bodies in the urban region in question (Paper III).
- Can nature-based solutions (NbS) contribute significantly to the reduction of local GHG emissions when implemented at a city scale? The hypothesis for this question was that modelling using GHG emissions source data be used to design a strategy for the spatial allocation of NbS across an urban region to achieve this locally, as the effectiveness of NbS at reducing emissions is dependent on the context in which they are implemented (Paper IV).

The overall aim of this thesis was to contribute to the development of sustainable cities through revealing how urban planning and policy decisions can be used to shape cities with lower contributions to climate change. Specific objectives of the work were to:

a) Improve understanding of cities as complex systems which form part of, and contain, many social, economic and natural systems (Papers I-IV)

b) Study the connections between urban-regional planning decisions and GHG emissions from the target urban-regional area (Papers II-IV)

c) Advance research in this subject area through tool and model development and analysis (Papers I-IV)

d) Investigate how new knowledge and modelling can be applied in practical planning to help cities move towards climate action goals such as ‘net-zero’ emissions (Papers I-IV).

These research objectives were addressed in a series of connected projects undertaken over the course of four years, which are described in Papers I-IV. Each paper contributed to one or more of the objectives in the following ways:

- Paper I addressed objectives (a) and (c) through adaptation and improvement of the Land use Evolution and impact Assessment Model (LEAM) to ensure that it accurately reflected the practical reality in Stockholm County. It addressed objective (d) by reflective collaboration with regional planners from the Stockholm County planning department to ensure that the models developed are both useful and applicable in practical planning.

- Paper II addressed objectives (a), (b), (c) and (d) through coupling LEAM with GHG modelling to investigate how urban growth is likely to impact GHG emissions in Stockholm and whether zoning policies can be used to mitigate future increases in emissions.
- Paper III addressed objectives (a) and (b) by investigating additional aspects of the urban carbon cycle, to better understand how the urban system interacts with natural systems through research and analysis (objective (c)). It addressed objective (d) through application of findings from the analysis to identify where and how urban and regional planners can intervene in efforts to achieve 'net-zero' emissions in coming decades.
- Paper IV addressed objectives (a), (b), (c) and (d) by using computer modelling to distribute the sources of regional GHG emissions locally within a city and to map how and where NbS could be used most effectively to reduce net urban GHG emissions in cities across Europe.

2 Theory and Literature Review

2.1 Planning Support Systems

Computer modelling was used in this thesis to help understand complex urban socio-ecological systems and handle the large amounts of data associated with these. In Paper I, this modelling took the form of planning support systems (PSS) adapted for use in Stockholm County. In Paper II, the PSS model was coupled with a GHG model, while Papers III and IV primarily made use of other forms of modelling and data processing (described later in this thesis).

Planning support systems are designed to help urban and regional planners understand complex urban systems and plan for more sustainable and resilient future cities (Deal et al., 2017a; Kalantari et al., 2019a; Pettit et al., 2018). For example, PSS can be used to analyse and link different aspects of urban planning (e.g. land use, transportation, water, and environmental issues) in order to improve understanding of these as an inter-connected system (Kalantari et al., 2019c; Kumar et al., 2019; Waddell, 2002). In this thesis, this is used particularly to explore the ways in which urban planning decisions can impact future urban GHG emissions. PSS are particularly helpful where they enable planners to make use of large amounts of data to make informed decisions for meaningful and effective actions (Harris and Batty, 1993; Klosterman, 1997; Rodrigo-Comino et al., 2018). PSS also allow users to simulate and analyse ‘what-if’ future scenarios, which is invaluable in a field where other physical experimentation and testing are often expensive or impossible (Quan et al., 2013). PSS can be used to understand possible future consequences of current policy decisions, by forecasting how their implementation is likely to impact future urban development (Deal et al., 2013).

Despite widespread availability of a range of potentially useful PSS, there is a notable lag in their implementation and use in practice (Russo et al., 2017). Studies conducted around the PSS availability-implementation gap have found that the reasons for this appear to be related to both the PSS themselves, and factors affecting the users which are independent of the technology. Examples of these include technology factors such as the PSS being expensive, complex to use, or requiring significant training for the users, and user factors such as institutional inertia (Vonk et al., 2005; Geertman and Stillwell, 2009). In order to encourage PSS uptake in planning practice, it is therefore important to consider the intended users and organisational context when developing these systems (Babelon et al., 2017; McEvoy et al., 2018). As with the development of other types of software, user involvement in the design of a PSS could be helpful both in tailoring it for use in the intended context, and in increasing planners’ trust and understanding of the tool, and thus increasing the likelihood of its successful adoption in planning practice (Alvertis et al., 2016; Bano and Zowghi, 2015; Pelzer et al., 2015).

Research and development on PSS will not assist in achieving sustainable urban and regional development unless the resulting PSS are actually used in practical planning, so that improved scientific knowledge can inform and improve policies and decisions. Paper I in this thesis describes the process of planner engagement in adapting an open-source PSS, LEAM (Deal and Pallathucheril, 2008), to the case of Stockholm County, Sweden (Kalantari et al., 2019a; Mörtberg et al., 2017; Pan et al., 2018). This region was chosen because there is a productive working relationship between researchers, Stockholm County planning authorities and the regional development board (Tillväxt- och regionplaneförvaltningen, TRF), and because the existing PSS for the county needed to be adapted and updated. This provided an opportunity to work in a deliberate, collaborative manner and document and study the process and outcomes.

2.2 Modelling Changing Urban Greenhouse Gas Emissions

In this thesis, we investigate the role of human-driven land use change in present and future climate change. This is important in understanding how the negative impacts of urban development on climate change can be reduced (Bierwagen et al., 2010). Both climate change and land use change affect urban social and ecological systems, and provision of ecosystem services (such as local climate regulation and carbon sequestration) by the latter (Destouni et al., 2013; Seung-Hwan et al., 2013; Pan et al., 2019b). Many studies of urban development and climate change have found that urbanization tends to lead to increased GHG emissions and a simultaneous loss of carbon sequestration capacity due to land use change, resulting in very significant net increases in GHG emissions to the atmosphere in some areas (Han et al., 2017; Larsen and Hertwich, 2010; Lubowski et al., 2006; Searchinger et al., 2008). Models can be used to understand the climate-change and environmental implications of land use changes, and to facilitate better decisions in regional land use planning for both reducing emissions increases, and protecting against the loss of important ecosystems (Deal et al., 2017b; Hobbs et al., 2016; Pan et al., 2018). Spatial-explicit modelling can be particularly helpful in identifying development areas which should be prioritised for emissions reduction (Pielke et al., 2002).

Factors which affect the eventual GHG emissions due to urban growth include increased energy usage, demand for transportation and the modal split of that travel, and changes in urban form together with the associated land use change (Chau et al., 2015; Gren et al., 2019; Hankey and Marshall, 2010; Kraucunas et al., 2015; Nejat et al., 2015). Other factors related to climate change, such as changes in rainfall patterns, can in turn affect urban development decisions. Increased flood risk, for example, could limit the location and configuration of new urban developments (Deng et al., 2013). Climate and land use change modelling needs to couple together multiple social and ecological system interactions and feedbacks (such as climate impacts on human socio-economic activities and human reactions that change emission patterns and volumes), in order to provide accurate and comprehensive scenario analysis to support relevant policy decisions.

In Paper II, we investigate the complex interactions, and their effects and feedbacks, between urbanisation and associated land use changes and climate change using a coupled social-ecological modelling approach. The model builds on existing approaches for constructing interactive and policy-driven scenarios of changes in land use and GHG emissions. In Paper II the modelling approach was applied to Stockholm County, Sweden, to assess whether coupled land use-GHG modelling can be used to inform policy and planning decisions.

2.3 Urban Carbon Accounting

Many countries and cities have committed to becoming 'carbon-neutral' within coming decades, e.g. as part of the Paris Agreement (United Nations, 2015). However, achieving carbon neutrality in urban systems is complex and challenging. It requires a good understanding of carbon dynamics in urban ecosystems, including identification and distinction of natural and human-perturbed carbon exchanges and their interactions. Paper III investigated the urban carbon cycle in depth in order to learn more about how and where urban planning and policy strategies could potentially be applied to help cities achieve their various 'net-zero' emissions and 'carbon neutrality' goals.

When trying to address and account for (urban) GHG emissions, it is common to break down the sources of these emissions following a 'bottom up' inventory methodology (Marcotullio et al., 2014). Much research has been conducted where these emissions come from and how we can reduce them directly (Pichler et al., 2017; Xu et al., 2019). The Intergovernmental Panel on Climate Change provides Guidelines for National Greenhouse Inventories or the World Resources Institute in its Global Protocol for Community-Scale Greenhouse Gas Emission Inventories, which are commonly used by cities and countries for bottom-up carbon accounting. While these types of inventories can be useful in identifying areas where cities can make changes to reduce their emissions, they only tend to consider the various sources of direct GHG emissions through human activity, and exclude other important aspects of the urban carbon cycle, such as the role of blue and green spaces (Fong et al., 2014; IPCC, 2006; Kennedy and Sgouridis, 2011).

Studies have shown that green spaces have the potential to play a significant role in the urban carbon cycle both through direct sequestration, and by helping to reduce overall emissions through strategies like nature-based solutions (Baró and Gómez-Baggethun, 2017; Christen et al., 2011; Kalantari et al., 2019b; Vaccari et al., 2013). There is also considerable evidence that inland waters are a source of large amounts of GHGs to the atmosphere and that human activities have significantly affected this contribution (Cole et al., 2007; Raymond et al., 2013; Tranvik et al., 2009). 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 sea parts located in or next to urban areas can be sources of GHGs to the atmosphere (Melaku Canu et al., 2015). Considering and understanding the role of blue-green areas in the urban carbon cycle, and including these in carbon accounting, can help identify new or modified actions and policies to reduce overall GHG emissions and aid cities in achieving their various 'net-zero' emissions goals.

2.4 Nature-based Solutions for Sustainable Cities

As mentioned above, nature-based solutions (NbS) can play an important role in helping to reduce cities' contributions to global GHG emissions, and in dealing with the consequences of climate change (Griscom et al., 2017; Keith et al., 2021). In terms of reducing carbon emissions, most attention has been paid to the direct vegetative sequestration offered by NbS (Mori et al., 2021). However, our findings in Paper III suggest that carbon sequestration can only offset a limited proportion of total anthropogenic carbon emissions, especially in urban settings. To understand the full potential of NbS reducing net GHG emissions, their indirect impacts that are connected to social and economic systems should also be considered (Seddon et al., 2020). Beyond direct carbon sequestration, NbS can provide various ecosystem services which support human well-being. Green infrastructure can provide local climate regulation through e.g. creating shade and increasing humidity through transpiration (Velasco et al., 2021; Xi et al., 2022). Ecosystem services provided by NbS can create a more pleasant environment for walking and cycling, encouraging a shift towards more active transport choices, which in turn can prevent urban sprawl and reduce dependence on cars (Ki and Lee, 2021; van den Bosch and Nieuwenhuijsen, 2017).

Paper IV in this thesis assessed and quantified potential roles of NbS in the reduction of carbon emissions from EU cities in these and other ways, including human behaviour intervention, resource saving and carbon sequestration, for different categories of NbS (green-blue infrastructure, road green, improved access to green space, green belts, and building green). Based on sector-wise carbon emissions and local context on the land use grid (30x30 m) of 54 major European cities, these five types of NbS were spatially allocated to each city and the emissions reduction potential was estimated for each sector and each city.

3 Description of Study Areas and Planning Support System

3.1 Stockholm

The primary study area used in this thesis work was Stockholm County (6,519 km^2),the largest metropolitan area and most populous region in Sweden. It lies on the east coast (Figure 3.1, inset) and includes the Swedish capital Stockholm, a second city (Södertälje), various smaller towns and villages and the Stockholm Archipelago, which extends out into the Baltic Sea. Stockholm County lies in the boreo-nemoral mixed-forest biome (Elmhagen et al., 2015) and its landscape includes urban areas (approximately 35% of total regional area), urban green spaces (7%), open water (both lakes and sea, 23%), coniferous (24%) and mixed (coniferous/deciduous, 4%) forests and arable land (7%) (Goldenberg et al., 2017).

The Stockholm region has recently experienced major population growth. In 2022, 2,440, 027 people lived in Stockholm County, representing 23% of Sweden's total population(Statistiska Centralbyrån, 2023). According to the planning office at Region Stockholm, the population of Stockholm County is expected to grow by nearly 30% from 2014 to 2040, to around 2.8 million inhabitants, mostly due to immigration and urbanisation (Statistiska Centralbyrån, 2016; Tillväxt- och Regionplaneförvaltningen, 2017). Providing housing and infrastructure for this growing population is a challenge in a region which is already struggling with a housing shortage (Moore, 2018).

In parallel, Stockholm (both City and County) aims to be a worldwide leader in reducing GHG emissions, with the City of Stockholm having committed to being fossil fuel-free by 2050 (a deadline recently brought forward to 2040), based on its Strategy for a fossil fuel-free Stockholm (referred to hereafter in this thesis as 'Strategy 2040') (Stockholms Stad, 2016). In 2022, 5,449,291 tons carbon dioxide equivalents (t CO2e) were emitted in Stockholm County, which is equivalent to 2.23 t CO2e per capita. This is a significant decrease from 1990, when per-capita emissions were 5.4 t CO2e, and in line with the goal of 2.3 t CO2e per capita by 2020 stated in Strategy 2040. However, in order to meet their commitments in the Paris Climate Accords, Stockholm County will still need to decrease their emissions by 12.4% per year until 2045 (ClimateVisualizer, 2022; Region Stockholm, 2022; Statistiska Centralbyrån, 2023; Stockholms Stad, 2016). It should also be noted that these emissions statistics exclude the emissions associated with consumer goods produced outside of Stockholm County, as well as a large portion of those associated with international travel, which together comprise a significant proportion of the overall carbon emissions associated with the Stockholm region and Sweden as a whole (Schmidt et al., 2019). This exclusion enables a focus in this thesis on the natural and social systems related to land use within the region and provides insights into how planning and policy can be altered to reduce the emissions associated with these. How-

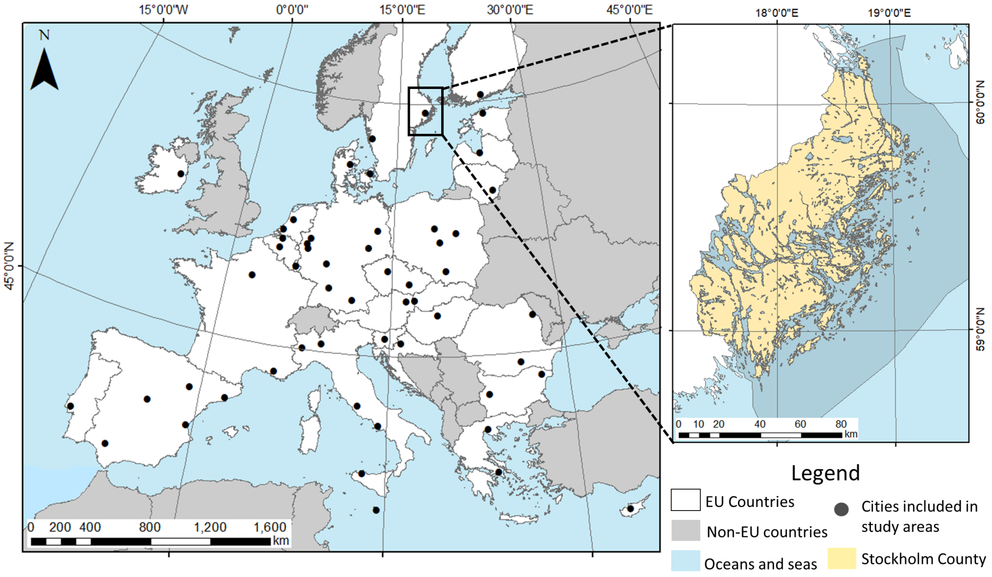

Figure 3.1. Map of Europe showing the location of the European Union (EU) city regions included in the analysis in Paper IV and that of Stockholm County (inset), the study area in Papers I-III. A full list of the included EU cities is provided with the supplementary material to Paper IV (Pan et al., 2023).

ever, this should be kept in mind when considering whether or not Stockholm County (and other net-importer urban regions) could truly be said to have achieved their goals of ‘net-zero’ emissions in a wider context.

3.2 European Union Cities

In Paper IV, the study area was expanded from Stockholm to 54 city regions across Europe, shown in Figure 3.1. These cities were selected because large amounts of data (as of 2022) were available for, and consistent across, the respective countries through the European Commission and other EU bodies. The process began by selecting all EU national capitals, so that at least one city was included from each of the 27 countries. The remaining 27 cities in the dataset were selected based on the locations of the highest emissions in the EU, and then to include a variety of different cities with different characteristics, such as size and population density.

The European Union (EU) has pledged to decrease net emissions by 55% by 2030 (compared with 1990 levels), a target which was increased to 57% in June 2022 through the inclusion of additional land use and carbon sequestration goals (European Parliament, 2022). This climate action is to be led by 100 cities in EU member states which have pledged to achieve climate neutrality by 2030 (European Commission, 2022), some of which are included in the study area for Paper IV. Their goals include emissions reductions and increased carbon sequestration in and around urban areas by 2030.

3.3 Land-use Evolution and Impact Assessment Model (LEAM)

The Land-use Evolution and impact Assessment Model (LEAM) first developed at the Department of Urban and Regional Planning, University of Illinois at Urbana-Champaign, USA, was adapted and improved for use in Stockholm County (Paper I) and then applied as part of a coupled socio-ecological modelling framework (Paper II), with the results being used in a carbon cycle assessment for Stockholm County (Paper III). LEAM is a geographically-based model, which produces maps showing where development (both residential and commercial) is likely to occur in the future, based on inputs of current land use, topography, and urban development drivers such land zoning and development restrictions, population changes, and population and employment centres (Mörtberg et al., 2017, 2013; Pan et al., 2018). The probability of development for each 30x30 m cell is calculated using Monte Carlo simulations, based on its proximity to development attractors (Deal et al., 2013). The model can be accessed online, through an interface in which the user is prompted to upload various input data (see Table A1 in Appendix) (Deal et al., 2016). The model output maps show the most likely locations for residential and commercial developments to occur for given population growth by a future date. These output maps can be coupled with other models or additional integrated model modules to analyse environmental impacts, as is demonstrated with GHG modelling in Paper II of this thesis. Figure 3.2 presents a schematic diagram of the functioning, inputs and outputs of LEAM Stockholm.

LEAM is designed as a tool with which users can test different future development scenarios for cities. Starting with the current conditions, it can show how different development drivers, such as planning and policy decisions, are likely to shape the city into the future. This can be used both to help planners understand how decisions will affect the city in the future, and as a way to find out which policies should be put into place now in order to achieve a desired future outcome, such as ‘net-zero’ GHG emissions (Deal et al., 2017b; Haslauer et al., 2012). The impacts of various decisions can be tested iteratively in a process called backcasting, in order to establish which changes should be made in order to push development towards the desired future condition, or away from an undesirable outcome (Deal and Chakraborty, 2010; Goldenberg et al., 2017, 2018).

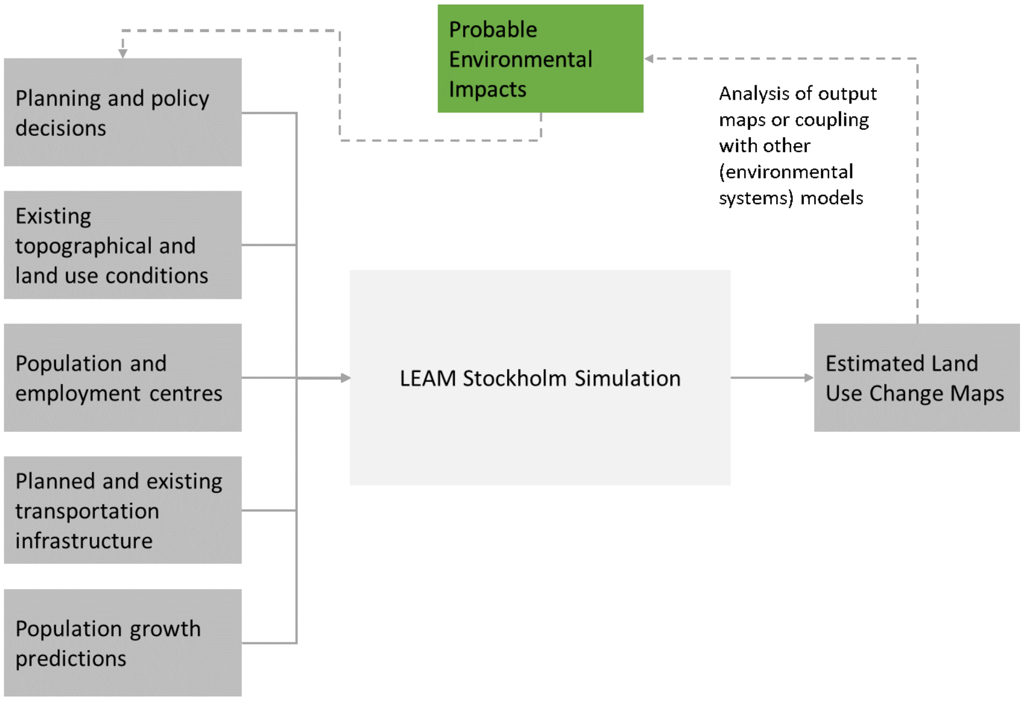

Figure 3.2. Schematic illustration of LEAM Stockholm, showing how input drivers (left-hand side) are most likely to drive development in a study area, by estimated land use change maps (right-hand side). Solid arrows show the LEAM modelling process, which the dashed arrows show how the model can be coupled with external analysis or other models to create an iterative scenario analysis. Figure 2 in Paper I (Page et al., 2020).

4 Data

This chapter describes the data used in the various modelling tasks included in this thesis. Further details about the data, including individual sources, are provided in Table A1 in Appendix A to this thesis.

4.1 LEAM Stockholm Update

In adapting LEAM to Stockholm County (documented in Paper I), regional topography, land use, population and employment centres, road networks and population demographic projections were included. Another model input was a no-growth map, which was created using maps of protected areas and other areas unsuitable for urban development, such as potential flood zones. Inputs for model adaptation included a public transport attraction map, created using data on existing and planned public transport stations and routes, and public transport travel data. A municipal population growth map was created using a map of the municipalities within Stockholm, together with population growth predictions for each municipality. In addition, the regional development plan for Stockholm (Regional Utvecklingsplan För Stockholmsregionen, hereafter referred to as '*RUFS 2050*') was used for comparison with the urban development simulation results produced by LEAM Stockholm (Tillväxt- och Regionplaneförvaltningen, 2017). The base year for the LEAM simulations was set at 2015 and the final year for all modelled scenarios was 2050, for direct comparison with *RUFS 2050*.

4.2 Coupled LUC-GHG Modelling in Stockholm

In addition to the data described above, which were used in land use modelling for applied land use change (LUC) modelling, further data concerning land cover, GHG emissions and sequestration and climate planning documents were used in coupling the LUC model output results with GHG emissions in Stockholm County (Paper II). Land use data were compiled from Urban Atlas data and updated using Corine Land Cover data (European Environment Agency, 2019, 2020). Data on planned future developments were obtained from *RUFS 2050*.

Data on anthropogenic GHG emissions to the atmosphere in both the base year and the future were derived from Stockholm County's climate planning document, together with Stockholm Stad's *Strategy 2040* (Stockholms Stad, 2016; Tillväxt- och Regionplaneförvaltningen, 2016). The emissions quantifications from *Strategy 2040* were adapted and used for the modelling scope of this thesis. Geographically, Stockholm County, which is a larger area than Stockholm City and its vicinity (the focus of *Strategy 2040*), was modelled in order to also capture GHG emissions from incoming-outgoing transportation between the main urban areas in the region. Data on transportation emissions in the larger geographical area were obtained from Stockholm County's climate planning document (Tillväxt- och Regionplaneförvaltningen, 2016). For the emissions scope in the analysis, land use development beyond Stockholm City was also modelled in order to estimate future emissions growth in energy use of buildings (not considering building manufacturing activities). Furthermore, only road and rail passenger vehicles were accounted for in the transportation emissions calculations.

Finally, a carbon sink map of the study region was created based on the latest available Corine Land Cover map from the European Environmental Agency, considering six land use classes: forest, shrubs, grass, cultivated crops, pasture, and wetlands (including both woody wetlands and herbaceous wetlands). Within forest areas, carbon sink values in the model were assigned considering different vegetation types and ages, given the carbon sequestration potential of (i) young and productive forests and (ii) established or naturally occurring forests. Forest age and type data were obtained from Copernicus Forests Dominant Leaf Type. Further details and sources for this data are provided in Table A1.

4.3 More Complete Carbon Accounting for Stockholm

The land cover data described above were also used in creating a carbon sink map for Stockholm County in Paper III, with the addition of more and updated land cover classes from a previous publication (Goldenberg et al., 2018). The carbon sequestration potential values used in Paper III (and in Paper II) were those selected after a search of the available literature. They are listed in Table 4.1.

In addition to land cover data, national survey maps including stream length from Lantmäteriet were used in calculating emissions from water bodies. The emissions values for water bodies in Stockholm County (Table 4.2) were compiled from a search of the available literature.

The annual emissions considered in the case study were those reported by Stockholm County. These include emissions from road and rail transportation of people and goods, as well as aircraft take-off and landing emissions from the county's two airports. Building emissions included here are those associated with the everyday functioning of buildings (including from the production of electricity to power the buildings), and industrial emissions are those originating from industrial activities within the county. The planned future emissions by 2045 used in the case study were also taken from Region

Table 4.1. Summary of carbon sequestration potential value used for land cover classes in Stockholm County in Papers II & III (Page et al., 2021; Pan et al., 2020)

Land Cover Type	**Carbon sequestration potential ($\mathrm{kgCO_2}$-eq $\mathrm{km^{-2}\ yr^{-1}}$)**	**Source**
Urban fabric – discontinuous structures	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 marshes1	0.769	(Charpentier et al., 2010)

Table 4.2. Greenhouse gas (GHG) emissions potential of the various water bodies in Stockholm County (Page et al., 2021)

Water Body Type	**Emissions ($kgCO_2$-eq km^{-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 4.3. Stockholm County urban emissions recorded in 2014 and predicted emissions for the year 2045 (Page et al., 2021; Tillväxt- och Regionplaneförvaltningen, 2016)

Emissions Source	**2014 Emissions ($10^9 kgCO_2$-eq)**	**2045 Emissions ($10^9 kgCO_2$-eq)**
Buildings	2.49	0.5
Transport	2.9	0.25
Industry	0.48	0.2
Total	5.87	0.95

Stockholm's 2016 report on climate efforts in the county (Tillväxt- och Regionplaneförvaltningen, 2016). Recorded urban emissions in Stockholm County in 2014 and predicted emissions in 2045 are shown in Table 4.3.

4.4 Spatial Emissions Distributions and Allocations of NbS

Global carbon grid data from the Global Infrastructure Emissions Database (GID) were downscaled in Paper IV to assess sectoral carbon emissions in each land use grid. The GID provides GHG emissions maps (year 2019) at a scale of $0.1° \times 0.1°$for six source sectors: power, industry, residential, transport, shipping, and aviation (Global Infrastructure Emissions Database, 2021; Tong et al., 2018). In Paper IV, the industry, residential, and transport emissions were assessed to allocate NbS. Maps from the GID showing emissions for the three sectors included in Paper IV (residential, transport, industry) are shown in Figure 4.1. Socio-economic and ecosystem variables used to downscale carbon emissions into a land use grid included population density, building density, land use structure, industrial and commercial units, and road networks. The data were acquired from either EU or global data sources that are open to the public, including Copernicus, EuroStat, and OpenStreet Map. Data on the GHG emissions reduction potential of NbS were generated through a review of the available literature on this topic following from that in Cong et al. (2023), the full results of which can be found in the supplementary material to Paper IV of this thesis.

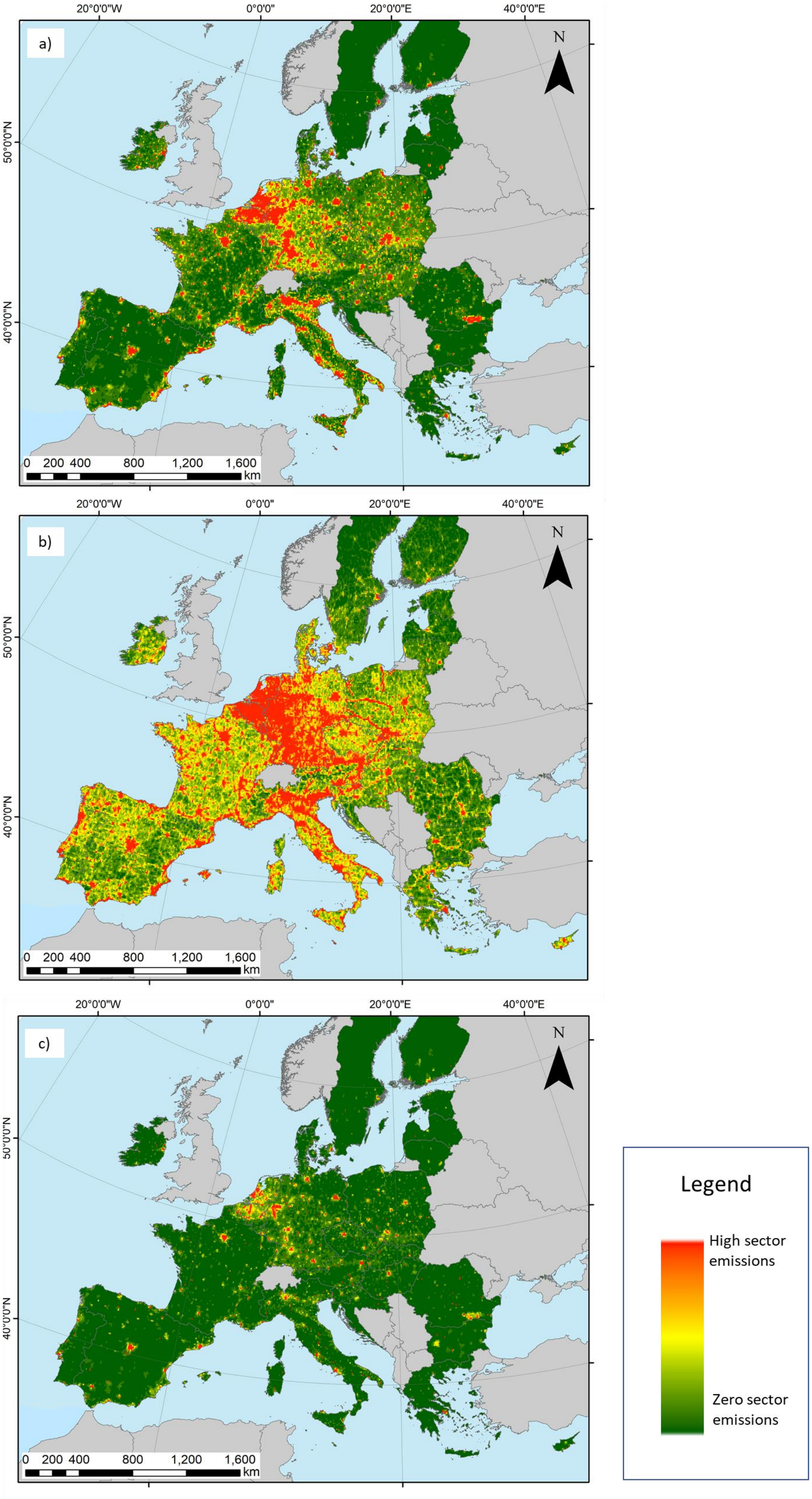

Figure 4.1. Global Carbon Grid emissions across the European Union for the three sectors considered in this thesis: a) residential, b) transport and c) industry, for the year 2019. Adapted from Figure 2 in Paper IV (Pan et al., 2023).

5 Methods

5.1 Collaborative LUC Model Adaptation

Development of LEAM Stockholm was conducted with significant input from planners at Region Stockholm as target future users of the PSS. Involvement of the planners in model development and adaptation was continuous and interactive.

The model adaptation process began with a meeting to discuss necessary functionality and questions about the model and its potential (from the planners) and questions about the Stockholm Region (from the researchers). This was followed by an iterative adaptation process with quarterly project meetings between researchers and planners in which the model was assessed, researchers' questions answered, and planners' needs and ideas were discussed. Changes were then made to the model and the effects were discussed at the next meeting, which led to further ideas for model expansion/changes, and so forth. These meetings typically lasted several hours and roughly comprised: i) presentations by the researchers, detailing the current project status and demonstrating the latest available outputs, ii) discussion of the presentations, with researchers answering planners' questions and vice versa, iii) discussion of any data needs, and iv) discussion of plans and ideas. The ideas and adaptations emerging from meetings were processed (investigated for feasibility etc.) by the researchers after each meeting, with follow-ups by email with the planners to clarify details and data needs.

This participatory process was ongoing and iterative and Paper I provides a snapshot of how this led to some significant changes in LEAM Stockholm. The planners were involved in all stages, which served the dual purpose of ensuring that the model update was as accurate and useful as possible, and helping the planners to understand and use the PSS. Portions of the participatory process were also reflected upon and discussed by the researchers and one of the planners during and after the process, in order to learn more about how this kind of process can be used to increase the use of PSSs in practice. The results presented in Paper I are a novel contribution to the body of scientific literature on that topic.

The technical task of adapting LEAM Stockholm was performed in three steps:

i. An update and verification of the input data for LEAM Stockholm was run using the latest version of all necessary input files. This step only included policy interpretation and updating of existing data, and no further adaptations to the model. The output was used as the baseline when assessing effects of adaptations to LEAM Stockholm.

ii. Addition of public transport to LEAM Stockholm by including public transport stops as development attractors, to account for the impact of public transport on development.

iii. Addition of individual population growth factors for each municipality within Stockholm County, rather than one overall factor for the entire county, for improved representation of individual municipal development goals and demographic projections.

5.2 Coupled LUC and GHG Modelling

Following adaptation and testing, LEAM Stockholm was used in an integrated modelling framework to investigate the regional GHG emissions within a dynamic urbanisation context, and to assess the impact of policy scenarios, as described in Paper II. This modelling framework is intended to be used within a multidisciplinary collaboration between researchers, practical planners, and other stakeholders. In addition to LEAM, it includes (i) a model to calculate GHG emissions under land use change scenarios, and (ii) a pathway to translate scenario modelling into useful policy practices, through comprehensive modelling accounting for feedbacks (Figure 4).

The coupled system model includes land use scenarios which are dynamic and complex, influenced by socio-economic policy scenarios, land use decisions, and associated GHG emission impacts. This modelling approach integrates socio-economic and land use policies together with and ecological processes, namely GHG emissions and their global climate impacts. The coupled model provides insights into GHG emissions associated with urbanisation and human-driven land use changes, through assessment of carbon sink losses, emissions from new residential and commercial buildings, and transportation emissions associated with urban sprawl. The model can be used to test the environmental impact of various policies (as is done in Paper II), in order to facilitate informed planning and policy decisions.

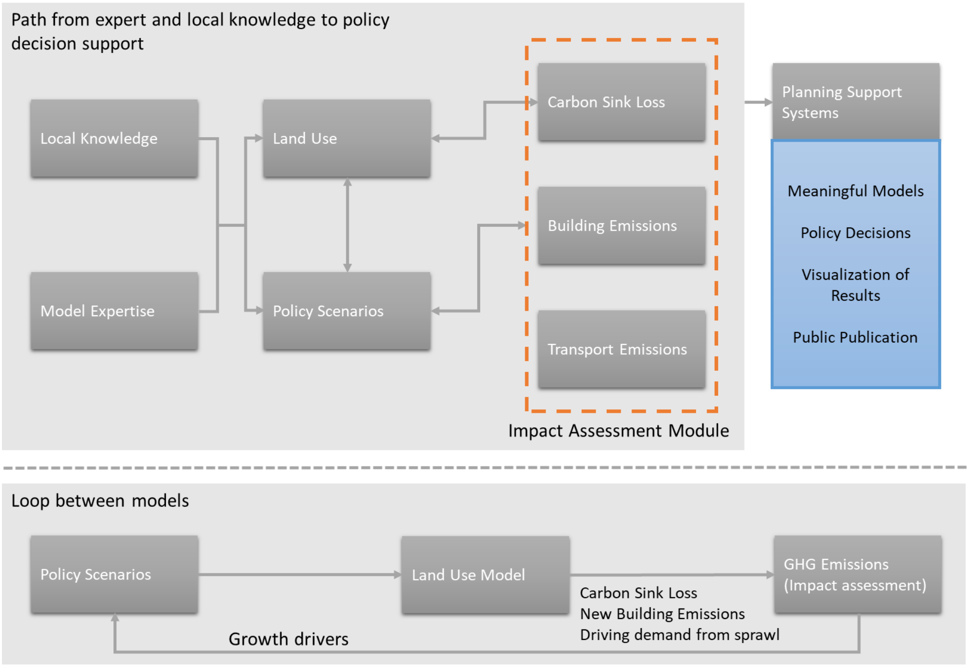

Figure 5.1. Framework for social–ecological process and system modelling and pathway to policy decision support. Adapted from Figure 2a in Paper II (Pan et al., 2020).

In applying the socio-ecological modelling framework to the case region, LEAM Stockholm was used to forecast scenarios of land use changes in the region. The model was used to identify highly probable re-development areas among existing developed land and to create probability maps of future commercial and residential growth based on different policy scenarios. This was coupled with a GHG emissions model, to calculate the emissions connected to the modelled land use changes modelled for each scenario. This includes emissions (or loss of sequestration capacity) deriving from three sectors:

i. Loss of green areas due to urban expansion. The vegetative carbon sink map of Stockholm County created allows carbon sink losses to be calculated based on the number of land cover cells (30x30 m scale) originally representing high-value carbon sinks (such as wetlands and forests with trees of young ages) that are converted into urban built-up areas (residential or commercial cells). The map was created based on the latest available land use map, other data about the vegetation in Stockholm County as described in Section 4.2, and a literature study of the carbon sequestration potential of various vegetative land use classes (see Table 4.1).

ii. Building energy emissions. Spatial-explicit land use simulations (using LEAM) were made to identify probable locations for new residential and commercial developments in the Stockholm region. The results were used together with historic density and development pattern information, as well as data about current and planned future energy use, insulation standards and so forth (described in Section 4.2), to calculate GHG emissions. For example, simulated new urban growth that occurs at the urban fringe or in suburban areas is more likely to involve single-family houses and large manufacturing companies, and has higher related GHG emissions per capita (Pan et al., 2019a). On the other hand, in-fill developments at the urban core are more likely to involve high-density apartments and offices, with smaller living areas requiring less energy for heating and lighting per resident, and consequently lower GHG emissions. Equations and further details of the calculations used for building energy emission estimation are provided in Paper II.

iii. Transport emissions. Different transport emissions associated with changing urban development patterns for 2040 scenarios were calculated based on the LEAM forecast of urban expansion (including urban form), together with passenger vehicle GHG emissions calculated using the linear population density function in Hankey and Marshall (2010). Studies have found that vehicle kilometres travelled (VKT) in and through an urban area increase with population and employment growth, and that total driving demand is also closely related to the urban form (Cervero and Murakami, 2010; Ewing and Hamidi, 2015). Low-density and sprawl development can drive and increase GHG emissions (Liu and Shen, 2011). Again, further details of these calculations can be found in Paper II.

Three scenarios for urban growth in Stockholm County were developed and simulated using LEAM. The first was a 'LEAM reference' scenario, in which the most likely development was modelled using LEAM, where development followed patterns decided by socio-economic drivers and no additional policies. The second was a 'Strategy 2040 baseline' scenario, in which development was shaped by the policies included in the Strategy 2040. The third was a LEAM 'mitigation zoning' (MZ) scenario, in which the model was used to simulate local planning reaction to potential GHG emissions. The key assumptions in each scenario are listed in Table 5.1. Note that all scenarios used the same population change (from 2,163,000 in 2014 to 2,800,000 in 2040) and employment growth projection (from 1,150,000 in 2014 to 1,500,000 in 2040). The difference between the scenarios was the urban growth pattern, and the resulting effects on GHG emissions.

Feedbacks of human responses and adaptation to climate change were incorporated into the social-ecological modelling approach. In the MZ scenario, a key assumption was that policymakers have strong awareness of urban growth and land use change interactions, and their associated generation of GHG emissions (spatial emission intensity), and make adaptive policy changes at five-year intervals based on dynamic (annual) information about GHG emissions.

Table 5.1. Key assumptions made in the three scenarios for urban growth in Stockholm County. Adapted from Table 1 in Paper II (Pan et al., 2020).

Scenario	**Key assumptions**
Baseline (Strategy 2040)	GHG emissions in 2040 were projected based on the proportional population increase projected in *Strategy 2040* (Stockholms Stad, 2016)
Reference (LEAM)	GHG emissions in 2040 were simulated based on the socio-ecological land use change model and considering the impact of the new commercial and residential development on carbon sinks, and building and transportation energy use.
Mitigation zoning (LEAM)	GHG emissions in 2040 were simulated based on the reference (LEAM) model, but areas in which residential and commercial growth could lead to high future GHG emissions were designated as no-growth zones (so development was shifted elsewhere or into more dense forms).

5.3 Systems Breakdown Analysis for Urban Carbon Accounting

In Paper III, a systems breakdown analysis (SBA) approach for carbon accounting in urban regions was developed and tested. The SBA method is intended to help understand urban carbon cycles by investigating the various system components and the GHG emissions and sequestration processes within and between these in a regional system, and ensure that important local sources and sinks (such as water bodies and green areas) are not overlooked. Figure 5.2 illustrates the social and ecological systems and their components considered in this methodology. The solid, coloured, arrows in the diagram show the links investigated in Paper III, while arrows with dashed grey lines indicate links that may exist, but were not investigated within the scope of this thesis. As shown in Figure 5.2, GHGs in the atmosphere are influenced both by social systems (i.e. anthropogenic GHG emissions), and by processes within the natural systems (namely water emissions and vegetative sequestration). In applying the SBA methodology to the Stockholm case study in Paper III, these various emissions and sequestrations were calculated as follows:

i. Urban emissions from three sectors (buildings, transportation, and industry) were extracted from local planning documents as described in section 4.3 and shown in Table 4.3.

ii. Removal of carbon from the atmosphere via vegetative sequestration is calculated from a land cover map and the sequestration potential of different types of vegetation as described in Section 5.2, where land use change modelling was coupled with GHG emissions. The per-area sequestration potential of each land cover type is shown in Table 4.1.

iii. To calculate GHG emissions or sequestration by water bodies in a region, the types and extents of the various water bodies in the region were identified and their area is multiplied by the per-area emissions value for each type of water body found through a literature and data search (Table 4.2).

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 in Figure 5.2. In the methodology developed in Paper III, the results of the Strategy 2040 scenario for Stockholm County modelled with LEAM in Paper II (see Section 5.2) were used to assess how such land use changes can be expected to affect GHG emissions and sequestration in the future. The first of these impacts the possible loss of vegetative carbon sinks due to urban expansion; if these sinks are not protected in the study region their sequestration capacity will be lost. 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 the methodology developed in Paper III, the calculations of blue-green emissions and sequestration as described above are performed again using modelled future land use maps from LEAM, in combination with available emissions plans, predictions and policies, in order to establish future emissions and sequestration in the urban carbon cycle for a study region. The results of both the present and future carbon accountings are finally analysed to identify places where effective action can be taken through planning and policy to reduce future net GHG emissions and meet climate change goals. The results can also be used to assess existing plans and policies on which future predictions are based, informing policymakers whether these are likely to achieve climate change goals or need to be changed to improve the likelihood of success.

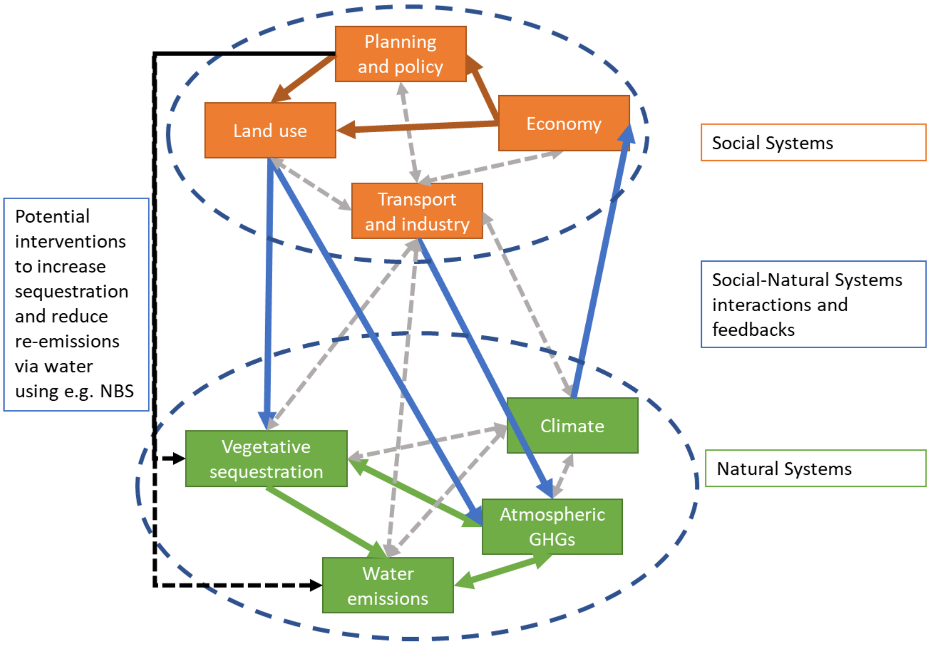

Figure 5.2. Conceptual basis of the systems breakdown analysis (SBA) methodology. The diagram shows the natural and social systems contributing to the carbon cycle in an urban region and the links between these systems and their components. Solid arrows show links investigated in Paper III of this thesis, while the dashed arrows show possible relationships and links which were not investigated in this thesis (Page et al., 2021).

5.4 Spatial Emissions Distributions and Allocations of NbS

In Paper IV, a four-step approach was used for estimating and projecting the emissions reduction potential of NbS in the 54 selected EU cities. This methodology followed from that developed by Cong et al. (2023) for spatial allocation of NbS in Stockholm, which was extended and applied across 53 additional cities.

First, a systematic meta-analysis of 587 articles concerning NbS was conducted in order to estimate the effects of five categories of NbS implementations on carbon emissions reductions from three sectors (transport, residential, industrial), in addition to carbon sequestration. The meta-summary method was then used to: (i) extract relevant findings from each article; (ii) abstract generalised principles from these findings (including the direction and intensity of carbon mitigation effect, and the conditions in which the NbS were applied); and (iii) condense these into key NbS strategies which were considered in subsequent analysis. Through the meta-analysis, 20 studies were identified that applied statistical tests to determine the significance of GHG emissions reduction effects from various NbS in urban environments. From these papers, we summarised results showing the contributions of different NbS to urban emissions reductions. For each study, the summary included: (i) the impact of the NbS studied on local GHG emissions; (ii) how this impact was quantified; and (iii) relevant information about the location or environment in which the NbS was applied.

Second, NbS implementations were spatially allocated to 30x30 m land use grids for each of the 54 cities, following the methodology described in Cong et al. (2023). Spatial allocation of the most effective NbS for emissions reduction was based on sectoral carbon emissions in each land use grid for the transport, residential, and industrial sectors in each city. Certain NbS types were considered most effective in reducing emissions in each sector, such as green building for residential emissions, road green (i.e. adding green elements such as trees along roads) for transport emissions, and green-blue infrastructure for industrial emissions. Carbon emissions from the GID for each of these sectors were downscaled to the land use grid using socio-economic and ecosystem co-variates including population density, building density, land use structure, industrial and commercial units, and road networks as follows:

i. Transport emissions were distributed to roads using binary disymmetric mapping (road = 1, non-road = 0), and then the emissions were adjusted for each road segment cell by road classes and population density.

ii. For residential emissions, a relationship between residential carbon emissions and population and building density was constructed using population density and land use data as described in Section 4.4. To estimate the function between residential carbon emissions and population and building density, different functional forms were tested, including a linear model, local polynomials and a random forest model, with a cross-validation method for model selection (70% observations as training data, 30% as test data). It was found that the random forest model produced the lowest root mean square error and therefore it was applied to obtain residential CO_2 emissions estimates.

iii. For industrial emissions, binary disymmetric mapping (industry = 1, non-industry = 0) was again used to distribute emissions to industrial and commercial complexes that cause major carbon emissions. The location of these industry cells were determined using land cover data as described in Section 4.4.

In addition to down-scaled carbon emissions, socio-economic variables (including population density, building density, road networks, and land use structure) and biophysical variables (including ecosystem services and vegetative sequestration) were used to determine the allocation of NbS.

Third, following the allocation of NbS across each of the 54 cities, their carbon emissions reduction potential was calculated and summarised at a city scale. The ecosystem service of carbon sequestration potential of vegetation was calculated using land cover types, similarly to the method described in Section 5.2. The percentage of carbon emissions that could be saved in NbS for each sector (residential, industrial, transport) and the total amount of sequestration for each city from the meta-analysis results was then estimated, with summation of NbS implemented in each city determined by the allocation across the city.

Finally, to project how NbS could contribute to the climate action goals of the 54 case study cities by 2030, the net carbon emissions reduction in each European city was compared with its (emission mitigation pathway) Representative Concentration Pathway for different shared socio-economic pathways in 2030. Equations and further details of the calculations described in this section can be found in Paper IV.

6 Results

6.1 Improved LEAM Stockholm Output

Model development for LEAM Stockholm resulted in a model which produced results that closely matched the regional development featured in RUFS 2050. The updated and improved model showed development patterns that followed public transport routes more closely than before, thanks to the addition of public transport attractors, and denser development than before, due to the inclusion of municipal growth goals. Figure 6.1 shows the results of the updated LEAM Stockholm overlaid on a map of the planned development from *RUFS 2050*.

6.2 Policy to Reduce Emissions due to Urban Expansion

Through coupling the improved LEAM Stockholm model with GHG emissions data (Paper II), emissions associated with the different future development scenarios described in Table 5.1 were calculated. The results are shown in Table 6.1, and the development under different scenarios is shown in Figure 6.2.

Due to expected population growth in Stockholm County creating demand for more housing, the LEAM modelling projected that there will be urban expansion consisting of an area of 1.40 km^2 of single-family homes and 10.82 km^2 of multi-family homes in the region by 2040, at a similar density to the current housing stock. Most of the new development was projected to occur in the central city core, with some developments also occurring in smaller secondary cores, and in the planned new urban core around Märsta and Arlanda Airport in the north-west. This last development, together with that in other northern suburbs, may contribute to urban sprawl and be associated with higher residential and transportation energy use than the more compact development seen in the rest of the region.

Table 6.1. Greenhouse gas (GHG) emissions driven by carbon sink losses and new development (building and transportation network) in i) existing conditions (2014) when the *Strategy 2040* plans were published; ii) a "Strategy 2040 Baseline" scenario, based on current land use trends; iii) a "Reference Scenario" integrating both socio-ecological processes (LEAM) and GHG emissions models; and iv) a "Mitigation Zoning Scenario", assuming political strategies for spatial restrictions to new urban development in 2040 (Pan et al., 2020).

Scenario	**Carbon sink loss** (Mt CO_2-eq yr^{-1})	**Building GHG emissions** (excluding manufacturing activities) (Mt CO_2-eq yr^{-1})	**Road passenger-vehicle transport emissions** (Mt CO_2-eq yr^{-1})	**Total** (Mt CO_2-eq yr^{-1})
2014 – Existing conditions	Not included	1.60	1.86	3.46
Baseline (Strategy 2040)	Not included	2.03	3.05	5.08
Reference (LEAM)	0.02	2.83	2.63	5.48
Mitigation Zoning (LEAM)	0.01	2.72	2.46	5.19

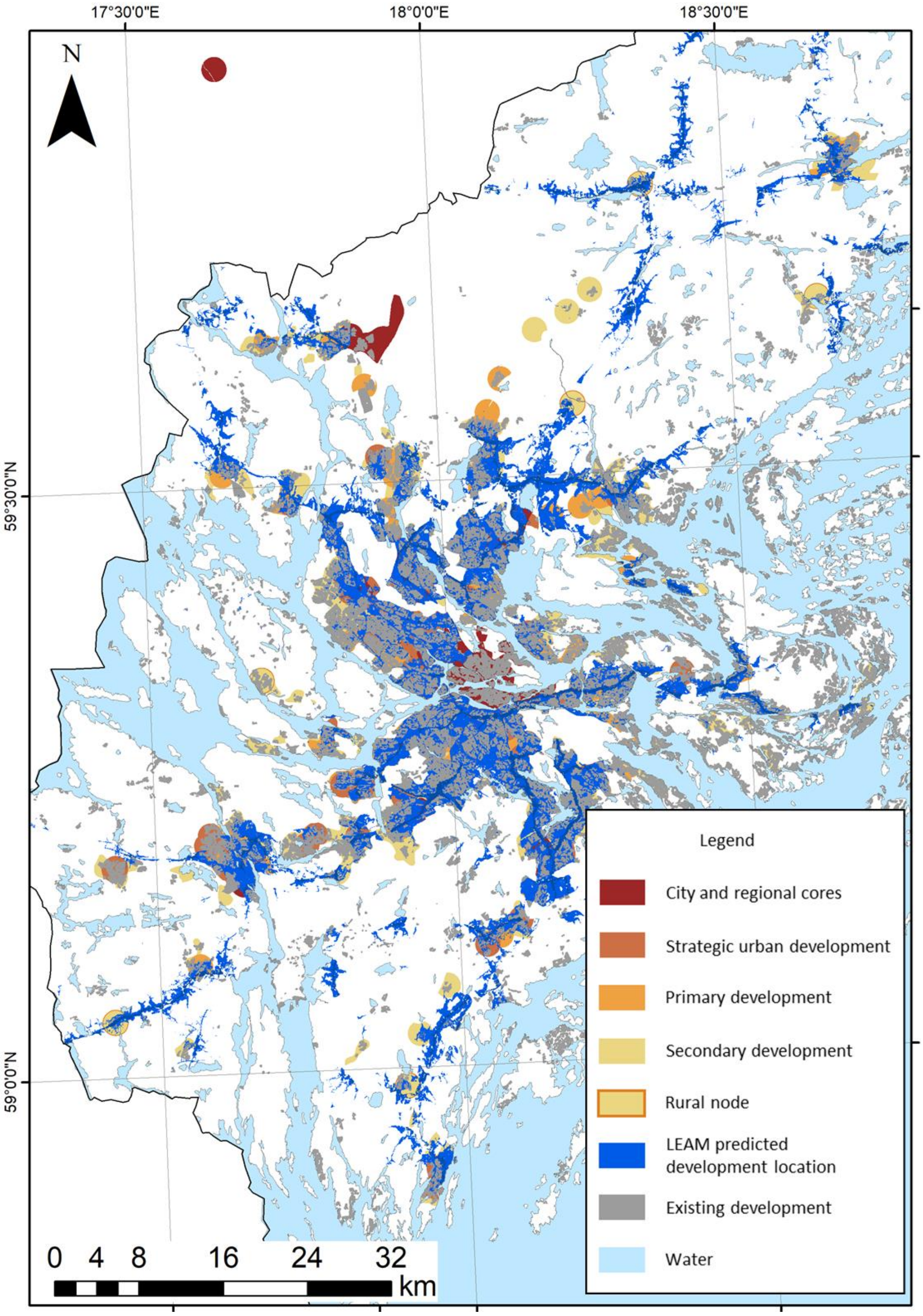

Figure 6.1. Modelling results for the Stockholm County study region obtained using LEAM Stockholm (dark blue) superimposed on planned development (red, orange and yellow) according to the regional development plan for Stockholm (*RUFS 2050*). Adapted from Figure 4 in Paper I (Page et al., 2020; Tillväxt- och Regionplaneförvaltningen, 2017).

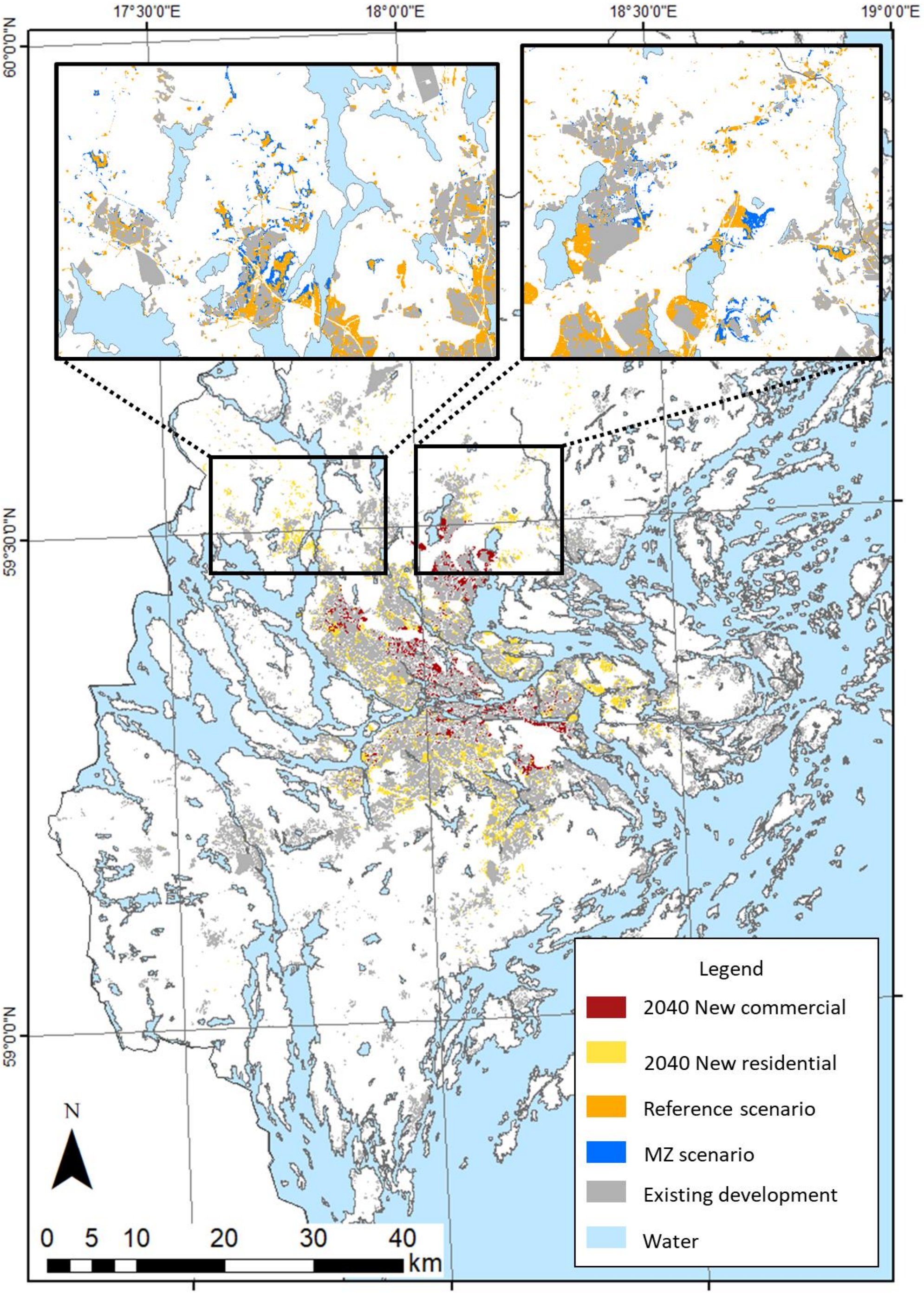

Figure 6.2. Location of urban developments in the LEAM mitigation zoning (MZ) scenario for Stockholm County by 2040. The inset maps highlight Brunna (left) and east Brottby (right) because urban developments are largely shifted to these areas in the MZ scenario. Adapted from Figure 5 in Paper II (Pan et al., 2020).

In the LEAM MZ scenario, this development was instead shifted to the Brunna and east Brottby urban clusters (highlighted in Figure 6.2), which had relatively low carbon sink potential and required only about 70% of the travel time and distance to the main urban core when compared to travel from the Märsta and Arlanda Airport regions. In the LEAM MZ scenario, urban growth was also shifted away from those areas at the city fringe in areas where there is currently forest which would be lost due to development, thereby reducing the loss of carbon sequestration capacity due to land use change.

The lowest future emissions (5.08 Mt CO_2-eq yr^{-1}) were found for the Strategy 2040 baseline scenario (Table 6.1). This is because the emissions calculated from *Strategy 2040* incorporated reductions due to other measures (including improvements in technology and building standards, as well as transport policy changes) than just urban growth management policies. In the LEAM reference and MZ scenarios, the effects of these measures were excluded from the emissions calculations in order to isolate the effects of zoning policy of emissions. The LEAM reference scenario produced future emissions of 5.48 Mt CO_2-eq yr^{-1}, where the increase of 0.4 Mt CO_2-eq yr^{-1} over the *Strategy 2040* scenario represents the GHG emissions increase caused by the urban growth and land use changes modelled in the LEAM baseline scenario. In the MZ scenario, the total future emissions were calculated to be 5.19 Mt CO_2-eq yr^{-1}. In this scenario, there is only a 0.11 Mt CO_2-eq yr^{-1} increase over the *Strategy 2040* scenario; the use of the MZ policy instrument reduced the increase in emissions due to urban development in this scenario by 0.29 Mt CO_2-eq yr^{-1} (72.5%) when compared with the LEAM reference scenario in which no zoning policy was applied.

6.3 Emissions and Sequestration in Stockholm County

Total emissions and sequestration in Stockholm County in 2014 and 2045 as calculated in carbon accounting in Paper III are shown in Figure 6.3. In brief, the calculated sequestration for 2014 was 1.61 Mt CO_2-eq, which will be reduced to 1.57 Mt CO_2-eq by 2045, due to land use change. Combined fresh- and sea water emissions for both 2014 and 2045 were calculated to be 0.47 Mt CO_2-eq. Urban emissions in 2014 were 5.87 Mt CO_2-eq, while the planned urban emissions for 2045 are considerably lower, with a total of just 0.95 Mt CO_2-eq. If this planned reduction in urban emissions is achieved, the remaining carbon sequestration capacity in 2045 should be sufficient to offset both the urban and water emissions, if this capacity is protected and can be maintained in spite of possible climate change impacts in the intervening years.

6.4 Reduced Urban Emissions Through NbS in European Cities

The GHG emissions for 15 of the 54 selected EU cities are shown per sector in Figure 6.4, together with the potential reductions in these emissions through the use of spatially prioritised NbS as modelled in Paper IV, as well as the current GHG emissions per capita for these cities. The down-scaled emissions are also shown for Helsinki in Figure 6.5, with different patterns of NbS allocations based on their emissions pattern for Helsinki and three other cities shown in Figure 6.6 (the down-scaled emissions and NbS allocation maps for all 54 cities are provided in supplementary material to Paper IV). If the spatially prioritised NbS were to be implemented in practice, they could prevent large proportions of carbon emissions from different sectors. For all cities, NbS could reduce total carbon emissions on average by 17.4%, with 8.1% in the residential sector, 14.0% in the industrial sector and 9.6% in the transport sector. Of the remaining carbon emissions, 5.6%

could be offset through carbon sequestration. The largest emissions reductions would occur in the industrial sector, with green infrastructure contributing most effectively due to saving resources (water, energy, building materials) and reducing maintenance costs associated with industrial buildings. Additionally, large manufacturing plants have more available space for the implementation of green infrastructure, its location at the site of industrial emissions means that some of these emissions could be directly offset through carbon sequestration.

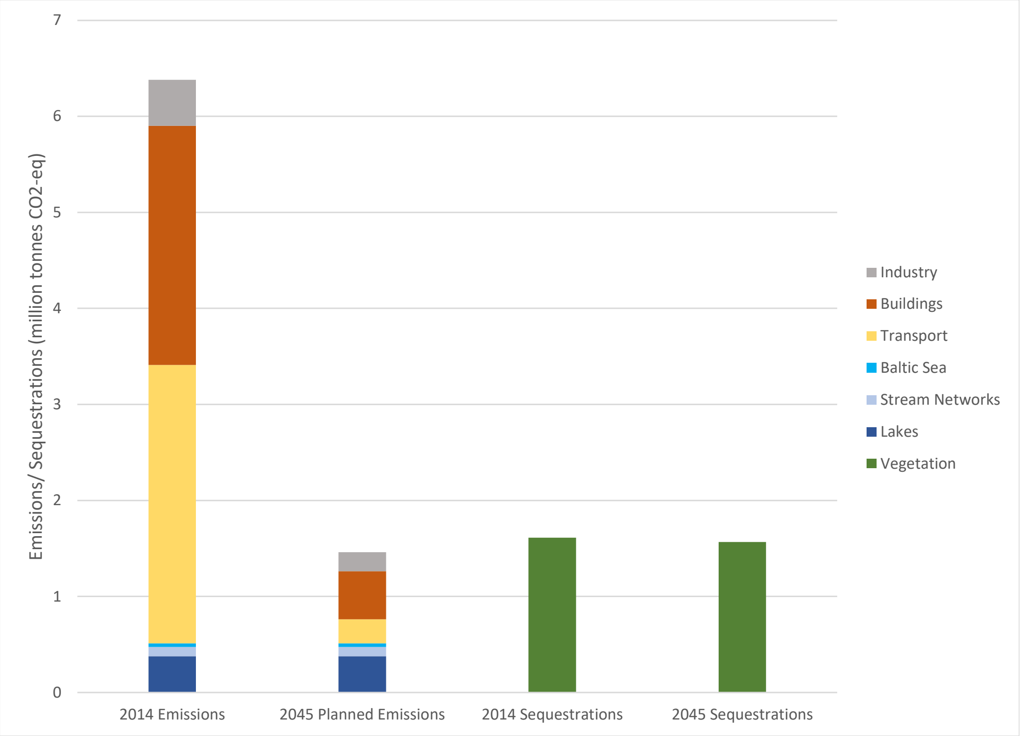

Figure 6.3. Measured annual urban greenhouse gas emissions and calculated water emissions and vegetative sequestration in Stockholm County in 2014 and predicted values for 2045 (Page et al., 2021).

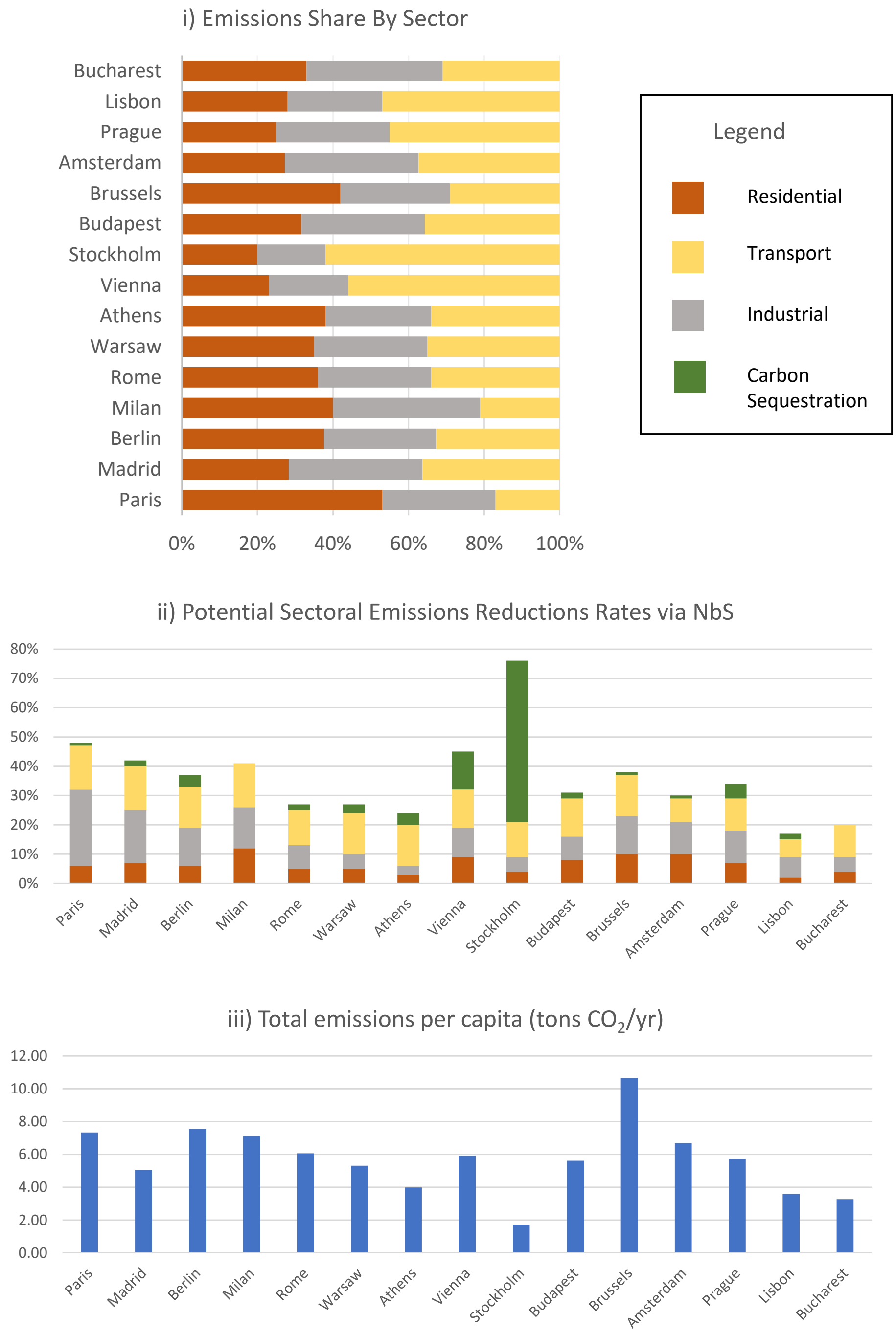

Figure 6.4. Graphs showing i) the split of GHG emissions across the three sectors considered in this study, ii) the potential reduction of emissions in each of these sectors, plus additional sequestration potential, if targeted NbS were implemented across the city, and iii) per-capita GHG emissions for 15 of the 54 cities modelled in this study. Produced from Table 1 in Paper IV (Pan et al., 2023).

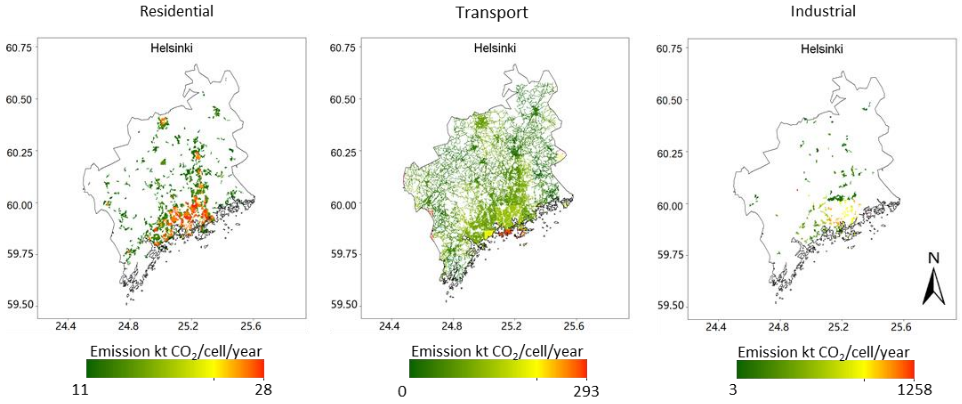

Figure 6.5. An example of down-scaled sectoral emissions shown for Helsinki for the year 2019. Latitude and longitude shown on the edges of each frame. Adapted from the supplementary material to Paper IV (Pan et al., 2023).

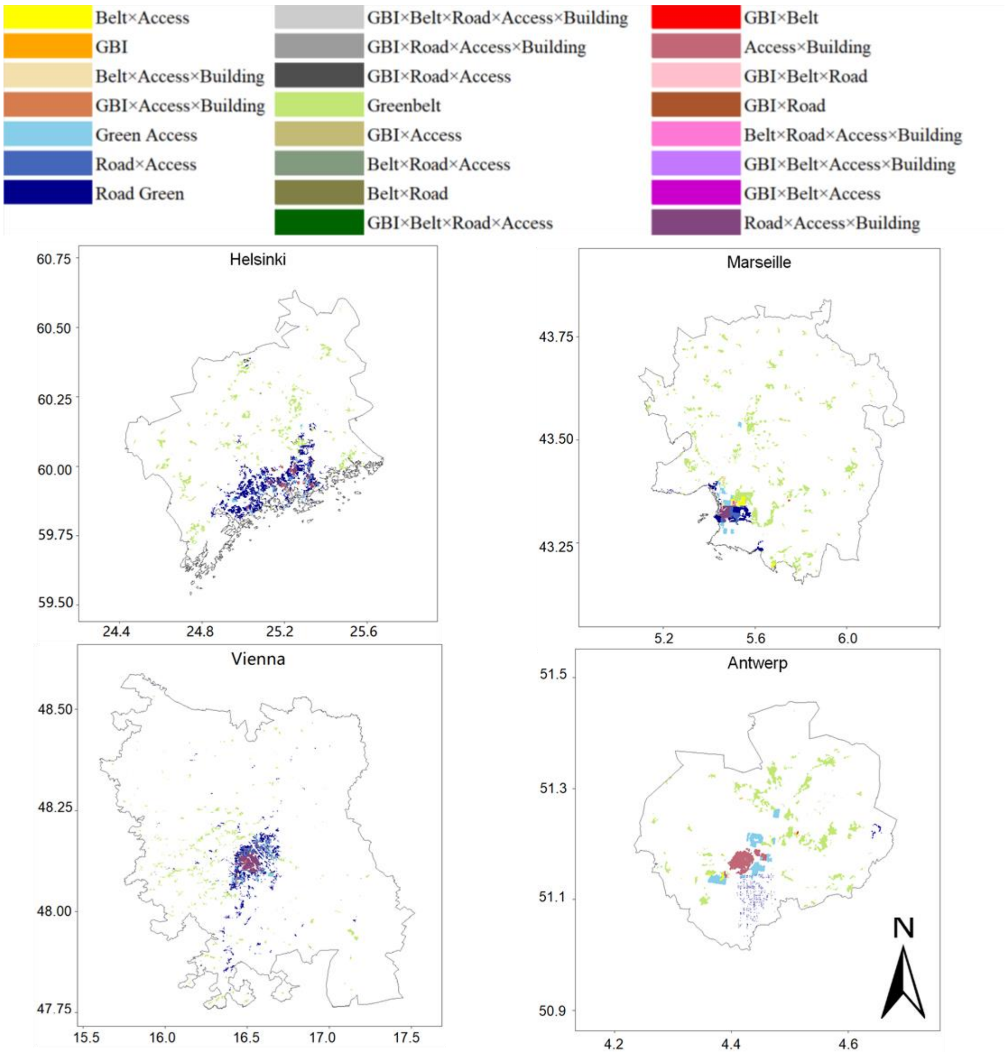

Figure 6.6. Examples of spatial allocation of prioritised NbS implementations in four of the selected EU cities. Latitude and longitude shown on the edges of the frame for each city. Adapted from the supplementary material to Paper IV (Pan et al., 2023).

7 Discussion

The intention with planner engagement in development of LEAM Stockholm was to increase planners' contributions, understanding and willingness to use LEAM Stockholm. As a result of their engagement, the adapted LEAM Stockholm was better suited to specific planning needs and able to produce results of higher quality, thanks to the use of the most relevant, complete and up-to-date data. Following model development, the results obtained using LEAM Stockholm and comparisons with *RUFS 2050* were discussed with the planners. The planners found it reassuring that, despite some differences in approach and related differences in output, both models yielded largely consistent results. They also recognised and appreciated that LEAM Stockholm is more flexible than the “black box” models they've worked with previously, and particularly liked that LEAM can be modified to test multiple future scenarios to support them in making better-informed decisions.

At the final meeting with planners documented in Paper I, both researchers and planners agreed that the model improvements made through engaging with the planners were very helpful in making LEAM Stockholm “much more relevant” for the planners to use in their work. In particular, incorporation of public transport made the model more accurate and thus more likely to be used in planning for Stockholm, given the importance of public transport in this region. Based on this feedback, work to improve public transport modelling in LEAM Stockholm continued after completion of this reflective and interactive model adaptation process. The planners also suggested further model improvements, some of which have proven useful in the ongoing research and development on LEAM Stockholm. Paper I describes and reflects on model updates and planner interactions which took place until the end of 2019, but the cooperation was still ongoing at the time of writing this thesis (2023). Significant new model adaptations have been made in the intervening years and the planners' continued trust and interest in LEAM Stockholm was clearly demonstrated at the most recent meeting (in October 2022), during which future practical planning projects using the model were discussed.

The improved LEAM model provided a reliable basis for the subsequent coupled socio-ecological modelling approach used to analyse the potential of planning and policy in reducing the GHG emissions related to urban development in Stockholm (Paper II). Here, the we found that the urban growth modelled with LEAM Stockholm would lead to GHG emissions in the LEAM reference scenario which were 7.9% higher than those extrapolated from population growth projections and per-capita emissions reduction trends in the *Strategy 2040* baseline scenario (Table 6.1). This increase in emissions was found to be relatively small in the Stockholm region, due to a number of factors such as widespread existing protections for green spaces around the city preventing urban sprawl to some degree even in the LEAM reference scenario. In other regions, this increase could be considerably larger, and the coupled modelling approach developed and used in this thesis could be important for facilitating assessments and developing strategies to reduce emissions due to urban growth.

The emissions calculated for the LEAM reference scenario in our Stockholm case study were higher than those in both the *Strategy 2040* baseline scenario and the LEAM MZ scenario. The fact than GHG emissions were higher in the LEAM reference scenario than those extrapolated from *Strategy 2040* for the baseline scenario indicates that the simple extrapolation method is insufficient for capturing the full future GHG emissions from urban expansion and associated land use changes. More comprehensive modelling, such as that conducted for the LEAM reference and MZ scenarios in Paper II, is needed instead for testing different policy and management scenarios in order to suggest relevant measures for efficient emissions reduction through urban planning and policy.

The zoning policy applied in the MZ scenario helped to reduce emissions when compared with the LEAM reference scenario. This reduction was achieved through limiting development which would lead to higher increases in both building and transport energy use. Urban sprawl taking place in suburban areas traditionally favours single-family residence developments, resulting in higher per-capita emissions from the energy use of buildings. This sprawl also leads to increased per-capita travel demand, resulting in relatively high per-capita VKT and associated transportation GHG emissions. The MZ policy shifted sprawling suburban developments to other locations where the urban form would be denser, and the demand for travel (particularly by car) would be reduced, thereby reducing modelled emissions associated with this development in 2040. This policy also helped to reduce the net GHG emissions increase by limiting urban expansion in natural (forested) areas, to prevent the in loss of carbon sinks.

The MZ scenario developed in Paper II provides an example of a spatially explicit policy instrument, which can be used to target reduction of urban growth in areas with high potential emissions or high carbon sink potential. Although the GHG emissions reduction using the MZ policy tool was relatively small (less than 10%) relative to the reference scenario for the Stockholm case study, this effect could be much greater in other parts of the world. For example, in US cities Ewing and Hamidi (2015) found that 9% of VKT could be reduced if compact growth strategies were adopted instead of urban sprawl. The potential to reduce emissions from urban development in Stockholm (and other similar European cities) is lower because there is historically a much less sprawling urban pattern than US cities. However, this type of spatial growth management policy can still be a useful strategy for emissions reduction in urban and regional planning in Stockholm, extending and complementing the total set of policy instruments and measures will be needed to achieve 'net-zero' emissions goals in the County. The effects of such policies can readily be tested for Stockholm, as shown in Paper II, using the LEAM-based PSS adapted and calibrated for easy use by planners in Stockholm County. Learnings from the Stockholm case in this thesis can also be applied to development and use of PSSs for coupled socio-ecological modelling to formulate and test specific zoning policies as a tool for emissions reduction in other regions where there is significantly more scope for these reductions than in Stockholm, such as US cities (Pan et al., 2019a).

To complement the work in this thesis using modelling to suggest GHG reduction policies for urban development, other aspects of the urban carbon cycle in Stockholm were also investigated to assess this as part of a larger socio-ecological system, particularly the role of the many green-blue areas in Stockholm County. From the carbon accounting results for Stockholm County shown in Figure 6.3, it can be seen that there is a significant planned reduction in urban emissions from 2014 to 2045. Although many of the plans to reduce emissions in the region are being implemented, it remains to be seen whether Stockholm County can actually achieve the 12.4% annual reduction needed to meet their climate action goals (ClimateVisualizer, 2022; Region Stockholm, 2022).

Even if these large emissions reductions are achieved, Stockholm County will still rely on significant carbon sequestration by the vegetation within the county in order to achieve net-zero emissions by 2045. The carbon accounting results in this thesis (Figure 8) indicated that current carbon sequestration capacity in the county should be sufficient to offset the planned emissions in 2045, if this capacity can be maintained decades into the future despite climate change and land use changes. The vast majority (1.18 Mt CO_2-eq) of this sequestration potential in Stockholm (estimated in Paper III to be 1.61 Mt CO_2-eq) came from the large areas of forest (both deciduous and coniferous) in the county. The remainder of the sequestration potential came from urban and suburban green spaces including gardens and parks (0.32 Mt CO_2-eq), together with other land uses such as agriculture and wetlands (0.11 Mt CO_2-eq combined).

Based on current plans and policy for urban expansion in Stockholm to house the growing population, land use modelling in this thesis indicated that 2.86% of the current sequestration capacity will be lost, resulting in vegetative sequestration of 1.57 Mt CO_2-eq by 2045 (extension to 2045 of the LEAM reference scenario described in Table 5.1). Protection and inclusion of green spaces within and around the urban centres are already prioritised in the plans for future development in Stockholm County (Tillväxt- och Regionplaneförvaltningen, 2017), which is why the modelled loss of vegetation was quite small despite considerable planned development and urban expansion. However, in other regions (such as the previously discussed US cities with a tendency to sprawl), much greater loss of vegetative sequestration potential might be expected if land use planning policies are not put into place protect existing green spaces (Pan et al., 2019a). Even in Sweden, large forest areas have been lost to harvesting in recent years (Ceccherini et al., 2020), so further forest protections through policy and other NbS are likely to be needed to maintain sufficient carbon sequestration in the county, particularly when taking into consideration potential climate change impacts of the ability of even the existing forests to continue to thrive and sequester carbon (Díaz et al., 2009; Luyssaert et al., 2007; Newton and Cantarello, 2015; Thompson et al., 2009).

Applying the SBA approach for quantifying GHG emissions and sequestration to the case study of Stockholm County in Paper III of this thesis provides new insights into the relationship between vegetative carbon sequestration and carbon emissions from water bodies. When considering the urban carbon cycle, we found that a large proportion of the carbon found in water bodies and emitted to the atmosphere as GHGs arrives in these water bodies via the vegetation in the associated hydrological catchment (Cole et al., 2007; Cvetkovic et al., 2012; Destouni et al., 2010; Humborg et al., 2010). This re-emission of GHGs via water bodies can be seen as lowering the efficiency of vegetative sequestration. For example in our Stockholm case study we found that about 32% of the carbon fixed by plants is re-emitted via various water bodies in the county. Improved understanding of these green-blue catchment-water body interactions of carbon could be key to achieving net-zero emissions, as a 32% reduction in the efficiency of vegetative sequestration is considerable in a region which will rely heavily on these sequestrations to achieve their climate action goals.

When studying water emissions in Paper III, we found the GHG emissions from the fresh water lakes in Stockholm (particularly Lake Mälaren) to be significant in our urban carbon accounting for the region, and also notable in that they were considerably higher than the average reported for large (>100 km^2) Swedish lakes (Humborg et al., 2010), and also higher than the values calculated for the other two largest lakes in Sweden (Vättern and Vänern) (Alin and Johnson, 2007). The reasons for the unusually high emissions from the fresh waters in Stockholm County are likely related to human activities in the region (Tranvik et al., 2009; Wallin et al., 2020) and this could therefore be a useful intervention point in the urban carbon cycle to reduce emissions by, for example, implementing NbS to better manage urban runoff and other factors contributing to the high levels of carbon in the water bodies. By identifying such intervention points, the SBA methodology has shown itself to be a useful tool which can be used in making informed urban planning and policy decisions which foster sustainable urban development.

The finding that water bodies (and particularly inland water bodies) and their integration of carbon from their whole catchment areas can contribute significantly to GHG emissions could also be relevant for urban carbon accounting in other places where large water bodies exist in the urban area. Since many cities worldwide are located close to water (and some, such as Venice and Amsterdam, have a similar integration of water throughout the urban fabric to that found in Stockholm), the consideration of emissions from water could become increasingly relevant as more cities strive to achieve ‘carbon neutrality’ and other climate action goals. This finding also revealed a need for further studies of GHG emissions from waters, specifically in urban regions, in order to find and implement solutions to reduce the anthropogenic contributions which could be causing these emissions to increase in urban regions like Stockholm.

Expanding the study scope to investigate how NbS use could be targeted to reduce urban carbon emissions across 54 EU cities (Paper IV) revealed that NbS can play an important role in reducing net urban GHG emissions. However, compared with carbon sequestration, the indirect effects of NbS on carbon emissions reduction through human behaviour changes and other co-benefits played a much larger role in reducing these emissions. NbS which were found to reduce emissions in this way include integrating and managing green-blue infrastructure in the city, the use of green building designs, increased access to green space, and creation of green streetscape and greenbelts. These had reduction effects on residential emissions (through reducing cooling and heating loads and encouraging pro-environmental habits), transportation emissions (by encouraging walking and cycling instead of automobile travel habits) and industrial emissions (through resource savings from green infrastructure).

We found that the effectiveness of these measures varied across different cities, and also according to where they were placed within a single city. For example, in Paper IV, streetscape greening was found to be most effective in more developed parts of the EU (such as Stockholm and Vienna), where modelling showed that these could potentially reduce transport emissions by more than 50% when coupled with other NbS measures. The effectiveness of a strategy such as green buildings varied with both urban development levels and climate, and we found that these could potentially reduce residential carbon emissions in highly developed cities with a large need for cooling (such as Milan and Paris) by more than 40%. Similarly, some types of green-blue infrastructure were found to be most effective in reducing emissions when placed at a large scale in the open spaces surrounding industrial areas. In cities where many such spaces exist (such as Madrid and Bucharest), these NbS could potentially reduce industrial emissions by around 35%. In Paper IV we found many examples of the various potential emissions reductions offered by NbS, and how this potential varies depending on location. A key takeaway from this study is that NbS can be very effective tools for reducing urban GHG emissions, but these need to be deployed in the correct urban and climatic contexts in order for their full emissions reductions potentials to be realised. At an EU scale, this could mean that it may be potentially more rewarding to focus investments in NbS spatial urban planning projects in those cities where the greatest emissions reduction benefits could be achieved for increased cost effectiveness in the EU as a whole, as has been shown in the case of other environmental pollutants (Jansson and Nohrstedt, 2001).

The carbon sequestration potential offered by the NbS modelled in Paper IV also varied greatly between cities, although this potential was consistently significantly less than the other emissions reductions potentials in all the cities except for Stockholm, as shown in Figure 10 for a selection of these cities. This is consistent with the results of previous studies which have estimated that in the most favourable scenario, the terrestrial biosphere in the EU can sequester 6.5-8% of projected anthropogenic emissions by 2030 (Schulp et al., 2008). Among the 54 cities analysed, Stockholm (55%) had by far the highest carbon sequestration potential, followed by Vienna (13%). Given the finding in Paper III that Stockholm County (even with this considerable sequestration capacity) could only reach its goal of 'net-zero' emissions by 2045 if it achieved very significant emissions reductions, NbS could be an especially useful tool to aid in reducing these emissions even further.

8 Conclusions and Future Outlook

This thesis analysed a set of European cities as complex socio-ecological systems in order to reveal the connections between urban-regional planning decisions and future GHG emissions from urbanising regions. Computer models proved useful in testing different tools and strategies for reducing urban emissions, such as zoning and use of NbS. Co-operation with planners in model development for the case study region of Stockholm County improved model functionality and accuracy and increased the likelihood of the PSS tools and research outcomes produced being used in practical planning.

Stockholm County was selected as a case because it has ambitious climate-action goals such as reaching ‘net-zero’ GHG emissions by 2040 while also providing for a rapidly growing population. The development necessary to house and provide jobs for Stockholm County’s new residents will inevitably increase urban GHG emissions. However, modelling work in this thesis showed that the increase can be minimised through the use of zoning, which reduces urban sprawl, low-density housing and carbon sink loss, and instead promotes denser development in areas from which residents can travel with fewer emissions. The effectiveness of this strategy even in a city such as Stockholm that already has a strong public transport system, applies zoning to protect green areas and is quite compact on a global scale indicates that it could be very effective in other cities with a stronger tendency for sprawl and car-oriented development, such as many US cities. However, a zoning strategy by itself will not be enough to help Stockholm County (or indeed any region) achieve carbon-neutrality and is just one tool available to planners, particularly when they have access to trusted PSSs to help them test different scenarios. Stockholm County is planning to introduce many other strategies to reduce emissions from building energy, industry and transportation, but even with very ambitious reduction targets the county will rely on carbon sequestration by its many forests and other green areas to achieve ‘net-zero’ emissions. Carbon accounting for Stockholm County in this thesis revealed that such carbon sequestration should be sufficient to offset the planned reduced emissions by 2045, provided that sequestration capacity can be maintained in coming decades despite ongoing climate change effects. When relying on carbon sequestration by vegetation, “blue” carbon emissions from the various water bodies in a region should also be considered. Analysis of this issue showed that GHG re-emissions via water in Stockholm County effectively reduced sequestration capacity in the county by 32%. Expansion of the analysis to 54 EU cities revealed that NbS can be effective in reducing net emissions from urban regions, but that carbon sequestration makes only a small contribution. Instead, targeted use of NbS to lower emissions through e.g. reducing the need for cooling in buildings at city scale can contribute significantly to achieving climate action goals for cities.

Many tools can be used in urban and regional planning to reduce urban GHG emissions and create more sustainable cities, and those tested in this thesis were found to be effective when applied individually. For the most effective climate action, however, the results indicated that these tools should be combined in a comprehensive climate action plan tailored to address the specific challenges in a region and bring cities closer to achieving truly sustainable urban development. Future studies should examine how this can be done in a way which meets the needs of the cities in question, and has the best chance of successful implementation.

Future studies are also needed to further examine the role of waters (especially fresh waters) in the urban carbon cycle in more cities than Stockholm; literature on this topic is scarce, and the results from Paper III indicate that water bodies could potentially play a significant role in the carbon cycles of other cities where blue areas are prevalent (such as Amsterdam, for example).

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References

Alin SR, Johnson TC. 2007. Carbon cycling in large lakes of the world: A synthesis of production, burial, and lake-atmosphere exchange estimates. Global Biogeochemical Cycles 21. doi:10.1029/2006GB002881.

Alvertis I, Koussouris S, Papaspyros D, Arvanitakis E, Mouzakitis S, Franken S, Kolvenbach S, Prinz W. 2016. User involvement in software development processes. Procedia Computer Science 97:73–83. doi:10.1016/j.procs.2016.08.282.

Antle JM, Apps M, Beamish RJ, Chapin T, Cramer W, Frangi J, Laine J, Erda L, Magnuson JJ, Noble I, Price J, Prowse T, Root T, Schulze ED, Sirotenko O, Sohngen B, Soussana JF, Takle E. 2001. Ecosystems and their goods and services. In: JJ McCarthy, OF Canziani, NA Leary, DJ Dokken, KS White, editors. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Cambridge, UK: Cambridge University Press. p. 235–342.

Babelon I, Ståhle A, Balfors B. 2017. Toward Cyborg PPGIS: exploring socio-technical requirements for the use of web-based PPGIS in two municipal planning cases, Stockholm region, Sweden. Journal of Environmental Planning and Management 60:1366–1390. doi:10.1080/09640568.2016.1221798.

Bano M, Zowghi D. 2015. A systematic review on the relationship between user involvement and system success. Information and Software Technology 58:148–169. doi:10.1016/j.infsof.2014.06.011.

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

Batista E, Silva F, Dijkstra L, Poelman H. 2021. The JRC-GEOSTAT 2018 population grid. JRC Technical Report. Forthcoming. Technical report. European Commission.

Bettencourt LMA. 2021. Introduction to urban science: evidence and theory of cities as complex systems. The MIT Press. doi:10.7551/mitpress/13909.001.0001.

Bierwagen BG, Theobald DM, Pyke CR, Choate A, Groth P, Thomas JV, Morefield P. 2010. National housing and impervious surface scenarios for integrated climate impact assessments. Proceedings of the National Academy of Sciences 107:20887–20892. doi:10.1073/pnas.1002096107. Publisher: Proceedings of the National Academy of Sciences.

Ceccherini G, Duveiller G, Grassi G, Lemoine G, Avitabile V, Pilli R, Cescatti A. 2020. Abrupt increase in harvested forest area over Europe after 2015. Nature 583:72–77. doi:10.1038/s41586-020-2438-y.

Cervero R, Murakami J. 2010. Effects of built environments on vehicle miles traveled: Evidence from 370 US urbanized areas. Environment and Planning A: Economy and Space 42:400–418. doi:10.1068/a4236. Publisher: SAGE Publications Ltd.

Charpentier M, Wigand C, Hyman J. 2010. Estimates of carbon sequestration in tidal coastal wetlands along the US East Coast.

Chau CK, Leung TM, Ng WY. 2015. A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Applied Energy 143:395–413. doi:10.1016/j.apenergy.2015.01.023.

Christen A, Coops NC, Crawford BR, Kellett R, Liss KN, Olchovski I, Tooke TR, van der Laan M, Voogt JA. 2011. Validation of modeled carbon-dioxide emissions from an urban neighborhood with direct eddy-covariance measurements. Atmospheric Environment 45:6057–6069. doi:10.1016/j.atmosenv.2011.07.040.

ClimateVisualizer. 2022. Historia - Stockholms läns koldioxidbudget.

Cole J, Priarie Y, Caraco N, McDowell W, Tranvik LJ, Striegl RG, Duarte C, Kortelainen P, Downing JA, Middelburg J, Melack J. 2007. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. Ecosystems 10:172–185. doi:https://doi.org/10.1007/s10021-006-9013-8.

Cong C, Pan H, Page J, Barthel S, Kalantari Z. 2023. Modeling place-based nature-based solutions to promote urban carbon neutrality . [manuscript].

Cvetkovic V, Carstens C, Selroos JO, Destouni G. 2012. Water and solute transport along hydrological pathways. Water Resources Research 48. doi:10.1029/2011WR011367.

Deal B, Chakraborty A. 2010. Cyber-physical planning support systems: Advancing participatory decision making in complex urban environments. International Journal of Operations and Quantitative Management: Special Issue on Complex Systems 16:353–367.

Deal B, Kim JH, Hewings GJD, Kim YW. 2013. Complex urban systems integration: The LEAM experiences in coupling economic, land use, and transportation models in Chicago, IL. In: F Pagliara, M de Bok, D Simmonds, A Wilson, editors. Employment Location in Cities and Regions: Models and Applications. Advances in Spatial Science. Berlin, Heidelberg: Springer. p. 107–131. doi:10.1007/978-3-642-31779-8_6.

Deal B, Pan H, Han J. 2016. LEAM home.

Deal B, Pan H, Pallathucheril V, Fulton G. 2017a. Urban resilience and planning support systems: The need for sentience. Journal of Urban Technology 24:29–45. doi:10.1080/10630732.2017.1285018.

Deal B, Pan H, Timm S, Pallathucheril V. 2017b. The role of multidirectional temporal analysis in scenario planning exercises and Planning Support Systems. Computers, Environment and Urban Systems 64:91–102. doi:10.1016/j.compenvurbsys.2017.01.004.

Deal BM, Pallathucheril V. 2008. Simulating Regional Futures: The Land-use Evolution and impact Assessment Model (LEAM). In: R Brail, editor. Planning support systems for cities and regions. Cambridge, Massachusetts: Lincoln Institute of Land Policy. p. 61–84.

Deng X, Zhao C, Yan H. 2013. Systematic modeling of impacts of land use and land cover changes on regional Climate: A review. Advances in Meteorology 2013:e317678. doi:10.1155/2013/317678. Publisher: Hindawi.

Destouni G, Jaramillo F, Prieto C. 2013. Hydroclimatic shifts driven by human water use for food and energy production. Nature Climate Change 3:213–217. doi:10.1038/nclimate1719. Number: 3 Publisher: Nature Publishing Group.

Destouni G, Persson K, Prieto C, Jarsjö J. 2010. General quantification of catchment-scale nutrient and pollutant transport through the subsurface to surface and coastal waters. Environmental Science & Technology 44:2048–2055. doi:10.1021/es902338y.

Díaz S, Hector A, Wardle DA. 2009. Biodiversity in forest carbon sequestration initiatives: not just a side benefit. Current Opinion in Environmental Sustainability 1:55–60. doi:10.1016/j.cosust.2009.08.001.

Elmhagen B, Destouni G, Angerbjörn A, Borgström S, Boyd E, Cousins S, Dalén L, Ehrlén J, Ermold M, Hambäck P, Hedlund J, Hylander K, Jaramillo F, Lagerholm V, Lyon S, Moor H, Nykvist B, Pasanen-Mortensen M, Plue J, Prieto C, van der Velde Y, Lindborg R. 2015. Interacting effects of change in climate, human population, land use, and water use on biodiversity and ecosystem services. Ecology and Society 20:23. doi:10.5751/ES-07145-200123.

European Commission. 2022. Commission announces 100 cities participating in EU Mission.

European Environment Agency. 2018. Dominant Leaf Type 2015 — Copernicus Land Monitoring Service.

European Environment Agency. 2019. Corine Land Cover (CLC) 2018.

European Environment Agency. 2020. Urban Atlas 2018.

European Parliament. 2022. Fit for 55: Parliament agrees to higher EU carbon sink ambitions by 2030 | Nyheter | Europaparlamentet.

Ewing R, Hamidi S. 2015. Compactness versus sprawl: A review of recent evidence from the United States. Journal of Planning Literature 30:413–432. doi:10.1177/0885412215595439. Publisher: SAGE Publications Inc.

Fong WK, Sotos M, Doust M, Schultz S, Marques A, Deng-Beck C. 2014. Global protocol for community-scale greenhouse gas emission inventories. Technical report. World Resources Institute. USA.

Geertman S, Stillwell J. 2009. Planning support systems: content, issues and trends. In: S Geertman, J Stillwell, editors. Planning Support Systems Best Practice and New Methods. The GeoJournal Library. Dordrecht: Springer Netherlands. p. 1–26. doi:10.1007/978-1-4020-8952-7_1.

Global Infrastructure Emissions Database. 2021. GIDmodel – Tracking global infrastructure emissions.

Goldenberg R, Kalantari Z, Cvetkovic V, Mörtberg U, Deal B, Destouni G. 2017. Distinction, quantification and mapping of potential and realized supply-demand of flow-dependent ecosystem services. Science of The Total Environment 593-594:599–609. doi:10.1016/j.scitotenv.2017.03.130.

Goldenberg R, Kalantari Z, Destouni G. 2018. Increased access to nearby green–blue areas associated with greater metropolitan population well-being. Land Degradation & Development 29:3607–3616. doi:10.1002/ldr.3083.

Gren Colding J, Berghauser-Pont M, Marcus L. 2019. How smart is smart growth? Examining the environmental validation behind city compaction. Ambio 48:580–589. doi:10.1007/s13280-018-1087-y.

Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, Schlesinger WH, Shoch D, Siikamäki JV, Smith P, Woodbury P, Zganjar C, Blackman A, Campari J, Conant RT, Delgado C, Elias P, Gopalakrishna T, Hamsik MR, Herrero M, Kiesecker J, Landis E, Laestadius L, Leavitt SM, Minnemeyer S, Polasky S, Potapov P, Putz FE, Sanderman J, Silvius M, Wollenberg E, Fargione J. 2017. Natural climate solutions. Proceedings of the National Academy of Sciences 114:11645–11650. doi:10.1073/pnas.1710465114. Publisher: Proceedings of the National Academy of Sciences.

Han J, Meng X, Zhou X, Yi B, Liu M, Xiang WN. 2017. A long-term analysis of urbanization process, landscape change, and carbon sources and sinks: A case study in China's Yangtze River Delta region. Journal of Cleaner Production 141:1040–1050. doi:10.1016/j.jclepro.2016.09.177.

Hankey S, Marshall JD. 2010. Impacts of urban form on future US passenger-vehicle greenhouse gas emissions. Energy Policy 38:4880–4887. doi:10.1016/j.enpol.2009.07.005.

Harris B, Batty M. 1993. Locational Models, Geographic Information and Planning Support Systems. Journal of Planning Education and Research 12:184–198. doi:10.1177/0739456X9301200302.

Haslauer E, Biberacher M, Blaschke T. 2012. GIS-based Backcasting: An innovative method for parameterisation of sustainable spatial planning and resource management. Futures 44:292–302. doi:10.1016/j.futures.2011.10.012.

Hobbs TJ, Neumann CR, Meyer WS, Moon T, Bryan BA. 2016. Models of reforestation productivity and carbon sequestration for land use and climate change adaptation planning in South Australia. Journal of Environmental Management 181:279–288. doi:10.1016/j.jenvman.2016.06.049.

Humborg C, Mörth CM, Sundbom M, Borg H, Blenckner T, Giesler R, Ittekkot V. 2010. CO2 supersaturation along the aquatic conduit in Swedish watersheds as constrained by terrestrial respiration, aquatic respiration and weathering. Global Change Biology 16:1966–1978. doi:10.1111/j.1365-2486.2009.02092.x.

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Japan: Institute for Global Environmental Strategies (IGES).

Jansson Nohrstedt P. 2001. Carbon sinks and human freshwater dependence in Stockholm County. Ecological Economics 39:361–370. doi:10.1016/S0921-8009(01)00224-5.

Kalantari Z, Ferreira C, Page J, Goldenberg R, Olsson J, Destouni G. 2019a. Meeting sustainable development challenges in growing cities: Coupled social-ecological systems modeling of land use and water changes. Journal of Environmental Management 245:471–480. doi:10.1016/j.jenvman.2019.05.086.

Kalantari Z, Ferreira CSS, Deal B, Destouni G. 2019b. Nature-based solutions for meeting environmental and socio-economic challenges in land management and development. Land Degradation & Development 31:1867–1870. doi:10.1002/ldr.3264. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ldr.3264.

Kalantari Z, Ferreira CSS, Koutsouris AJ, Ahlmer AK, Cerdà A, Destouni G. 2019c. Assessing flood probability for transportation infrastructure based on catchment characteristics, sediment connectivity and remotely sensed soil moisture. Science of The Total Environment 661:393–406. doi:10.1016/j.scitotenv.2019.01.009.

Keith H, Vardon M, Obst C, Young V, Houghton RA, Mackey B. 2021. Evaluating nature-based solutions for climate mitigation and conservation requires comprehensive carbon accounting. Science of The Total Environment 769:144341. doi:10.1016/j.scitotenv.2020.144341.

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

Ki D, Lee S. 2021. Analyzing the effects of Green View Index of neighborhood streets on walking time using Google Street View and deep learning. Landscape and Urban Planning 205:103920. doi:10.1016/j.landurbplan.2020.103920.

Klosterman RE. 1997. Planning support systems: A new perspective on computer-aided planning. Journal of Planning Education and Research 17:45–54. doi:10.1177/0739456X9701700105.

Kraucunas I, Clarke L, Dirks J, Hathaway J, Hejazi M, Hibbard K, Huang M, Jin C, Kintner-Meyer M, van Dam KK, Leung R, Li HY, Moss R, Peterson M, Rice J, Scott M, Thomson A, Voisin N, West T. 2015. Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA). Climatic Change 129:573–588. doi:10.1007/s10584-014-1064-9.

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

Kumar V, Parihar RD, Sharma A, Bakshi P, Singh Sidhu GP, Bali AS, Karaouzas I, Bhardwaj R, Thukral AK, Gyasi-Agyei Y, Rodrigo-Comino J. 2019. Global evaluation of heavy metal content in surface water bodies: A meta-analysis using heavy metal pollution indices and multivariate statistical analyses. Chemosphere 236:124364. doi:10.1016/j.chemosphere.2019.124364.

Kätterer T, Bolinder MA, Berglund K, Kirchmann H. 2012. Strategies for carbon sequestration in agricultural soils in northern Europe. Acta Agriculturae Scandinavica, Section A — Animal Science 62:181–198. doi:10.1080/09064702.2013.779316.

Landschützer P, Gruber N, Bakker DCE, Schuster U. 2014. Recent variability of the global ocean carbon sink. Global Biogeochemical Cycles 28:927–949. doi:10.1002/2014GB004853.

Lantmäteriet. 2017. GSD-Fastighetskartan vektor.

Larsen HN, Hertwich EG. 2010. Implementing carbon-footprint-based calculation tools in municipal greenhouse gas inventories. Journal of Industrial Ecology 14:965–977. doi:10.1111/j.1530-9290.2010.00295.x. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1530-9290.2010.00295.x.

Lavalle C, Kompil M, Aurambout JP. 2015. UI - Boundaries for the functional urban areas (LUISA Platform REF2014) Publisher: European Commission, Joint Research Centre (JRC).

Le Quéré C, Peters GP, Andres RJ, Andrew RM, Boden TA, Ciais P, Friedlingstein P, Houghton RA, Marland G, Moriarty R, Sitch S, Tans P, Arneth A, Arvanitis A, Bakker DCE, Bopp L, Canadell JG, Chini LP, Doney SC, Harper A, Harris I, House JI, Jain AK, Jones SD, Kato E, Keeling RF, Klein Goldewijk K, Körtzinger A, Koven C, Lefèvre N, Maignan F, Omar A, Ono T, Park GH, Pfeil B, Poulter B, Raupach MR, Regnier P, Rödenbeck C, Saito S, Schwinger J, Segschneider J, Stocker BD, Takahashi T, Tilbrook B, van Heuven S, Viovy N, Wanninkhof R, Wiltshire A, Zaehle S. 2014. Global carbon budget 2013. Earth System Science Data 6:235–263. doi:https://doi.org/10.5194/essd-6-235-2014.

Liu C, Shen Q. 2011. An empirical analysis of the influence of urban form on household travel and energy consumption. Computers, Environment and Urban Systems 35:347–357. doi:10.1016/j.compenvurbsys.2011.05.006.

Lubowski RN, Plantinga AJ, Stavins RN. 2006. Land-use change and carbon sinks: Econometric estimation of the carbon sequestration supply function. Journal of Environmental Economics and Management 51:135–152. doi:10.1016/j.jeem.2005.08.001.

Luyssaert S, Inglima I, Jung M, Richardson AD, Reichstein M, Papale D, Piao SL, Schulze ED, Wingate L, Matteucci G, Aragao L, Aubinet M, Beer C, Bernhofer C, Black KG, Bonal D, Bonnefond JM, Chambers J, Ciais P, Cook B, Davis KJ, Dolman AJ, Gielen B, Goulden M, Grace J, Granier A, Grelle A, Griffis T, Grünwald T, Guidolotti G, Hanson PJ, Harding R, Hollinger DY, Hutyra LR, Kolari P, Kruijt B, Kutsch W, Lagergren F, Laurila T, Law BE, Maire GL, Lindroth A, Loustau D, Malhi Y, Mateus J, Migliavacca M, Misson L, Montagnani L, Moncrieff J, Moors E, Munger JW, Nikinmaa E, Ollinger SV, Pita G, Rebmann C, Roupsard O, Saigusa N, Sanz MJ, Seufert G, Sierra C, Smith ML, Tang J, Valentini R, Vesala T, Janssens IA. 2007. CO2 balance of boreal, temperate, and tropical forests derived from a global database. Global Change Biology 13:2509–2537. doi:10.1111/j.1365-2486.2007.01439.x.

Länsstyrelsen Stockholm. 2011. Kartläggning av riskerna för översvämning i tunnelsystemen i Stockholms län. text. Länsstyrelsen i Stockholms Län. Stockholm.

Marcotullio PJ, Sarzynski A, Albrecht J, Schulz N. 2014. A top-down regional assessment of urban greenhouse gas emissions in Europe. AMBIO 43:957–968. doi:10.1007/s13280-013-0467-6.

McEvoy S, van de Ven FHM, Blind MW, Slinger JH. 2018. Planning support tools and their effects in participatory urban adaptation workshops. Journal of Environmental Management 207:319–333. doi:10.1016/j.jenvman.2017.10.041.

Melaku Canu D, Ghermandi A, Nunes PALD, Lazzari P, Cossarini G, Solidoro C. 2015. Estimating the value of carbon sequestration ecosystem services in the Mediterranean Sea: An ecological economics approach. Global Environmental Change 32:87–95. doi:10.1016/j.gloenvcha.2015.02.008.

Miljömålse. 2018. Dataunderlag – Åkermark.

Moore K. 2018. Sweden’s housing problem. Publisher: Montly Policy Review.

Mori AS, Dee LE, Gonzalez A, Ohashi H, Cowles J, Wright AJ, Loreau M, Hautier Y, Newbold T, Reich PB, Matsui T, Takeuchi W, Okada Ki, Seidl R, Isbell F. 2021. Biodiversity–productivity relationships are key to nature-based climate solutions. Nature Climate Change 11:543–550. doi:10.1038/s41558-021-01062-1.

Mörtberg U, Goldenberg R, Kalantari Z, Kordas O, Deal B, Balfors B, Cvetkovic V. 2017. Integrating ecosystem services in the assessment of urban energy trajectories – A study of the Stockholm Region. Energy Policy 100:338–349. doi:10.1016/j.enpol.2016.09.031.

Mörtberg U, Haas J, Zetterberg A, Franklin JP, Jonsson D, Deal B. 2013. Urban ecosystems and sustainable urban development—analysing and assessing interacting systems in the Stockholm region. Urban Ecosystems 16:763–782. doi:10.1007/s11252-012-0270-3.

Nag SK, Liu R, Lal R. 2017. Emission of greenhouse gases and soil carbon sequestration in a riparian marsh wetland in central Ohio. Environmental Monitoring and Assessment 189:580. doi:10.1007/s10661-017-6276-9.

Nejat P, Jomehzadeh F, Taheri MM, Gohari M, Abd Majid MZ. 2015. A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries). Renewable and Sustainable Energy Reviews 43:843–862. doi:10.1016/j.rser.2014.11.066.

Newton AC, Cantarello E. 2015. Restoration of forest resilience: An achievable goal? New Forests 46:645–668. doi:10.1007/s11056-015-9489-1.

OpenStreetMap. 2021. OpenStreetMap.

Page J, Kåresdotter E, Destouni G, Pan H, Kalantari Z. 2021. A more complete accounting of greenhouse gas emissions and sequestration in urban landscapes. Anthropocene 34:100296. doi:10.1016/j.ancene.2021.100296.

Page J, Mörtberg U, Destouni G, Ferreira CSS, Näsström H, Kalantari Z. 2020. Open-source planning support system for sustainable regional planning: A case study of Stockholm County, Sweden. Environment and Planning B: Urban Analytics and City Science 47:1508–1523. doi:https://doi.org/10.1177/2399808320919769.

Pan H, Deal B, Destouni G, Zhang Y, Kalantari Z. 2018. Sociohydrology modeling for complex urban environments in support of integrated land and water resource management practices. Land Degradation & Development 29:3639–3652. doi:10.1002/ldr.3106.

Pan H, Page J, Shi R, Cong C, Cai Z, Barthel S, Thollander P, Colding J, Kalantari Z. 2023. Potential contribution of prioritized spatial allocation of nature-based solutions to climate neutrality in major EU cities. [Manuscript]. doi:10.21203/rs.3.rs-2399348/v1.

Pan H, Page J, Zhang L, Chen S, Cong C, Destouni G, Kalantari Z, Deal B. 2019a. Using comparative socio-ecological modeling to support Climate Action Planning (CAP). Journal of Cleaner Production 232. doi:10.1016/j.jclepro.2019.05.274.

Pan H, Page J, Zhang L, Cong C, Ferreira C, Jonsson E, Näsström H, Destouni G, Deal B, Kalantari Z. 2020. Understanding interactions between urban development policies and GHG emissions: A case study in Stockholm Region. Ambio 49:1313–1327. doi:10.1007/s13280-019-01290-y.

Pan H, Zhang L, Cong C, Deal B, Wang Y. 2019b. A dynamic and spatially explicit modeling approach to identify the ecosystem service implications of complex urban systems interactions. Ecological Indicators 102:426–436. doi:10.1016/j.ecolind.2019.02.059.

Pelzer P, Arciniegas G, Geertman S, Lenferink S. 2015. Planning support systems and task-technology fit: a comparative case study. Applied Spatial Analysis and Policy 8:155–175. doi:10.1007/s12061-015-9135-5.

Pettit C, Bakelmun A, Lieske SN, Glackin S, Hargroves Khomson G, Shearer H, Dia H, Newman P. 2018. Planning support systems for smart cities. City, Culture and Society 12:13–24. doi:10.1016/j.ccs.2017.10.002.

Pichler PP, Zwickel T, Chavez A, Kretschmer T, Seddon J, Weisz H. 2017. Reducing urban greenhouse gas footprints. Scientific Reports 7:14659. doi:10.1038/s41598-017-15303-x.

Pielke RA, Marland G, Betts RA, Chase TN, Eastman JL, Niles JO, Niyogi DDS, Running SW. 2002. The influence of land-use change and landscape dynamics on the climate system: relevance to climate-change policy beyond the radiative effect of greenhouse gases. Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences 360:1705–1719. doi:10.1098/rsta.2002.1027.

Quan SJ, Minter JD, Yang PPJ. 2013. A GIS-based performance metrics for designing a low energy urban agriculture system. In: S Geertman, F Toppen, J Stillwell, editors. Planning Support Systems for Sustainable Urban Development. Lecture Notes in Geoinformation and Cartography. Berlin, Heidelberg: Springer. p. 225–247. doi:10.1007/978-3-642-37533-0_13.

Raymond PA, Hartmann J, Lauerwald R, Sobek S, McDonald C, Hoover M, Butman D, Striegl R, Mayorga E, Humborg C, Kortelainen P, Dürr H, Meybeck M, Ciais P, Guth P. 2013. Global carbon dioxide emissions from inland waters. Nature 503:355–359. doi:10.1038/nature12760.

Region Stockholm. 2022. Koldioxidbudget för Stockholms län 2022 [Kombinerad].

Rodrigo-Comino J, Senciales JM, Cerdà A, Brevik EC. 2018. The multidisciplinary origin of soil geography: A review. Earth-Science Reviews 177:114–123. doi:10.1016/j.earscirev.2017.11.008.

Russo P, Lanzilotti R, Costabile MF, Pettit CJ. 2017. Adoption and Use of Software in Land Use Planning Practice: A Multiple-Country Study. International Journal of Human–Computer Interaction 34:57–72. doi:10.1080/10447318.2017.1327213.

Schmidt S, Södersten CJ, Wiebe K, Simas M, Palm V, Wood R. 2019. Understanding GHG emissions from Swedish consumption - Current challenges in reaching the generational goal. Journal of Cleaner Production 212:428–437. doi:10.1016/j.jclepro.2018.11.060.

Schulp CJE, Nabuurs GJ, Verburg PH. 2008. Future carbon sequestration in Europe—Effects of land use change. Agriculture, Ecosystems & Environment 127:251–264. doi:10.1016/j.agee.2008.04.010.

Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu TH. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319:1238–1240. doi:10.1126/science.1151861. Publisher: American Association for the Advancement of Science.

Seddon N, Chausson A, Berry P, Girardin CAJ, Smith A, Turner B. 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philosophical Transactions of the Royal Society B: Biological Sciences 375:20190120. doi:10.1098/rstb.2019.0120. Publisher: Royal Society.

Seung-Hwan Y, Jin-Yong C, Sang-Hyun L, Yun-Gyeong O, Dong Koun Y. 2013. Climate change impacts on water storage requirements of an agricultural reservoir considering changes in land use and rice growing season in Korea. Agricultural Water Management 117:43–54. doi:10.1016/j.agwat.2012.10.023.

Smith P, Andrén O, Karlsson T, Perälä P, Regina K, Rounsevell M, Wesemael BV. 2005. Carbon sequestration potential in European croplands has been overestimated. Global Change Biology 11:2153–2163. doi:10.1111/j.1365-2486.2005.01052.x.

Statistiska Centralbyrån. 2016. Sveriges framtida befolkning 2016–2060. Technical Report SCB-2016-BE18SM1601_pdf. Statistiska Centralbyrån.

Statistiska Centralbyrån. 2023. Population by region and year.

Stockholms Stad. 2016. Strategy for a fossil-fuel free Stockholm by 2040. Technical report. City Executive Office. Stockholm.

Storstockholms Lokaltrafik. 2017. Fakta om SL och länet 2016. Technical report. Trafikförvaltningen Stockholms läns landsting. Stockholm.

Thompson I, Mackey B, McNulty S, Mosseler A. 2009. Forest resilience, biodiversity, and climate change. Secretariat of the Convention on Biological Diversity, Montreal. Technical Series no. 43. 1-67. 43:1–67.

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

Tillväxt- och Regionplaneförvaltningen. 2016. Klimatarbetet i Stockholmsregionen. Technical Report TRN 2016-0082. Stockholms Läns Landsting. Stockholm.

Tillväxt- och Regionplaneförvaltningen. 2017. Regional Utvecklingsplan För Stockholmsregionen (RUFS) 2050.

Tong D, Zhang Q, Davis SJ, Liu F, Zheng B, Geng G, Xue T, Li M, Hong C, Lu Z, Streets DG, Guan D, He K. 2018. Targeted emission reductions from global super-polluting power plant units. Nature Sustainability 1:59–68. doi:10.1038/s41893-017-0003-y. Number: 1 Publisher: Nature Publishing Group.

Tranvik LJ, Downing JA, Cotner JB, Loiselle SA, Striegl RG, Ballatore TJ, Dillon P, Finlay K, Fortino K, Knoll LB, Kortelainen PL, Kutser T, Larsen S, Laurion I, Leech DM, McCallister SL, McKnight DM, Melack JM, Overholt E, Porter JA, Prairie Y, Renwick WH, Roland F, Sherman BS, Schindler DW, Sobek S, Tremblay A, Vanni MJ, Verschoor AM, Wachenfeldt Ev, Weyhenmeyer GA. 2009. Lakes and reservoirs as regulators of carbon cycling and climate. Limnology and Oceanography 54:2298–2314. doi:10.4319/lo.2009.54.6_part_2.2298.

United Nations. 2015. The Paris Agreement.

United Nations Development Programme. 2023. Sustainable Development Goals.

Vaccari FP, Gioli B, Toscano P, Perrone C. 2013. Carbon dioxide balance assessment of the city of Florence (Italy), and implications for urban planning. Landscape and Urban Planning 120:138–146. doi:10.1016/j.landurbplan.2013.08.004.

van den Bosch M, Nieuwenhuijsen M. 2017. No time to lose – Green the cities now. Environment International 99:343–350. doi:10.1016/j.envint.2016.11.025.

Velasco E, Segovia E, Choong AMF, Lim BKY, Vargas R. 2021. Carbon dioxide dynamics in a residential lawn of a tropical city. Journal of Environmental Management 280:111752. doi: 10.1016/j.jenvman.2020.111752.

Vonk G, Geertman S, Schot P. 2005. Bottlenecks blocking widespread usage of planning support systems. Environment and Planning A: Economy and Space 37:909–924. doi:10.1068/a3712.

Waddell P. 2002. UrbanSim: Modeling urban development for land use, transportation, and environmental planning. Journal of the American Planning Association 68:297–314. doi: 10.1080/01944360208976274.

Wallin MB, Audet J, Peacock M, Sahlée E, Winterdahl M. 2020. Carbon dioxide dynamics in an agricultural headwater stream driven by hydrology and primary production. Biogeosciences 17:2487–2498. doi:https://doi.org/10.5194/bg-17-2487-2020.

Wu T, Wang Y, Yu C, Chiarawipa R, Zhang X, Han Z, Wu L. 2012. Carbon Sequestration by Fruit Trees - Chinese Apple Orchards as an Example. PLOS ONE 7:e38883. doi:10.1371/journal.pone.0038883.

Xi C, Ding J, Wang J, Feng Z, Cao SJ. 2022. Nature-based solution of greenery configuration design by comprehensive benefit evaluation of microclimate environment and carbon sequestration. Energy and Buildings 270:112264. doi:10.1016/j.enbuild.2022.112264.

Xu C, Haase D, Su M, Yang Z. 2019. The impact of urban compactness on energy-related greenhouse gas emissions across EU member states: Population density vs physical compactness. Applied Energy 254:113671. doi:10.1016/j.apenergy.2019.113671.

A Data summary

Table A.1. Summary of data sources used in modelling in Papers I-IV. Adapted and extended from Supplementary Table 1 in Paper I (Page et al., 2020)

Data Type	**Description**	**Used in**	**Source**
Demographic projection (Stockholm)	Tables of current and predicted population values for the entire Stockholm County, and for individual municipalities.	LEAM input, Papers I & II	(Tillväxt- och Regionplaneförvaltningen, 2017)
Flood maps	Flood potential maps for Stockholm County	LEAM input, Papers I & II	(Länsstyrelsen Stockholm, 2011)
Forest data	Forest age and type data from Copernicus Forests Dominant Leaf Type (DLT-2015-20m) maps.	Carbon sink mapping, Paper II	(European Environment Agency, 2018)
FUAs	Functional urban area boundaries for the cities in Europe	Study boundaries, Paper IV	(Lavalle et al., 2015)
GHG emissions (GID)	Global emissions grid for different sectors	GHG emissions, Paper IV	(Global Infrastructure Emissions Database, 2021)
Land use	Land use/cover classification map for Stockholm County updated in 2011 and 2018.	LEAM input, Paper I and carbon sequestration mapping, Paper III.	(Goldenberg et al., 2018)
	Corine land cover (CLC) file for the whole of Europe, updated 2018 (CLC European seamless vector database version 18_5)	Input for LEAM and sequestration mapping, Papers II & III, and emissions breakdown and NbS allocation, Paper IV	(European Environment Agency, 2019)
	Urban Atlas land cover files available for European cities, with finer detail but less coverage than CLC	Used to refine CLC data as needed, input for LEAM and sequestration mapping, Papers II & III	(European Environment Agency, 2020)
Municipal growth map (Stockholm)	Municipality map with a growth factor for each municipality, based on the demographic projection	LEAM input, Papers I & II	(Tillväxt- och Regionplaneförvaltningen, 2017)
Municipality border map (Stockholm)	Borders of the municipalities in the county	LEAM input, Papers I & II	(Tillväxt- och Regionplaneförvaltningen, 2017)
Population and employment centres (Stockholm)	Map of the existing population and employment centres in Stockholm County.	LEAM input, Papers I & II	(Mörtberg et al., 2017; Statistiska Centralbyrån, 2016)

Data Type	**Description**	**Used in**	**Source**
Population	Population grid for the whole of Europe from Eurostat.	Input for emissions breakdown and NbS allocation, Paper IV	(Batista et al., 2021)
Public transport stations (Stockholm)	Public transport stops in Stockholm County, including train, tram, light rail, metro stations, and major bus stops. Also includes planned future stations on existing and planned transport lines.	LEAM input, Papers I & II	(Tillväxt- och Regionplaneförvaltningen, 2017)
Public transport travel (Stockholm)	Tables listing the numbers of people boarding public transportation vehicles daily at each station.	LEAM input, Papers I & II	(Storstockholms Lokaltrafik, 2017)
Restricted areas (Stockholm)	Maps of protected areas such as nature reserves, along with other areas unsuitable for urban development as advised by Stockholm County, such as forests valuable for recreation, water bodies and parks.	LEAM input, Papers I & II	(Tillväxt- och Regionplaneförvaltningen, 2017)
Road network	Map of the existing road network in Stockholm County in 2015, plus additional planned road investments beyond 2015.	LEAM input, Papers I & II	(Tillväxt- och Regionplaneförvaltningen, 2017)
	Maps of the road network across the 54 selected EU cities from Open Street Maps	Input for emissions breakdown and NbS allocation, Paper IV	(OpenStreetMap, 2021)
Stream length	Stream data in Stockholm extracted from Lantmäteriet's product GSD-Fastighetskartan vektor	Fresh water emissions calculations, Paper III	(Lantmäteriet, 2017)
Topography (Stockholm)	Digital Elevation Model (DEM) of the county terrain.	LEAM input, Papers I & II	(Lantmäteriet, 2017)