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Stockholm University

Nature in urban regions

Understanding linkages and benefits to human populations

Romain Goldenberg

Doctoral Thesis in Physical Geography at Stockholm University, Sweden 2021

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Understanding linkages and benefits to human populations

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Academic dissertation for the Degree of Doctor of Philosophy in Physical Geography at Stockholm University to be publicly defended on Friday 12 March 2021 at 13.00 in De Geersalen, Geovetenskapens hus, Svante Arrhenius väg 14, and digitally via conference (Zoom), public link https://stockholmuniversity.zoom.us/j/62791936448

Abstract

The future of the world will be urban, with now the largest share of the global population in recorded history living in cities. Urbanization implies a progressive environmental and land-use transformation, from natural ecosystems to artificial materials, shaped by the tension between unregulated organic trends and urban planning. Being the living habitat of most of the current, and likely future generations, growing cities need to remain well functioning, equitable and livable, which includes access to natural areas and the benefits these can provide for urban inhabitants. A key scientific challenge is to understand and quantify these human-nature relationships at scales relevant for cities and urban management. This thesis aims at advancing spatially explicit quantification methods and knowledge regarding accessibility to nature and ecosystem services (i.e. benefits to humans provided by the natural environment) for different urban population groups and in various cities. A main urban study area is the Swedish Stockholm region, while comparative ecosystem service quantifications also extend to and across a large set of European cities. The methods include conceptual developments and spatial modeling for quantification of the targeted urban human-nature relationships. Results show a positive relationship between proximity to green-blue natural areas and income level of urban inhabitants, while dense urban, industrial and commercial areas are less desirable features associated with lower income levels. Income levels also correlate with ethnicity, which thereby also correlates with green-blue area proximity, highlighting an additional spatial segregation perspective for urban regions. A conflict emerging is that people who can afford it choose surroundings with more nature, while further urbanization requires further densification. Care must then be taken not to deplete vital natural areas to the detriment of urban populations, and in particular their less privileged parts. Results also highlight the need to account for the actual spatial connections of humans and their demands for nature's benefits with the natural areas that can supply these benefits. For example, for the service of local climate regulation (i.e. the ability of natural areas to dampen urban heat island effects and temperature extremes) the thesis investigates conditions in 660 European cities. Results show overall power-law relationships of ecosystem service realization with city population density, but also large variations among cities with similar population densities. Thus, variations in urban forms and land covers, resulting, e.g., from distinct histories and socio-economic evolutions of cities in different countries, lead to measurably better or worse outcomes for provision of the studied ecosystem service. In particular, large divergence is found between cities of eastern and western European countries. Methods developed and results obtained show a practically relevant, comparative quantification approach to cities and their urban ecosystem services as coupled socio-ecological systems, with implications for projection of change trends under urban and economic growth. These can be first steps towards further advancement and improvement needed for spatially explicit quantification and projection of urban ecosystem services and their incorporation in planning, strategy and practice for maintained and enhanced urban well-being.

Keywords: *ecosystem services, urban, socio-economics, green-blue areas, spatial accessibility, urban planning, Stockholm, Europe, cities.*

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Abstract

The future of the world will be urban, with now the largest share of the global population in recorded history living in cities. Urbanization implies a progressive environmental and land-use transformation, from natural ecosystems to artificial materials, shaped by the tension between unregulated organic trends and urban planning. Being the living habitat of most of the current, and likely future generations, growing cities need to remain well functioning, equitable and livable, which includes access to natural areas and the benefits these can provide for urban inhabitants. A key scientific challenge is to understand and quantify these human-nature relationships at scales relevant for cities and urban management. This thesis aims at advancing spatially explicit quantification methods and knowledge regarding accessibility to nature and ecosystem services (i.e. benefits to humans provided by the natural environment) for different urban population groups and in various cities. A main urban study area is the Swedish Stockholm region, while comparative ecosystem service quantifications also extend to and across a large set of European cities. The methods include conceptual developments and spatial modeling for quantification of the targeted urban human-nature relationships. Results show a positive relationship between proximity to green-blue natural areas and income level of urban inhabitants, while dense urban, industrial and commercial areas are less desirable features associated with lower income levels. Income levels also correlate with ethnicity, which thereby also correlates with green-blue area proximity, highlighting an additional spatial segregation perspective for urban regions. A conflict emerging is that people who can afford it choose surroundings with more nature, while further urbanization requires further densification. Care must then be taken not to deplete vital natural areas to the detriment of urban populations, and in particular their less privileged parts. Results also highlight the need to account for the actual spatial connections of humans and their demands for nature's benefits with the natural areas that can supply these benefits. For example, for the service of local climate regulation (i.e. the ability of natural areas to dampen urban heat island effects and temperature extremes) the thesis investigates conditions in 660 European cities. Results show overall power-law relationships of ecosystem service realization with city population density, but also large variations among cities with similar population densities. Thus, variations in urban forms and land covers, resulting, e.g., from distinct histories and socio-economic evolutions of cities in different countries, lead to measurably better or worse outcomes for provision of the studied ecosystem service. In particular, large divergence is found between cities of eastern and western European countries. Methods developed and results obtained show a practically relevant, comparative quantification approach to cities and their urban ecosystem services as coupled socio-ecological systems, with implications for projection of change trends under urban and economic growth. These can be first steps towards further advancement and improvement needed for spatially explicit quantification and projection of urban ecosystem services and their incorporation in planning, strategy and practice for maintained and enhanced urban well-being.

Sammanfattning

Världens framtid kommer att vara urban, med den största andelen av jordens befolkning sedan historisk tid nu boende i städer. Urbanisering innebär en progressiv transformation av vår miljö och markanvändning, från naturliga ekosystem till artificiella material, som formas av friktionen mellan oreglerade organiska trender och stadsplanering. Genom att utgöra livsmiljö för många i nuvarande, och troligtvis framtida generationer, behöver växande städer förbi välfungerande, rättvisa och beboeliga, med tillgång till naturområden och de fördelar de kan tillhandahålla för stadens befolkning. En vetenskaplig nyckelfråga handlar om att förstå och kunna kvantifiera förhållandena mellan människa och natur på skalor relevanta för städer och stadsförvaltning. Den här avhandlingen syftar till att vidareutveckla rumsliga kvantifieringsmetoder och kunskap angående tillgänglighet till naturområden och ekosystemtjänster (dvs. de bidrag människan erhåller från naturen) för olika invånargrupper och städer. Ett huvudsakligt urbant studieområde i avhandlingen är den svenska Stockholmsregionen och jämförande kvantifieringar av ekosystemtjänster görs också för ett stort antal europeiska städer. Metoderna omfattar konceptuella utvecklingar och rumslig modellering för kvantifiering av specifika urbana förhållanden mellan människa och natur. Resultaten visar på positiv relation mellan närhet till (gröna-blå) naturområden och invånares inkomstnivå, medan förtätade urbana, industriella och kommersiella områden är mindre åtråvärda inslag förknippade med lägre inkomstnivåer. Inkomstnivåer korrelerar också med etnicitet, som i sin tur också korrelerar med närhet till gröna-blå områden, vilket framhäver ytterligare ett rumsligt segregeringsperspektiv för urbana regioner. En konflikt finns därmed i att de som har råd i större utsträckning väljer områden med mer natur, medan fortsatt urbanisering kräver utökad förtätning. Försiktighet krävs så att vitala naturområden inte utarmas till skada för den urbana befolkningen och särskilt för dess mindre priviligierade delar. Resultaten tydliggör också behov av att ta hänsyn till faktiska rumsliga kopplingar mellan människors efterfrågan på ekosystemtjänster och de naturområden som kan tillhandahålla dessa tjänster. Till exempel, för ekosystemtjänsten att reglera det lokala klimatet (dvs. naturområdens förmåga att dämpa urbana värmeöar och extremtemperaturer), undersöker denna avhandling förhållandena i över 660 europeiska städer. Resultaten visar vissa övergripande relationer mellan faktisk realisering av ekosystemtjänster och städers befolkningstäthet, men också att stora variationer finns mellan städer med liknande befolkningstäthet. Variationer i urbana former och marktäckning, till exempel på grund av olika historiska arv och socioekonomiska utvecklingar i olika länders städer, innebär mätbart bättre eller sämre förutsättningar för realisering av den undersökta ekosystemtjänsten. Specifikt framträder stora skillnader mellan öst- och västeuropeiska städer. De utvecklade metoderna och erhållna resultaten i den här avhandlingen visar på ett praktiskt relevant tillvägagångssätt för jämförande kvantifiering av urbana ekosystemtjänster som kopplade socio-ekologiska system i olika städer, med implikationer för framtidsprojektion av förändringstrender under urban och ekonomisk tillväxt. De kan utgöra första steg mot fortsatta framsteg och förbättringar som behövs för explicit rumslig kvantifiering och projektion av urbana ekosystemtjänster samt deras inkorporering i planering, strategi och praktik för att upprätthålla och stärka urbant välmående.

Dissertation content

This doctoral thesis consists of a summary and four papers (I-IV). The papers are referred to as Papers I to IV in the summary text, and are appended to the end of the thesis and reprinted with permission from the respective copyright holders:

I **Goldenberg, R.**, Kalantari, Z. and Destouni, G., 2018. Increased access to nearby green–blue areas associated with greater metropolitan population well-being. *Land Degradation & Development*, 29(10), pp.3607-3616. doi: 10.1002/ldr.3083.

Supplementary material to Paper I

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

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

IV **Goldenberg, R.**, Kalantari, Z. and Destouni, G., 2020. Comparative quantification of local climate regulation by green-blue urban areas in cities across Europe *[manuscript]*.

Supplementary material to Paper IV

Author contributions

I **RG** led the writing, compiled the datasets and did the data analysis. The study and related methods were designed by **RG** with help from **GD** and **ZK**. The writing was assisted by all co-authors.

II **RG** compiled the datasets and did the data analysis. The study and related methods were designed by **RG** with help from **UM** and **ZK**. **UM** led the writing, and was assisted by all co-authors.

III **RG** led the writing, compiled the datasets and did the data analysis. The study and related methods were designed by **RG** with help from **GD**, **UM** and **ZK**. The writing was assisted by all co-authors.

IV **RG** led the writing, compiled the datasets and did the data analysis. The study and related methods were designed by **RG** with help from **GD**. The writing was assisted by all co-authors.

Contents

Abbreviations

CLMS	Copernicus Land Monitoring Service
DAAC	Distributed Active Archive Center
DEM	Digital elevation model
DLT	Dominant leaf type
EEA	European Economic Area
Eff	Effectiveness measure
EFTA	European Free Trade Association
ES	Ecosystem service
EU 28	European Union
FUA	Functional urban area
GDP	Gross domestic product
Gi*	Gettis-Ord Gi statistic
HDI	Human development index
IMD	Imperviousness degree
J	Jaccard index
mad	Median absolute deviation
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA EOSDIS	National Aeronautics and Space Administration Earth Observing System Data and Information System
NDVI	Normalized difference vegetation index
ORP	Office of regional planning, Stockholm Region
OSM	OpenStreetMap
PD	Population density
Pd	Potential demand
Ps	Potential supply
Rd	Realized demand
Rs	Realized supply
SCB	Statistics Sweden
SEDAC	NASA Socioeconomic Data and Applications Center
SEK	Swedish krona
SEPA	Swedish Environmental Protection Agency
SGU	Swedish Geological Survey
TCD	Tree cover density
UHI	Urban heat island

1 Introduction

1.1 Urbanization and city science

For the past 70 years, the world's population has gone through a rapid shift from rural to urban living. Cities are now home to the largest share of the global population in recorded history, with 55% being urban dwellers (United Nations et al., 2019). The future of the world's population is urban, and in Sweden for example close to 87% of the population already lives in urban areas (United Nations et al., 2019). While the land footprint of cities represents less than 0.5% of the Earth's total land area (Schneider et al., 2009), cities are engines of economic activity and growth, and dominate the global energy consumption and associated CO2 emissions (Intergovernmental Panel on Climate Change, 2014).

Recognizing this global trend, numerous calls have been made to develop 'sustainable urban systems'; with the general goal of creating more resource and energy efficient urban systems (Ahlfeldt et al., 2018), and limiting the expansion of cities (Artmann et al., 2019) while improving the quality of life and well-being of their inhabitants (Acuto et al., 2018; European Environment Agency, 2009; Rosa, 2017). The increased urban spatial pressure, while favoring a good land-use mix, leads to an apparent dilemma of the 'compact city paradox' (Burton, 2016; de Roo, 2000; Neuman, 2016). For example, fostering compact urban development to prevent long commuting distances (and reduce energy use) and diminish the conversion of surrounding natural lands is at odds with the goal of increasing environmental quality and reduce social disadvantages (such as a lack of green spaces) in the cities themselves (Artmann et al., 2019). Moreover, cities are critical for both climate change mitigation and societal adaptation to future warming, and thus need to provide liveable environments while avoiding detrimental consequences from competing development interests (Creutzig et al., 2019; Rosenzweig et al., 2018). Such complex endeavors strive for urban system efficiency, and for some ideal and optimal use of land resources in city planning.

Theories on how cities function as complex systems are recent, and suggest that certain scaling laws and patterns may emerge from urban conditions (Batty, 2008). It has been observed that many urban properties, as disparate as average employees' wages or road surface amount, for example, scale with city size (Bettencourt et al., 2007; Bettencourt, 2013), although the universality of such characteristics is still debated (Arcaute et al., 2015; Cottineau et al., 2017). In any case, tackling such sustainable development challenges for urban areas is important (Seto et al., 2017), and an integrated science of urban systems is needed to understand and study the relationships among social, ecological, economic and built infrastructure systems (Bettencourt and West, 2010; McPhearson et al., 2016). This requires interdisciplinary theories, methods and approaches, and quantitative city analytics to provide useful new insights for cities and urban life (Higham et al., 2017).

1.2 Benefits of nature for cities

Among various urban concerns, access to nature for the urban populations, and more generally nature presence in cities, is a central issue (Pincetl, 2012; Turner et al., 2004), as also recognized by the UN 2030 agenda for sustainable development (Rosa, 2017). Natural areas can provide benefits to urban residents, while differences in accessibility to nature in cities also raise issues of justice and equity (Jennings et al., 2012). The 'correct amount' of nature for sustainable urban life is unclear (Shanahan et al., 2015; Wolch et al., 2014), and although direct causal relationships are difficult to establish, there is evidence of a positive relationship between natural areas and beneficial health effects (Lee and Maheswaran, 2011; Tzoulas et al., 2007; World Health Organization 2016). Access to green spaces promote physical activity (McCormack et al., 2010; Richardson et al., 2013; Sallis et al., 2016), as well as psychological well-being and stress reduction (Fuller et al., 2007; Nutsford et al., 2013; Ward Thompson et al., 2012), for example. Surrounding greenness also has a positive association with several other health indicators (Ekkel and de Vries, 2017; Triguero-Mas et al., 2015). Spatial relationships, for example between socio-economic characteristics of a population (e.g. ethnicity, income, etc) and urban greenery, are currently investigated by researchers in different world regions and cities (Barbosa et al., 2007; Jenerette et al., 2007; Schwarz et al., 2015). However, there is a large variety of methods, as well as variations in scale, size and definition of spatial units of analysis, which may lead to contradictory results (Ekkel and de Vries, 2017; Tan and Samsudin, 2017).

Another large interest of urban sustainability is the potential of natural areas to alleviate some urban problems (Bolund and Hunhammar, 1999; Gómez-Baggethun et al., 2013). Such benefits from green (vegetated) and blue (water-covered) areas is now commonly referred to as ecosystem services (ES), meaning the direct and indirect benefits people obtain from ecosystems (Millennium Ecosystem Assessment, 2005). Starting in the 1990s, researchers began to describe and quantify (mostly in economic terms) the value of natural capital and its associated services, considering that these were not given enough consideration in policy decisions due to essentially being public goods, with value outside of the economic market (Costanza et al., 1997). In general, ES are classified into three broad categories: provisioning, regulating, and cultural, with these categories in turn depending on supporting services (e.g. nutrient cycling, soil formation, etc) necessary for proper ecosystem functioning (Millennium Ecosystem Assessment, 2005). Provisioning services refer to the production of natural resources (e.g. food, raw materials, etc), regulating services to the maintenance of essential ecological processes and life support systems (e.g. climate regulation, water regulation, waste treatment, etc), while cultural services refer to opportunities for cognitive development (e.g. recreation, aesthetics, etc) (de Groot et al., 2002). For cities, the regulation of local air temperature by green-blue areas can, for example, help improve thermal comfort (Doick et al., 2014; Oke et al., 2017), decrease health risks related to the urban heat island (UHI) effects (D'Ippoliti et al., 2010; Gunawardena et al., 2017), and contribute to urban adaptation strategies for future climate warming (Rosenzweig et al., 2018). Green-blue areas can also reduce and delay excessive stormwater runoff trough infiltration, interception or evapotranspiration (Ahiablame et al., 2012; Berland et al., 2017; Chan et al., 2018), and provide a number of other ecosystem services (Gómez-Baggethun et al., 2013; Lovell and Taylor, 2013).

1.3 Problem description: nature accessibility and ES Framework

Although the compact city has become a leading concept with a focus on proximity and accessibility (Burgess et al., 2002; Tunström et al., 2018), striving for proper implementation of this concept is not an easy road, and trade-offs may be required between various social, economic and environmental dimensions (Westerink et al., 2013). Furthermore, being a 'green city' does not necessarily mean an equity of outcomes (e.g. equal nature availability) for all inhabitants (Wolch et al., 2014). The access and presence of nature is an important factor for well-being, and studying current and future urban environments of residents can improve our understanding and highlight some priorities for sustainable cities.

Moreover, while nature in cities can help solve some urban problems, the actual application of the ES concept remains complex, with weak incorporation into urban policy and planning in most cities (Guerry et al., 2015; Haase et al., 2014). Nevertheless, advancing this application, for example by improving quantification and mapping capabilities, may be essential for helping to solve current and future urban challenges (de Groot et al., 2010). In particular, spatially explicit assessments and evaluations, which also include connection of nature's benefits with human beneficiaries, are recognized as important frontier factors in ES science (Kremer et al., 2016; Rieb et al., 2017). A range of challenges and research gaps still remain in ES research, in part due to different approaches, fragmented into various scientific disciplines, ambiguities in methods and in practice, and a variety of definitions employed (Bennett et al., 2015; Syrbe and Grunewald, 2017; Wolff et al., 2015).

In general, ES can be conceptualized as the relationship between supply, or the capacity of a natural area to provide a service, and demand, or the need of human populations for a service (Burkhard et al., 2012). However, few ES applications consider demand, and even fewer the connection between spatially explicit supply and demand (Rieb et al., 2017). This is a problem, because areas of ES provision (supply) and use (demand) differ over a landscape but are connected by some form of spatial transfer pathway (Bagstad et al., 2013; Fisher et al., 2009; Syrbe and Walz, 2012), like air, water, or human movement, e.g., over the urban surface, through pipelines, or by vehicles, respectively. Applying ES supply and demand concepts, and assessing their actual connectivity at relevant spatial scale, is essential to understand the real benefits from nature for urban areas and their population.

1.4 Aims and scope of the thesis

Figure 1 illustrates schematically the scope of this thesis, which has the overarching aim to advance our understanding of sustainable urbanization, in particular by considering and providing insights on the function of urban areas as coupled socio-ecological systems.

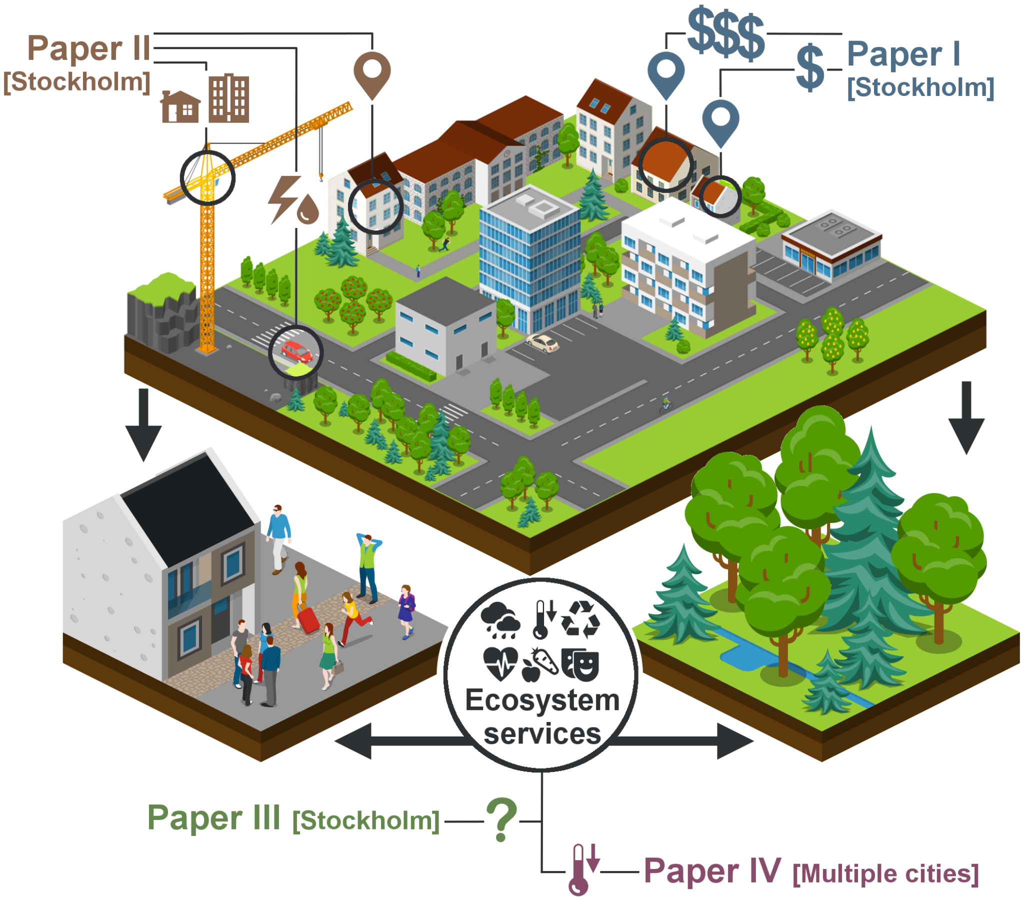

Figure 1: Overview of the scope of the thesis. Paper I focuses on the relationship between socio-economic background and local living environment. Paper II focuses on the relationship between scenarios of urban development, local environment and travel distances. Paper III develop a spatially explicit methodology for ES mapping and quantification, while paper IV further develop and apply the method for the ES of local climate regulation across 660 cities in Europe (created using icograms.com)

To meet this aim, four main objectives of the thesis are summarized as follows:

A. Investigate what constitutes a preferable environment for an urban population, by quantifying the relationship between the socio-economic conditions of inhabitants and the composition of their nearby living environment and nature accessibility. **[Paper I]**

B. Investigate trade-offs between various possible future urban development scenarios and associated nature accessibility, with particular focus on the potential tradeoff between energy/resource efficiency and urban population preferences for nature accessibility. **[Paper II]**

C. Extend the integrative framework of ecosystem services (ES) for spatially explicit quantification and study of the ES supply contributed by nature and how this can meet actual human demand for such ES contributions in urban regions. **[Paper III]**

D. Further develop and apply the above methodology (Objective C) across a range of multiple cities in order to investigate and quantify how characteristic ES supply-demand indicators relate to the varying population and socio-economic conditions of different cities **[Paper IV]**

For the quantitative investigations related to the different specific objectives, the thesis focuses on the urban Stockholm region as a main case study considered for objectives A-C (Fig. 1, Papers I-III). Stockholm City within this region is also included as part of a large set of European cities studied for the multi-city objective D (Fig. 1, Paper IV).

2 Studied areas

The Stockholm county, or Stockholm Metropolitan region (Fig. 2a) is composed of 26 municipalities, which also include the capital city of Sweden, Stockholm. The Stockholm region is located in northern Europe (59°N, 18°E) and a land surface of approximately 6'500 km^2. This is the most populous region in Sweden, with approximately 2'377'000 habitants in the whole region (∼365 people/km^2), of which 974'000 live in the capital Stockholm City (Statistics Sweden, 2019). Stockholm region includes a large share of green-blue areas in comparison with other urban regions in Europe (Fuller and Gaston, 2009), although its green structure has become increasingly fragmented in recent years due to increasing population and urban expansion (Colding, 2013). It is also facing a substantial projected increase in population, approximately 500'000 more people by 2050, an augmentation of 21% compared to current situation (Statistics Sweden, 2019). In this context, and considering additional economic and social pressures, current political ambitions are to preserve natural areas within Stockholm region (Kaczorowska et al., 2016).

To also move beyond the Stockholm region case study, this thesis includes cross-city investigation (Fig. 1, Paper IV) of a set of 660 cities, distributed over 37 countries in the European Union (EU28), West Balkans and European Free Trade Association (EFTA) (Fig. 2b). These cities represent a variety of climate, vegetation, urban form and population characteristics, with the spatial delineation and definition of the cities based on

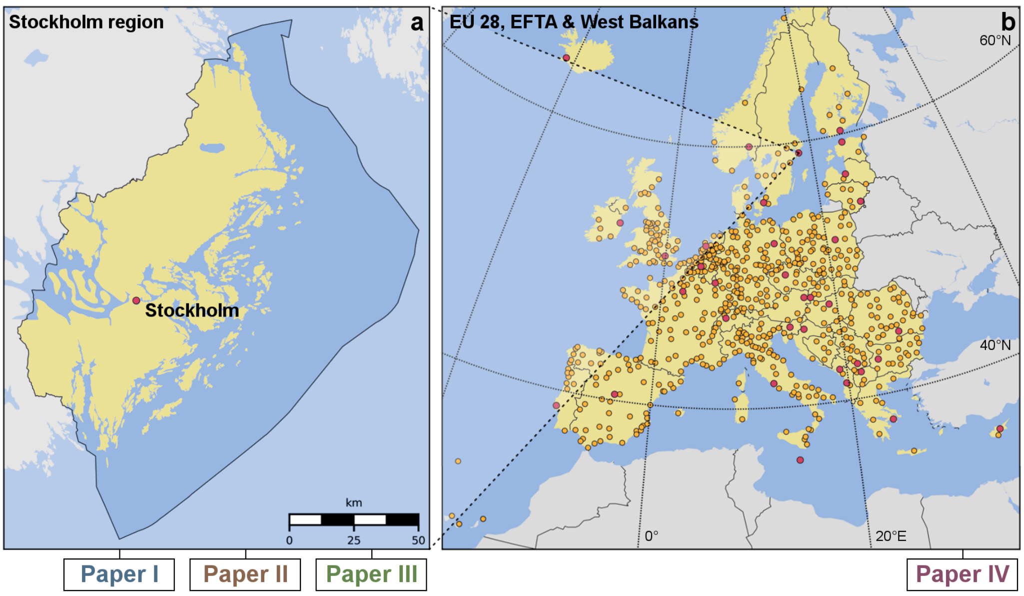

Figure 2: Overview of the thesis study sites from Paper I-IV. (a) Paper I-III consider the region of Stockholm, Sweden and (b) Paper IV includes 660 cities located in the European Union (EU 28), EFTA (European Free Trade Association) and West Balkans. Orange dots indicate cities, while red dots indicate capitals (modified from Fig. 1 in Paper I and Fig. 1 in Paper IV).

the official recommendations of the European statistics office (Eurostat, 2018). The city boundaries represent local administrative units, with at least 50% of the population living in one or more urban centers, and the latter identified as groups of grid cells with population density (PD) of at least 1'500 people/km^2 and collectively a population of at least 50'000 inhabitants (Eurostat, 2018). We focus here on the core cities, and not on larger urban zones (known as functional urban areas, or FUA) that also include lower density commuting zones. The city distribution over Europe depends on the considered countries, with for example 91 and 82 cities in Germany and France, respectively, 12 in Sweden, 2 each in Slovenia and Cyprus, and 1 each in Luxembourg and Iceland.

3 Methods

Methods in this thesis can be separated into two broad categories, considering quantitative measures of accessibility, and spatially explicit quantification of ES supply, demand and their connectivity. The methods are presented as such in the following sections, after first presenting the datasets and software used.

3.1 Datasets and software used

Spatial analyses, manipulations and modeling have been conducted using ArcMap (ESRI, 2020), the Python programming language (Van Rossum and Drake Jr, 1995), QGIS (QGIS Development Team, 2020), GME (Geospatial Modelling Environment - Hawthorne, 2014) and GeoDa (Anselin et al., 2010). All the spatial datasets used in Paper I-IV are summarized in Table 1 below, and further discussed in the following sections.

Table 1: Summary of the spatial datasets used in the four thesis papers.

Name [original name]	Resolution / Accuracy	Temporal reference	Source
Paper I			
Population count [B2_GRID]	250 m. in urban areas, 1km. in rural areas	2013	SCB (Statistics Sweden)
Median yearly income [IF1_GRID]	250 m. in urban areas, 1km. in rural areas	2012	SCB
Nationality [B5_GRID]	250 m. in urban areas, 1 km. in rural areas	2013	SCB
Land cover [Urban Atlas]	Geometric resolution: 0.25 ha, Positional accuracy: ±5 m.	2006	CLMS (Copernicus Land Monitoring Service)
Continuous habitat type mapping [Kontinuerlig Naturtypskartering]	25 m.	2004	SEPA (Swedish Environmental Protection Agency)
NDVI [MYD13Q1-MODIS/AQUA Vegetation Indices 16-Day L3 Global 250 m SIN Grid V006]	250 m.	June 2, 2015 to July 20, 2015 (3 × 16 days)	NASA EOSDIS Land Processes DAAC (LP-DAAC)
NDVI [MOD13Q1-MODIS/TERRA Vegetation Indices 16-Day L3 Global 250 m SIN Grid V006]	250 m.	June 10, 2015 to July 28, 2015 (3 × 16 days)	LPDAAC
Road network	-	2016	OSM (OpenStreetMap)
Paper II			
Population count [B2_GRID]	250 m. in urban areas, 1 km. in rural areas	2013	SCB
Employment statistics [A2_GRID]	250 m. in urban areas, 1 km. in rural areas	2012	SCB
Land cover [Urban Atlas]	Geometric resolution: 0.25 ha, Positional accuracy: ±5 m.	2006	CLMS
Continuous habitat type mapping [Kontinuerlig Naturtypskartering]	25 m.	2004	SEPA

Road network	-	2016	OSM
Regional development plans [Dense, Polycentric, Diffuse]	100 m.	2030	ORP (Office of Regional Planning, Stockholm Region)
Paper III			
Land cover [Swedish Land Cover Data]	25 m.	2000	Lantmäteriet (Swedish mapping, cadastral and land registration authority)
Continuous habitat type mapping [Kontinuerlig Naturtypskartering]	25 m.	2004	SEPA
Digital elevation model [Höjddata, grid 2+]	2 m.	2010	Lantmäteriet
Soil data [Jordater 1:25 000-1:100 000]	Varying resolution and precision	2010	SGU (Swedish Geological Survey)
Paper IV			
City boundaries [Urban Atlas]	Geometric resolution: 0.25 ha, Positional accuracy: ±5 m.	2012	CLMS
Land cover [Urban Atlas]	Geometric resolution: 0.25 ha, Positional accuracy: ±5 m.	2012	CLMS
Land cover [Corine Land Cover]	Min. mapping unit / width: 25 ha / 100 m., Geometric accuracy: better than 100 m.	2012	CLMS
Forests Dominant Leaf Type [DLT]	20 m.	2012	CLMS
Tree cover density [TCD]	20 m.	2012	CLMS
Water & Wetness [WAW]	20 m.	2015	CLMS
Imperviousness Density [IMD]	20 m.	2012	CLMS
Population Density [Gridded Population of the World, Version 4 (GPWv4): Population Density Adjusted to Match 2015 Revision UN WPP Country Totals, Revision 11]	30 arc-second (∼1 km. at the equator)	2015	SEDAC (NASA Socioeconomic Data and Applications Center)
NDVI [MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006]	250 m.	1st June to 1st September, 2011-2013 (7 × 16 days × 3 years)	LPDAAC
NDVI [MYD13Q1 MODIS/Aqua Vegetation Indices 16-Day L3 Global 250m SIN Grid V006]	250 m.	1st June to 1st September, 2011-2013 (6 × 16 days × 3 years)	LPDAAC

3.2 Analysis of accessibility and its relation to socioeconomics

For Papers I and II of the thesis, we modeled two different types of accessibility metrics, to assess the local living environment (Fig. 3a) and the amount of jobs reachable by motorized vehicles (Fig.3b). Such modelling was based on the road network of Stockholm region, with specificities of each method discussed further in the following. We also used different spatial datasets (listed in Table 1) for each paper, covering the whole region of interest.

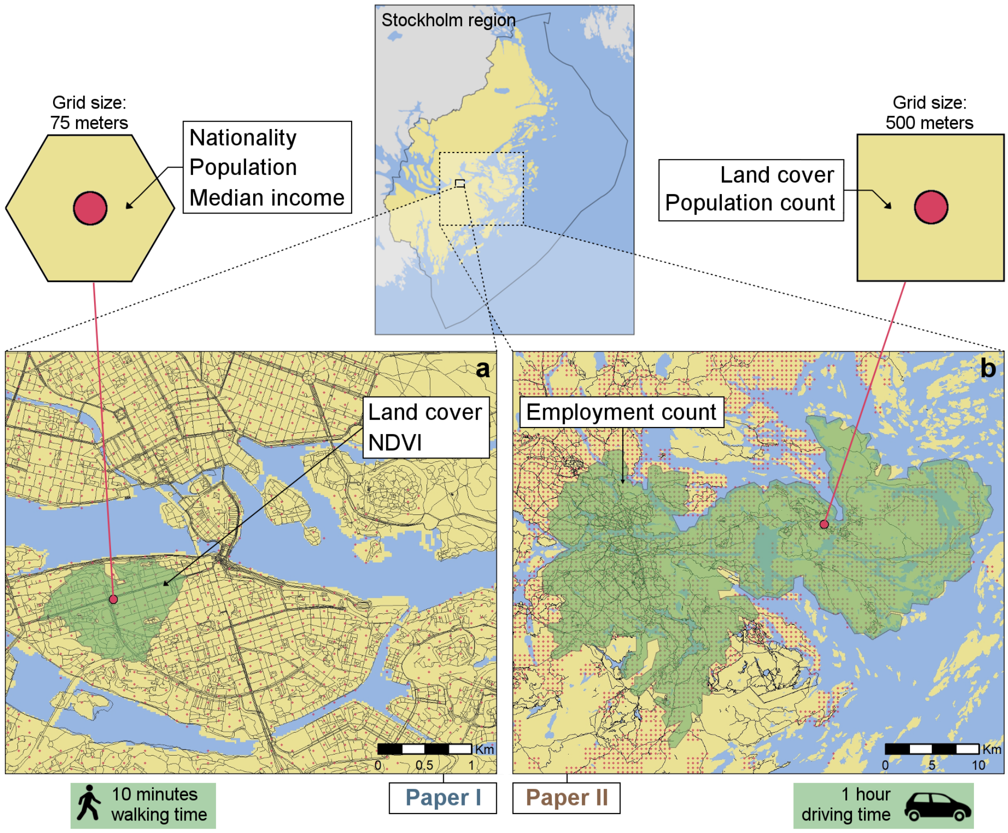

Figure 3: Graphical explanation of the methods used in Papers I-II, for a sample subset of the region and one sample data point. For Paper I, socio-economic variables are aggregated at 75 meters' hexagon scale, while physical cover is analyzed at walkshed scale (10 minutes walking time, propagated through the road network). For Paper II, physical cover and population counts are aggregated at 500 meters' square scale, while employment counts are calculated at driving scale (1 hour driving time, propagated through the road network).

3.2.1 Relationships between socio-economics and local environment

For Paper I, local landscape composition was assessed in relation to socio-economic measures, to understand urban population preferences for a living environment. Final land cover data (at 10 × 10 m. resolution) were synthesized by combining the Urban Atlas dataset and the Continuous Habitat Type Mapping (Table 1). The first provides excellent classification and resolution of urbanized areas, while the second provides better information on forested and natural areas. A regional dataset for NDVI was compiled from MODIS Vegetation index data, using 3 × 16 days (summer 2015) time slices from both the Aqua and Terra satellites. Final mean NDVI pixel values were produced, using only 'good data' pixel retrievals identified from the corresponding product quality control layers. For road network analysis, all road segments inaccessible by foot were excluded, with a travel speed for all remaining segments set at 5 km./hr.

All socio-economic datasets (population count, median yearly income, and nationality) were aggregated on a regular 75 × 75 m. hexagon grid (Section 2.2 in Paper I), with the center point of each hexagon used as network routing point for walking time calculations (Fig. 2a). We considered a 'walkshed' of 10 min., in any direction allowed by the road network, as representative of the local living environment. The final coverage included ∼49'000 center points (recording socio-economic variables) with associated 10 min. walksheds (recording land cover and NDVI variables) in the region (Figure 3a).

To identify variations in local living environment and socio-economic background of the population, we aggregated relative land cover shares (% of local environment) and NDVI values by median income or nationality bandwidth (over the whole region extent). We also calculated complementary statistics of absolute feature share per person (m^2/person) (Supplementary material Table 2 in Paper I). Lastly, we performed local spatial autocorrelations of high/low clusters for income values and nationality (Gettis-Ord Gi, or Gi*), and analyzed associated summary statistics.

3.2.2 Relationships between urban forms, job travels, and local environment

For Paper II, local landscape composition was assessed in relation to future urban developments. We used three alternative urban regional development scenarios (RUFS, 2010) created by the ORP (Office of Regional Planning, Stockholm). Those were named the 'Diffuse', 'Dense polycentric' and 'Dense monocentric' scenarios, projected from/to the year 2010/2030, with varying spatial extent and properties, representing possible and plausible future urban developments in the region. We used demographic projections from SCB (Statistics Sweden, 2019), with 445'000 new inhabitants projected to live in the region in the time period, and 2010 employment data (Statistics Sweden, 2019) to infer the ratio of jobs to population ($\sim$50 %), thus adding 225'000 new jobs in the region. For the three alternative scenarios, new 2030 population and employment locations were produced by simple linear regressions, based on the relation between percentage of local land conversion (i.e. for each raster pixel) and the total amount of land conversion for residential and commercial areas, respectively.

Final land cover data was created similarly to Paper I (and combined with scenarios for 2030 land cover). This dataset was aggregated with population counts (both current and scenarios) on a regular 500 × 500 m. square grid, with center points used as network routing points for driving time calculations. Here we considered a driving time of 1 hour, in any direction allowed by the road network, as a representative commuting time for work (see Section 2.4 in Paper II for more details). Final coverage included $\sim$10'000 center points (varying depending on the scenarios, recording land cover and population variables) with associated 1-hour driving areas (recording employment counts) in the region (Figure 3b). Based on this modelling, and for each scenario, we looked at the relationships between population counts and accessibility to jobs. We further compared those results with local variations in green-blue areas fractions per PD bandwidth, and mean area per capita.

3.3 Analysis for flow dependent ES

For Paper III and IV of the thesis, we developed and applied a spatially explicit framework for quantification and mapping of ES supply, demand, and their connectivity in urban regions, to advance understanding of the potential and actual (realized) benefits of nature, and how they can meet actual needs of urban populations. The rationale, definitions, modeling and applications of this quantification framework are further detailed in the following. The different spatial datasets used in Paper III-IV are listed in Table 1.

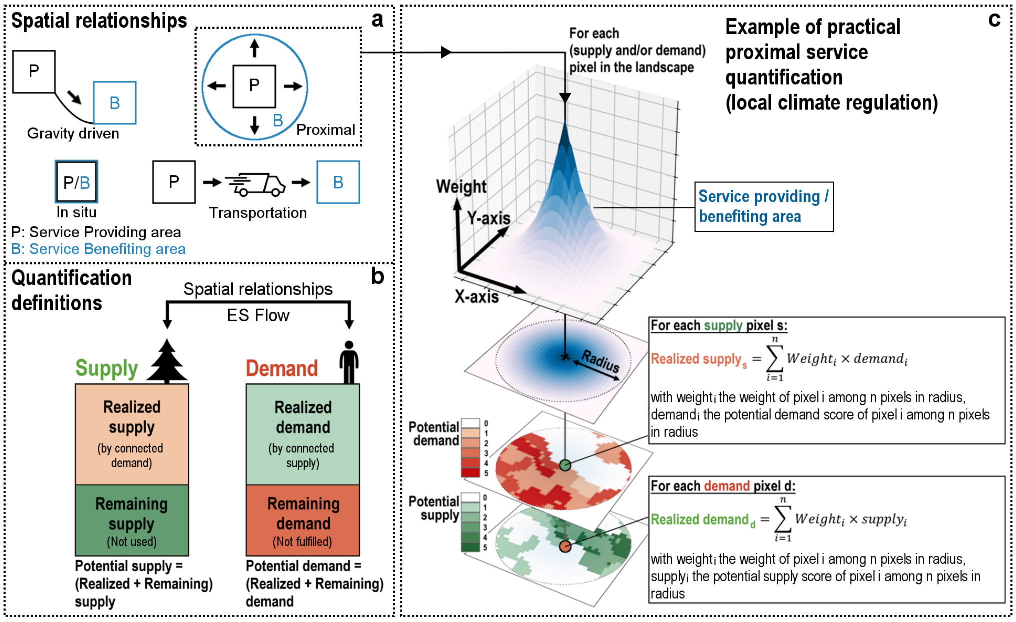

Figure 4: Schematic illustration of the concepts and methods developed and used in Paper III-IV. Panel (a) shows the different types of existing spatial relationships (ES flows) between service providing areas and service benefiting areas (or between supply and demand). Such spatial connections are scale dependents (adapted from Bagstad et al., 2013; Fisher et al., 2009; Serna-Chavez et al., 2014; Syrbe and Walz, 2012; Villamagna et al., 2013). Panel (b) shows a graphical explanation of the quantitative definitions developed in our work, dependent on the previous spatial relationships. Finally, panel (c) shows an example of practical quantitative application of these concepts, for the ES of local climate regulation, applied in Paper IV (modified from Fig. 1 and SI Fig. 2 in Paper IV).

3.3.1 Development and rationale of the ES modelling framework

The ES framework can be seen as an anthropocentric and utilitarian concept, with the value of services provided by ecosystems depending on the utility that people derive from their consumption, either directly or indirectly (Gómez-Baggethun et al., 2013). Adhering to this definition, recent research has started to define ES in separate terms of supply and demand, representing nature's benefits and human needs, respectively (seminal work from Burkhard et al., 2014, 2012). In parallel, spatial ES classification schemes, distinguishing between (natural) service providing areas (P in Fig. 4a) and (humans) service benefiting areas (B in Fig.4a) were progressively developed (seminal works by Bagstad et al., 2013; Fisher et al., 2009; Serna-Chavez et al., 2014; Syrbe and Walz, 2012; Villamagna et al., 2013). These broad spatial relationships over the landscape are (adapted from the previously cited literature, and illustrated in Fig. 4a):

- **In situ/local:** concern services that provide benefits in the same area where they are generated, with P and B being identical zones. Those are mostly indirect supporting services, such as nutrient cycling or soil formation for example.
- **Proximal:** benefits are derived at a certain distance from P, with the proximity between P and B playing a crucial role. Local climate regulation (local changes in temperature) or air purification are examples of proximal services.
- **Gravity driven:** Concern services where the benefits and connection between P and B depend on natural processes, generally related to water movements in the landscape. Storm water regulation, flood protection or nutrient regulation are examples of such services.

- **Transportation (human dependent):** Concern services where the relationship between P and B depend on human movement, transport and logistics. This can relate for example to accessibility, or the movement of people to natural areas, or commodities produced in P later transported to B. Recreational activities are an example of the former, while the production of food or wood harvesting are examples of the latter.

- **Global:** Concern services where B cannot be restricted spatially, and is assumed to benefit the whole planet. Global climate regulation (sequestration of CO2 by ecosystems) is an example.

Despite such conceptual progress in the recent scientific literature (last 10 years), practical applications of the concepts are still lacking. While ES exist only if there is some transfer of associated goods and services to a beneficiary, the actual demand for such services (the human side of this equation) and the connections between spatially disaggregated ES demand and supply are seldom considered (Cortinovis and Geneletti, 2018; Rieb et al., 2017; Schirpke et al., 2019b; Schröter et al., 2016). Moreover, varying definitions and understanding of these relationships introduce considerable ambiguity conceptually and in practice (Locke and McPhearson, 2018; Schirpke et al., 2019a; Syrbe and Grunewald, 2017). To the best of the author's knowledge, only one spatially explicit model considers these important aspects, which was in development for the last decade and only recently released in a limited provisional version (Martínez-López et al., 2019; Villa et al., 2014).

As such, the following definitions were developed and employed in this thesis work (Fig. 4b):

- **Potential supply (Ps)**: 'the hypothetical maximum capacity for service provision' of a particular ecosystem to human well-being.

- **Potential demand (Pd)**: 'the hypothetical maximum service need' of humans in a particular area, regardless of its fulfillment.

- **ES Flow**: 'the spatial transfer path between supply and demand areas', with the realized service (or actual service) depending on such spatial relationship. ES flow will depend on the service considered, and the spatial relationships described previously (Fig. 4a).

- **Realized supply (Rs)**: 'the part of the supply actually used' by service-consuming human beneficiaries in a ES flow's range.

- **Realized demand (Rd)**: 'the part of the demand actually met' by service-providing natural areas in a ES flow's range.

with:

Ps = Rs + Remaining supply (not used)

Pd = Rd + Remaining demand (not fulfilled)

These definitions distinguish between a potential ES (which may or may not actually exist, in the meaning of fulfilling an actual ES demand) and a realized ES (where the spatial connection with human beneficiaries is clear and thus the ES exists in the abovementioned meaning).

3.3.2 First fundamental application of the ES model

For Paper III, we assessed two regulating ES: local climate regulation, i.e., the dampening/cooling effects of green-blue areas on nearby air temperature, and storm water regulation, i.e., the green-blue area capacity to regulate the amount of water runoff occurring in the landscape. We focused here on the Stockholm region, with final land cover data (at 25 × 25 m. resolution) created by combining the Swedish land cover data with the Continuous Habitat Type Mapping (Table 1). This served as the basis to calculate scores of Ps and Pd (as in the methods introduced in Burkhard et al., 2014, 2012) by using a look-up matrix approach (see Fig. 3 in Paper III). Each land cover class received a relative integer value index in the interval 0-5, for both Ps and Pd, based on available quantitative data and expert judgment for the ES of interest. A score of 0 indicates no relevant Ps capacity/no relevant Pd, while a score of 5 indicates the highest Ps capacity/highest Pd, for the ES of interest. This evaluation scheme is relatively simple and, as such, can be used for consistent large-scale quantification of both Ps and Pd over the whole regional landscape. We also used DEM (Digital Elevation model) and soil datasets (Table 1) to produce a complementary look-up matrix based on slope angle and soils infiltration rates, used for the ES of storm water regulation (see details in section 2.3 of Paper III).

To calculate actual realization of ES, we considered simplified representations of the natural flow of air (for the ES local climate regulation) and water (for the ES of storm water regulation). For local climate regulation, we discretized the regional landscape in 150 m. units, representing an idealized zone where air mixing occurs and thus the spatial reach between areas providing the ES (P in Fig.4a, with a specific Ps score) and areas needing the ES (B in Fig. 4a, with a specific Pd score). For storm water regulation, we computed water flow directions and flow convergence in the regional landscape, to identify flow directions and amounts (and relative catchment area contributing water flow at each grid cell). We further quantified and mapped the connections between Ps, Pd, and the changes implied by considering potential ES (no spatial connection between supply and demand) and remaining supply and demand beyond the actual ES realization (see details in section 2.4 of Paper III).

3.3.3 Further ES model development and multi-city application

For Paper IV, we focused on one ES (local climate regulation) for further development of our conceptualization and methods, and application to a large collection of urban systems (660 cities in the EU28, EFTA and West Balkans, Fig. 2b). Final land cover datasets were produced for each city at 20 × 20 m. resolution, using a collection of different products (listed in Table 1, with more details of the different steps in Methods section of Paper IV), and city delineations based on the official recommendations of the European statistics office (Eurostat, 2018). We further produced a look-up matrix associating Ps and Pd scores to each land cover class, based on their average NDVI, tree cover density, ground imperviousness, presence of water, PD, and our own expert assessment. These score values represent estimates of (Europe-wide) average capacity of a land cover category to provide or consume the studied ES; as such, this study did not differentiate regional and local capacities for the same land cover categories (even though these can vary, see Methods section of Paper IV).

To calculate the realization of this ES, and thus the actual service, we further developed a spatial ES flow model with ES decaying over the distance range 0-500 m. (Fig. 4c), and applied this to each supply/demand pixel within each city landscape. This distance range for ES decay is consistent with generally reported ranges of several hundred meters (Gunawardena et al., 2017; Santamouris et al., 2018). Realization of the ES was further calculated as (Fig. 4c):

$$Rs_p = \sum_{i=1}^{n} weight_i \cdot Pd_i \tag{1}$$

$$Rd_p = \sum_{i=1}^{n} weight_i \cdot Ps_i \tag{2}$$

where Rs_p and Rd_p are realized supply and demand, respectively, in pixel p, $weight_i$ is the weight in a surrounding pixel i, and Ps_i and Pd_i are potential supply and demand, respectively, in a surrounding pixel i. The spatial weight surface function is normalized, with $\sum weights = 1$ over the 500 m. radius. Each landscape pixel thus contained information about its Ps, Pd (based on the look-up matrix) and Rs, Rd (based on the spatial flow model).

Furthermore, we aggregated city results by considering two metrics of urban ES realization:

- City-average ratios of realized to potential ES supply (Rs/Ps) and demand (Rd/Pd), calculated as the sum of Rs (Rd) divided by the sum of Ps (Pd) over all pixels within each city (score-based analysis).
- Area fraction of pixels with Rs/Ps (Rd/Pd) $\geq$ 0.5, meaning areas with relatively high ES realization, relative to total city area (area-based analysis).

These metrics were analyzed for the set of all European cities, and comparatively for cities in different European countries or sub-regions. The multi-city results (over the whole dataset, or per country of origin, for example) yielded good power-law fits with PD of the general form:

$$r_i(PD) = A_i \cdot PD^{\beta_i}, \text{ with } r_i(PD) \leq 1 \tag{3}$$

In Eq. (3), index $i = d$ represents demand and $i = s$ represents supply, r is the measure of relative realization (realized divided by potential demand or supply for the city average metric; area of high demand or supply realization per total city area for the area fraction metric), A_i is the intercept and β_i the exponent for the power law fit, and the constraint $r_i(PD) \leq 1$ is due to the upper limits of $Ri \leq Pi$ imposed by definition on the considered variables (i.e. realized ES supply and demand cannot exceed the corresponding potential variables; and city area fraction cannot exceed total city area). Based on this equation, we further estimated a relative measure of effectiveness (denoted 'Eff' below), dividing relative realized ES demand (r_d) by relative realized ES supply (r_s) (for the city average metric; corresponding area divisions for the area fraction metric):

$$Eff(PD) = \frac{r_d}{r_s} = \frac{A_d \cdot PD^{\beta_d}}{A_s \cdot PD^{\beta_s}} = \frac{A_d}{A_s} \cdot PD^{(\beta_d - \beta_s)} \tag{4a}$$

with:

$$r_d = A_d \cdot PD^{\beta_d} \text{ if } r_d \leq 1, r_d = 1 \text{ otherwise} \tag{4b}$$

$$r_s = A_s \cdot PD^{\beta_s} \text{ if } r_s \leq 1, r_s = 1 \text{ otherwise} \tag{4c}$$

Eq. (4) shows that power-law relationship with PD thereby also emerges for the Eff measure, with exponent $(\beta_d - \beta_s)$ and scale factor A_d/A_s.

4 Results

4.1 Local living environment and population socio-economics

The results from the analysis of population preference for living environment shows distinct co-variations for different urban density classes. The high density urban class ($>30\%$ soil sealing, Fig. 5a) is the most common living environment for people with lower income ($50\text{-}350.10^3$ SEK), while the low-density urban class ($\leq 30\%$ soil sealing, Fig. 5b) progressively increases as the most common living environment for people with income up to $\sim 900.10^3$ SEK. This suggests that people with higher incomes, and thus greater possibilities to choose their living environment, clearly prefer lower-density urban parts. These generally contain a higher share of green areas, with a significant private portion (gardens and trees belonging to individual citizens or families). As for the high-density urban class, the average share of industrial and commercial zones within this (Fig. 5d) is highest in the living environment of people with low income ($50\text{-}300.10^3$ SEK) and decreases in the living environments of people with higher income (to constitute an area share below 5% for incomes above 450.10^3 SEK). Industrial and commercial zones are thus strongly avoided by richer parts of the population. Finally, average vegetation cover (NDVI value, Fig. 5c) is the smallest in the living environment of people at the lower end of the income range ($50\text{-}350.10^3$ SEK), and increases to a stable higher level for people with higher incomes (at $350\text{-}500.10^3$ SEK and above). The spread in NDVI values is also much higher at lower income levels, and significantly narrows above 500.10^3 SEK. This shows that richer parts of the population have on average more greenery in their living environment. Overall, the population with median income above 450.10^3 occupy around 50% of the regional area but represent 27% of the population (Fig. 3 in Paper I). The regional distribution of income is also correlated to country of origin (Fig. 8 in Paper I), generally implying lower median incomes in areas with non-EEA citizens. This also has implications for living environment, with more heterogeneous parts of the population having higher fractions of undesirable features (Fig. 5e, considering both the high-density urban class, and the industrial and commercial areas), and less vegetation (lower NDVI values, see SI Table A in Paper I) in their living environment.

Furthermore, local spatial autocorrelations (Gi*, 300m. weights with 9999 random permutations, $p<0.01$) show the spatial clustering of high/low income and nationality in the region (Fig. 6). We here look at representative such clusters, based on spatial locations and relationships, observing spatial similarity between low-income and non-EEA clusters (Jaccard index, J=0.34), and between high-income and EEA clusters (J=0.24), even though these cluster combinations are not exactly overlapping. In general, and although some variations exist, we can see also from this analysis that low-income and non-EEA clusters tend to have less vegetation (lower mean NDVI) and more undesirable city features (high-density urban, industrial and commercial areas) in their living environment, while the opposite applies to high-income and EEA-citizen clusters.

Finally, all above-discussed results are purely location based (i.e. not weighted with

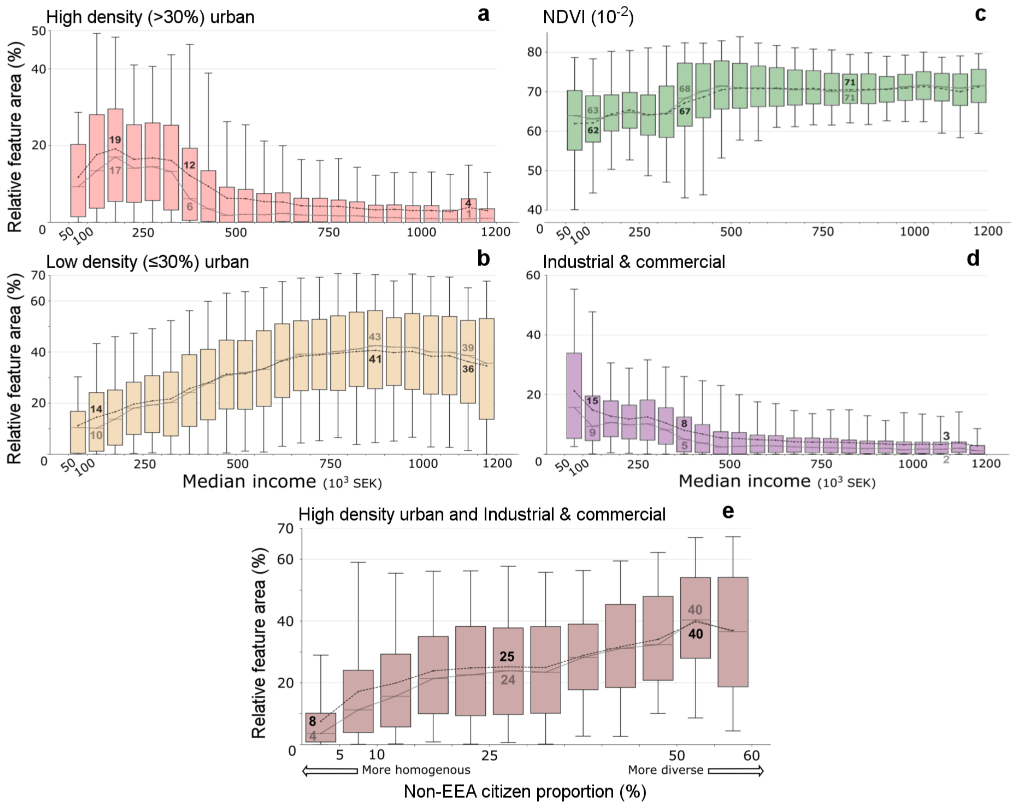

Figure 5: Income and nationality co-variations with urban landscape features. Income is measured in SEK (Swedish Krona) while nationality is measured by the relative fraction of non-EEA (European Economic Area) citizens. The different panels show income co-variations with (a) high density (>30% imperviousness) urban, (b) low density (≤30% imperviousness) urban, (c) NDVI, (d) industrial & commercial areas, and nationality co-variations with (e) combined high density and industrial & commercial areas. Box plot whiskers display the 5th and 95th percentiles, with the boxes indicating the usual first quartile, median and third quartile, for each income and nationality segment. Light grey lines (and numbers) indicate median values, while dark grey lines (and numbers) indicate mean values (modified from Figures 4,5,6 and 9 in Paper I).

PD). However, higher local PD is also correlated with lower local income level (Fig. 3 in Paper I) and population nationality (Fig. 8 in Paper I). Thus, per-capita shares of various urban features (i.e. absolute feature area per person) will show similar types of differences between more and less privileged parts of the population (SI Table B in Paper I).

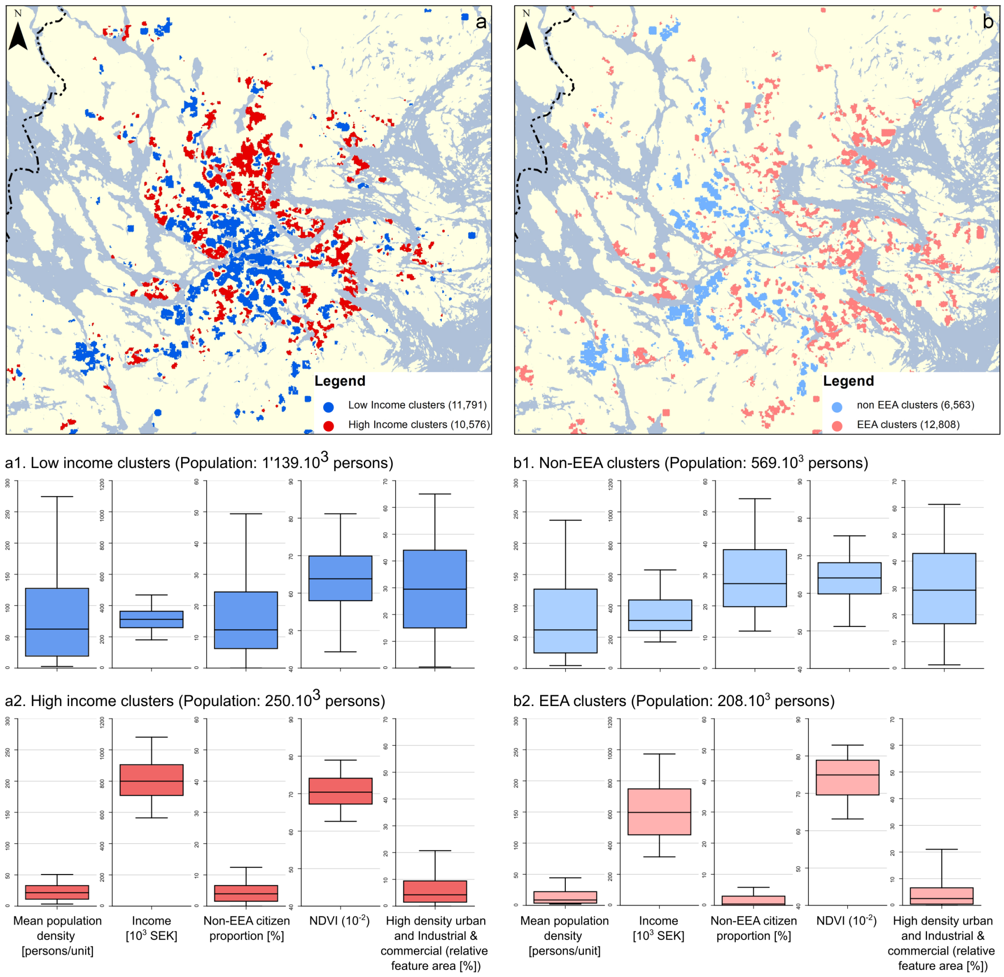

Figure 6: Stockholm region (subset) with associated high/low income and nationality clusters. Panel (a) shows high/low income clusters, with associated statistics presented in panels (a1) and (a2). Panel (b) shows high/low proportion clusters for EEA citizens, with associated statistics presented in panels (b1) and (b2). Box plot whiskers display the 5th and 95th percentiles, with the boxes indicating the usual first quartile, median and third quartile (modified from SI Fig. C in Paper I).

4.2 Urban forms, living environment, and job travels

In Paper II, we translated the three future (2030) scenarios (RUFS, 2010) into various population and employments densities, based on the baseline year 2010 (Fig. 7). The dense monocentric scenario (Fig. 7a1-7b1) generally aims at reducing the expansion of the city, avoid sprawling and thus reduce urban land use while increasing built density in and near existing built areas (with up to 18km^2 of additional built development). The dense polycentric scenario (Fig. 7a2-7b2) represents instead a set of neighboring interacting urban cores, sufficiently close to form a clustered urban area, but limiting density in the central node (to 111 km^2 of new built development). Finally, the diffuse scenario (Fig. 7a3-7b3) represents a sprawling scenario, where urban development is allowed to extend further (generally at lower density, up to 455 km^2 of new built development).

In general, results cluster towards higher population counts and job accessibility with increasing urban density scenario, which also tend to have increasing variations in PD due to greater influence of low-density outliers. The diffuse scenario thus shows the largest variations in job accessibility (median = 926.10^3 [median absolute deviation, mad = 336.10^3]) and the lowest variations in population density (median = 134 [mad =270])

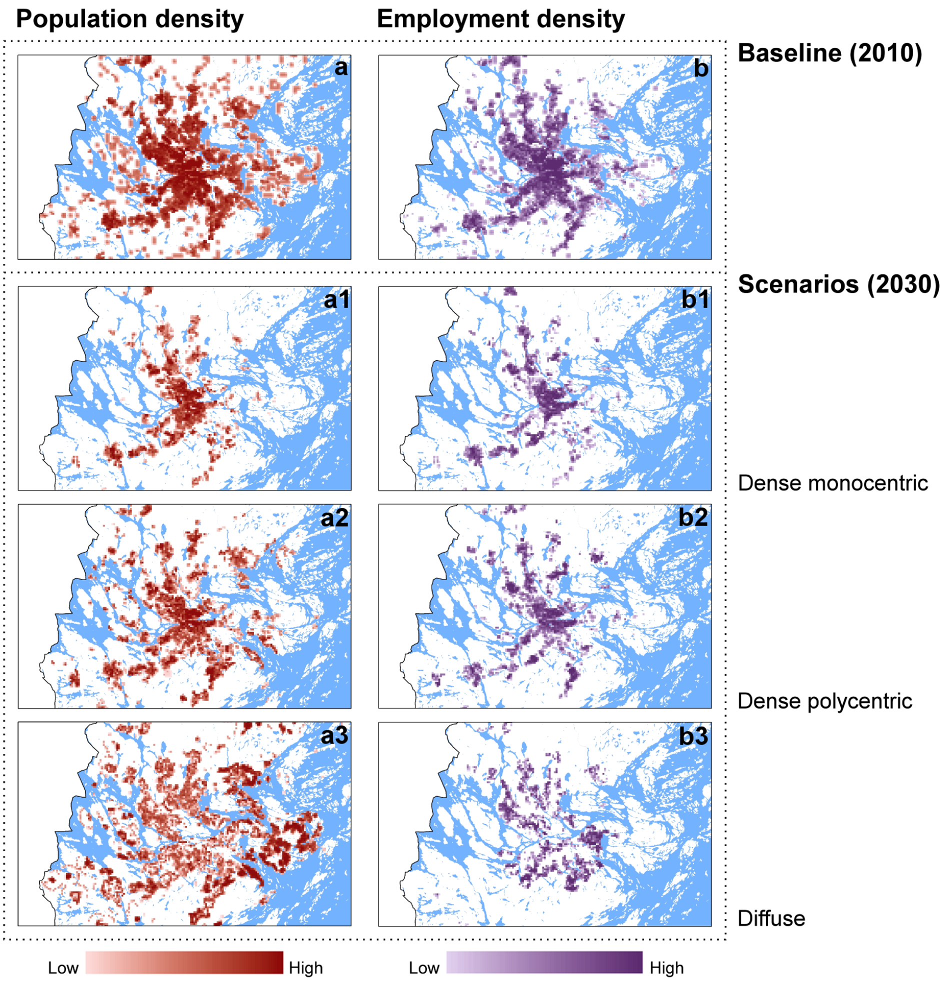

Figure 7: Baseline (2010) and projected (2030) population and employment density scenarios in the Stockholm region. Population density (people/km^2) is shown for the baseline 2010 case (a), and separately for the 2030 dense monocentric (a1), dense polycentric (a2) and diffuse (a3) scenarios. Employment density (jobs/km^2) is also shown for the baseline 2010 case (b), and separately for the 2030 dense monocentric (b1), dense polycentric (b2) and diffuse (b3) scenarios.

(Fig. 8c). On the other extreme, the monocentric scenario shows the lowest job and highest population density variations (median = 1'162.10^3 [mad = 106.10^3] for jobs, median = 585 [mad = 760] for population density) (Fig. 8a), while the polycentric scenario is intermediate (jobs median = 1'082.10^3 [mad = 184.10^3], population median = 313 [mad = 573]) (Fig. 8b). Looking at the local environment (Fig. 8d), the diffuse scenario has predictably the highest accessibility to natural land-cover types, with ∼16,6.10^3 m^2/person, followed by the scenarios of dense polycentric (∼7,3.10^3 m^2/person, 56% decrease from the diffuse scenario) and monocentric (1,7.10^3 m^2/person, 77% decrease from the polycentric scenario). These results represent the average situation per-unit (500 × 500 m) of urban development (representative of the average development location) and do not include the 2010 baseline population if this is located outside of the scenario. We can compare this to the average per-person situation (representative for the average population), considering also the baseline population, showing natural land-cover types of 868 m^2/person for diffuse, 316 m^2/person for polycentric, and 170 m^2/person for monocentric (to be compared with 840 m^2/person for the 2010 base scenario).

Each scenario thus involves distinct changes in land re-development and additional

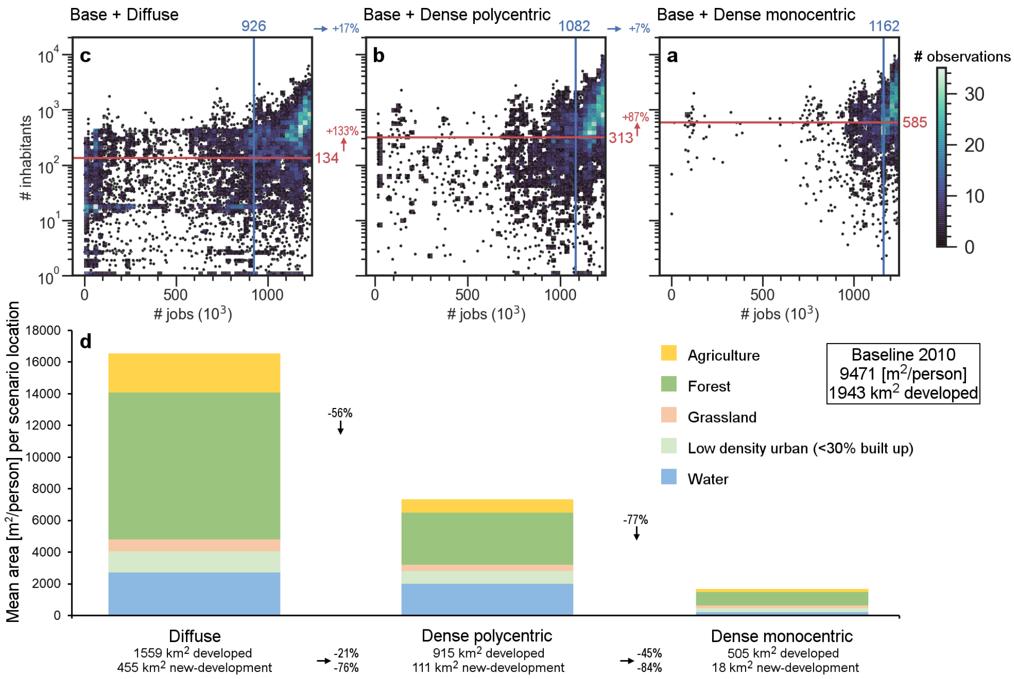

Figure 8: Relationships between population density and jobs accessibility, with associated average landscape composition for future scenarios of urban development in the Stockholm region. Population and job counts relationships are shown on semi-log plots for the combined (a) baseline+dense monocentric, (b) baseline+dense polycentric and (c) baseline+diffuse scenarios. Red lines indicate the median population density (with associated values and percentage increase between scenarios) while blue lines indicates median job accessibility (with associated values and percentage increase between scenarios). Associated average landscape compositions are shown in (d), with associated percentage value changes between scenarios. Landscape compositions consider baseline+scenarios population, but only for areas developed by the scenario of interest (modified from Fig. 3b and Fig. 4a in Paper II).

land consumption, with different implications for nature accessibility (and conservation), as well as PD and job accessibility. Despite these differences, the average-land cover mix is similar across the scenarios (Fig. 4b in Paper II), with differences in this aspect mainly relating to differences in the ratios of high-density (>30% soil sealed) to low-density (≤30% soil sealed) urban areas. This aspect and the other scenario results generally imply less natural areas (and potential ES of these) for urban inhabitants with increasing urban density, with no particular section of the population particularly deprived of, e.g., forested areas as long as the baseline 2010 green-blue area situation is conserved under the new developments.

4.3 Development of ES framework and first application

Fig. 9a-b shows scores for the potential ES of local climate regulation supply Ps (Fig. 9a) and demand Pd (Fig. 9b) in the Stockholm region, using a 0-5 index scale (with 0 representing lowest Ps and Pd, and 5 representing highest Ps and Pd). These potential ES results are calculated based only on landscape composition and generally highlight the more natural and urbanized parts of the regional landscape. For example, the urban center of Stockholm (outlined by rectangle in Fig. 9a and 9b) emerges as an area of high potential ES demand and relatively low potential ES supply for fulfilling the demand (relatively to less urbanized parts of the region).

Application of the simple ES flow modeling approach (as graphically explained in

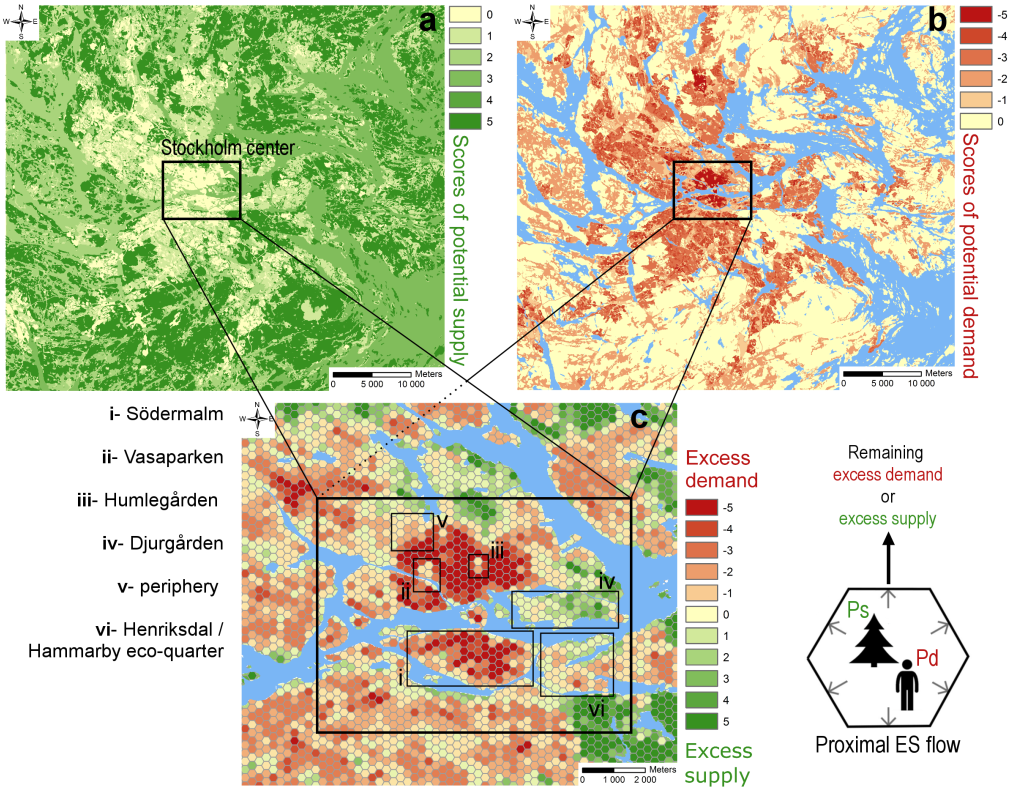

Figure 9: Mapped assessment results for the ecosystem service of local climate regulation in the region of Stockholm. Panels show (a) the potential service supply (Ps) and (b) the potential service demand (Pd) over the region, with (d) the net remaining excess demand or supply of the service around the Stockholm center. Highlighted locations in (d) shows some area of interest examples (adapted from Fig. 2 in Paper III).

Fig. 9) further highlights several areas of interest and significant spatial heterogeneity in this Stockholm center area (Fig. 9c). In general, some densely built parts of the center still exhibit large excess demand, even after considering supply realization, while other areas show a locally more well-balanced situation. For example, (i) and (ii) shows areas with nearby parks and water that contribute to balance the realization of ES supply and demand, (iii) shows the influence of a large urban park, (iv) and (vi) show areas with larger green area integration in urban zones (sometimes dominating, with some zones of excess supply), and (v) shows a boundary of the urban center, with progressive transition from densely built to lower build density and more presence of natural areas. A main implication of this simple ES modeling application is that, for similar residential areas (same Pd), actual ES realization depends on both landscape location and surrounding areas. Similarly, large forested areas located further away from the city center may have high capacity to regulate temperatures (high Ps) but will have virtually no ES realization impact (for this particular ES) if there are few human beneficiaries nearby.

Analogous ES quantification for the service of storm water regulation (with Ps and Pd scaled on 0-5 index scale and their net local per-pixel balance shown in Fig. 10a) shows similar spatial patterns as for the ES of local climate regulation in Fig. 9-b. A similar star shaped high-demand area appears (as natural and built areas are static in the landscape), but with different Ps and Pd scores for the two ES considered. Some highlighted (i-v in Fig. 10a) hotspots of high local supply of the ES of storm water regulation are located in areas with gravel/sandy glaciofluvial deposits and high forest cover fractions. However, total realization of this ES also depends on larger-scale water flows through the landscape, and upstream-downstream flow trajectory connections that can connect

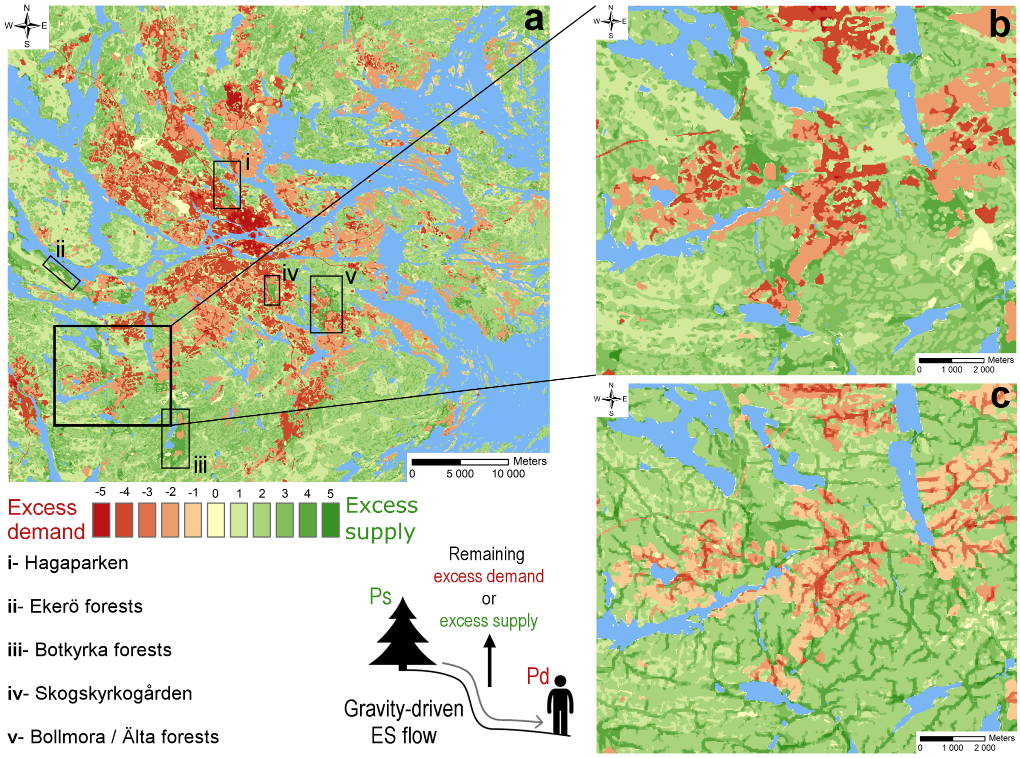

Figure 10: Mapped assessment results for the ecosystem service of storm water regulation in the region of Stockholm. The net sum of excess demand/supply over the region is shown in (a), with some examples of high supply hotspots highlighted. Panel (b) shows the same results in the example area of Tumba, with (c) showing associated results of remaining excess demand/supply after consideration of non-local water flow contributions from upstream areas for each grid cell in the landscape (adapted from Fig. 6 in Paper III).

ES supply and demand areas, and the convergence of water flow (water amount) at each point in the landscape (see further graphical explanation in Fig. 10). Looking at results in the example area of Tumba (Fig. 10b), we can then see differences between initial potential ES scores and final ES scores after account of these non-local water trajectories and larger-scale flow connection influences (Fig. 10c). Areas of net local ES supply that receive high water flow from upstream areas get higher total scores of excess ES supply (lower for low water flow). Analogous results are obtained for areas of net local ES demand; with the difference that ES flow to these areas also depends on the contribution of water infiltration in upstream areas of ES supply, intercepting some water flow before it reaches sealed urban areas of net ES demand. If enough water accumulation occurs in sealed areas of net ES demand (net Pd areas), the excess demand increases in the latter, whereas if some or most water accumulation occurs in net Ps areas, this is an additional ES supply contribution to downstream net demand areas which decreases their excess demand. In other words, this implies that upstream ES supply can reduce storm water regulation needs for downstream demand areas; but areas of net ES supply located downstream from net demand areas will have no ES effect on the latter.

These results represent simple first-order estimates, and initial steps toward more complex spatial modeling of ES supply, demand, and human-nature connectivity between them. Considering the ES of storm water regulation for example, a more comprehensive representation of water and associated ES flows could be derived from distributed hydrological modeling. However, the relatively simple approach developed and applied in Paper III is still useful for screening quantification and elucidation of main differences between potential and actual urban ES provision over a region.

4.4 Multi-city comparison for the ES of local climate regulation

Example quantification and mapping for one city (Stockholm, Fig. 11) from the total set of 660 European cities considered for quantitative ES indicator comparison shows the different calculated metrics of relative ES realization for the demand side of the considered ES of local climate regulation. Potential supply Ps (Fig. 11a) and demand Pd (Fig. 11b) are then derived from the look-up matrix (SI Fig. 1 in Paper IV), while the metrics of realized demand (Rd, Fig. 11c-d-e) are derived from the ES decay model relating supply and demand (discussed in methods section, Fig. 4c). The resulting Rd metric quantifies the human ES demand actually fulfilled (by the available supply) relative to the total potential human demand for this ES. Analogously, the corresponding Rs metrics (not shown here, see SI Fig. 3 in Paper IV) quantifies the ES supply actually used (for fulfilling demand) relative to the total potential supply of this ES.

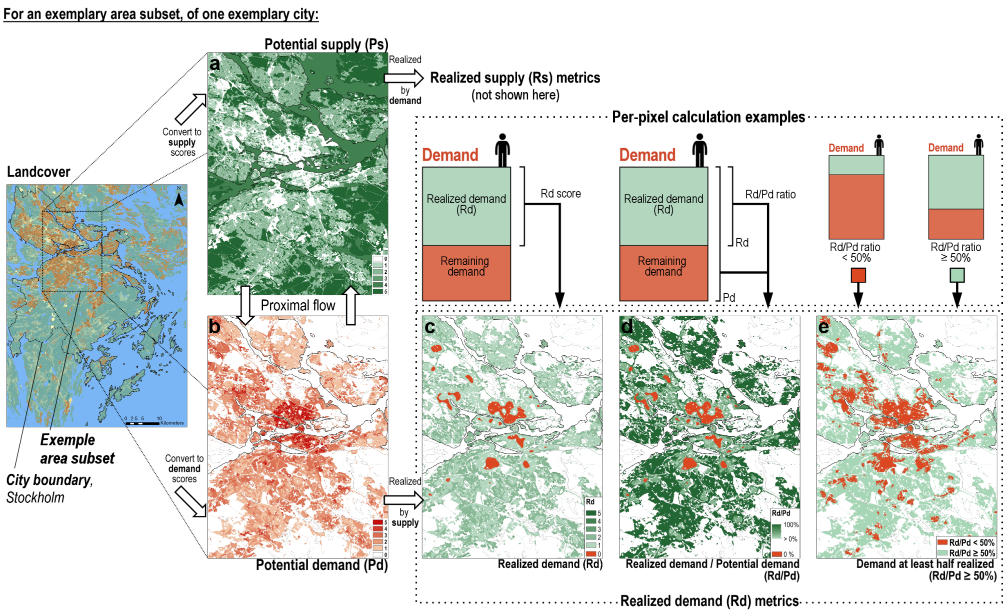

Figure 11: Detailed exemplification of mapping and quantification of potential and realized demand for local climate regulation in the city of Stockholm, Sweden. Ps (a) and Pd (b) maps are created according to the classification set in SI Fig. 1 in Paper IV. We then calculate and map Rs and Rd based on the flow dependence model described in methods (Fig. 4c). Rd (c) shows the absolute value of realized demand per pixel. Rd/Pd (d) shows the degree of realization to initial potential demand per pixel. Rd/Pd $\geq$ 50% (e) shows the area where pixels have their demand at least half realized. A quantification example of reported metrics for Stockholm is provided in Supplementary Information in Paper IV (adapted from SI Fig. 1 in Paper IV).

On average across all studied European cities, the resulting city-average ratio of realized supply Rs/Ps shows a sub-linear power-law rising trend with increasing PD (solid green line in Fig. 12a, power law exponent β = 0.62), while the corresponding realized demand ratio Rd/Pd exhibits a flatter sub-linear declining trend with increasing PD (solid red line in Fig. 12b, β = -0.15). In combination, these result characteristics imply that city growth (in terms of increasing PD) can be expected to use an increasingly larger part of a city's total ES supply for fulfilling a decreasing part of its total ES demand. City area fraction with high ES supply realization (area with Rs/Ps$\geq$0.5 per total city area) also increases with increasing PD (Fig. 12c). However, so does also the city area fraction with high ES demand fulfillment (area with Rd/Pd$\geq$0.5 per total city area) (Fig. 12d), thereby implying a somewhat more effective use of green-blue areas to fulfill actual ES demands in these city parts, than on average over the whole city, under PD growth.

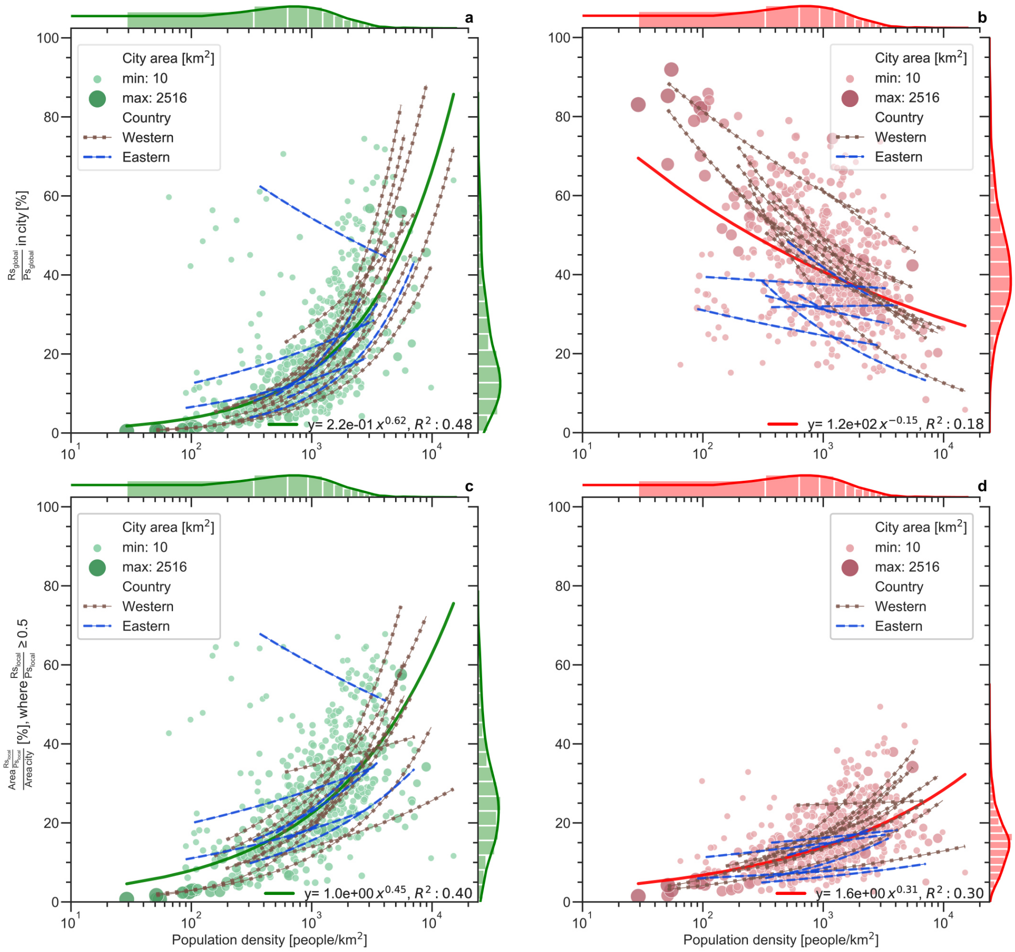

Figure 12: Relative ecosystem service (ES) realization versus population density in cities across Europe. For all 660 European cities studied (green and red symbols and associated solid lines for supply and demand, respectively), and cities within separate countries (blue dashed and brown filled-symbol lines for eastern and western European countries, respectively), results are shown for: city-average ratio of realized to potential ES (a) supply (Rs/Ps) and (b) demand (Rd/Pd); and city-area fraction with high degree (≥0.5) of local ES (c) supply and (d) demand realization. Solid lines show best power-law fit for all cities (whole-Europe results), with associated equation y and coefficient of determination R^2 values also given in each panel, along with histograms of the total number of observations in various population density and fraction intervals. Furthermore, the blue dashed and brown filled-symbol lines in each panel show the best power-law fit for cities within each eastern and western European country, respectively; associated scaling factor A, power-law exponents β, and coefficients of determination R^2 for each country and western and eastern European sub-region are listed in SI Table 2 in Paper IV, while full city-average and area-fraction results for each country are illustrated in SI Fig. 6 and Fig.7 in Paper IV, respectively (Fig. 2 in Paper IV).

In general, decrease of city-average Rd/Pd under PD growth can be attributed to the combined effects of increasing population pressure (increase in Pd due to urban expansion/densification), progressive decrease of supply resources (decrease in Ps, due to removal/replacement of natural areas), and/or progressive separation of Pd areas from Ps areas over the urban landscape. The ES realization metrics quantified here can be useful indicators of such influences and city performance under growth of PD, as a generally better predictor than growth in population or city area separately (SI Fig. 4-5 in Paper IV). Differences in ES realization between cities with similar PD likely depend on variations in, e.g., urban planning policies and practices, city history, and/or possible associated socio-economic conditions. Such factors may be more similar for cities in the same country than for cities in different countries and, in any case, the ES realization indicators developed in Paper IV may help in detecting such differences between cities. Indeed, results in Paper IV show that country-wise ES indicator relationships with PD exhibit better power-law goodness of fit (increase in resulting coefficient of determination R2) than the relationships for the entire 660-cities dataset (SI Fig. 6-7 and SI Table 2 in Paper IV). For city-average ES realization, mean R^2 for countries fitted individually is 0.64 for supply (Rs/Ps) and 0.39 for demand (Rd/Pd), while it is 0.48 and 0.18, respectively, for the whole Europe fitting. For area fractions with high ES realization, mean R^2 for country-wise fitting is 0.52 for supply and 0.38 for demand, while it is 0.40 and 0.30, respectively, for the whole Europe fitting. Nevertheless, the country-wise fits are still largely consistent with the whole-Europe results; however, distinct parameter differences emerge in the power-law β values between countries, and in particular between western and eastern European countries (SI Table 2 in Paper IV). Specifically, western cities (brown filled symbol lines, Fig. 12b) generally exhibit higher level of city-average demand fulfillment (Rd/Pd) than eastern cities (blue dashed lines) across the whole PD range, but the results are more mixed between western and eastern cities for city-average ES supply realization (Fig. 12a), as well as for the area-fraction indicators (Fig. 12c-d).

The above-discussed data-given power-law relationships between ES realization indicators and PD imply that these indicators and the associated effectiveness indicator Eff (discussed in methods section) can also be assessed for projected scenarios of possible future PD (assuming no major shifts in urbanization conditions). To illustrate this, Paper IV calculated Eff from the country-wise fitted indicator relationships for 100 $\leq$ PD $\leq$ 10'000 per km^2, representative of the range of PD in European cities (Fig. 13). Results show city average Eff >1 for cities with low PD (up to approximately 2'000-4'000 per km^2), implying greater relative city-average demand fulfillment than relative supply use (Fig. 13a). Generally higher Eff levels emerge for western cities until PD approaches and exceeds 5'000 km^2, where results mix and converge to generally low Eff $\leq$1. Eff for the area-fraction indicators shows mostly low values (Eff $\leq$1), implying relatively inefficient city-scale provision of high ES demand fulfillment, since that area fraction is smaller and increases less with higher PD than the area fraction with high local supply use (Fig. 13b). Only Sweden, Switzerland and Spain (western countries) are exceptions from this for small PD $\leq$1'000 km^2.

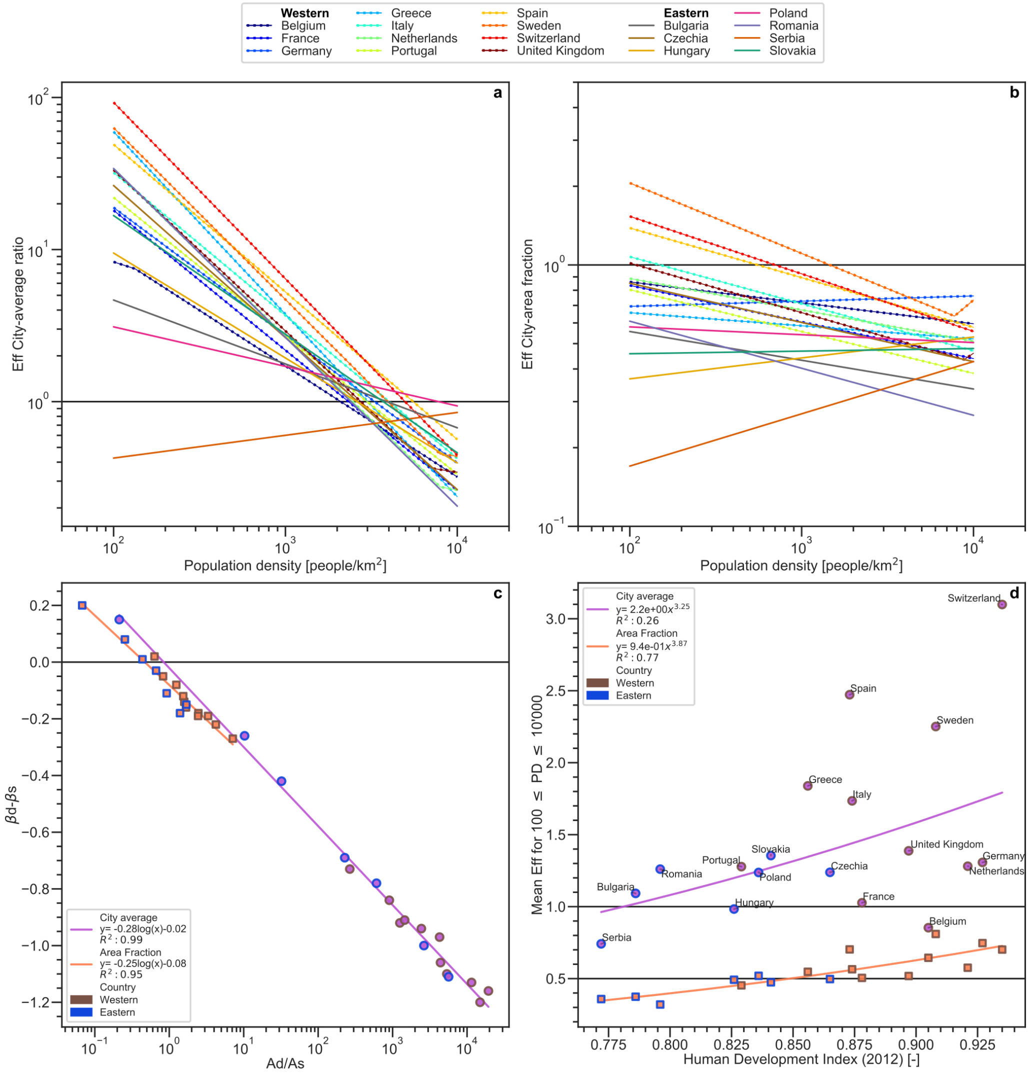

Figure 13: Effectiveness indicator (Eff) for individual eastern and western European countries. For each individual country (listed in SI Table 2 in Paper IV), Eff results are shown for: (a) city-average ratio and (b) city-area fraction of ES realization; (c) co-variation of Eff exponent ($\beta d - \beta s$) and scale factor (Ad/As); and (d) co-variation of average Eff (for $100 \leq$ PD $\leq$ 10'000 per km^2) and Human Development Index (HDI) for each country. Solid and dashed lines in panels (a) and (b) show Eff values for eastern and western countries, respectively. Purple and orange lines/symbols in panels (c) and (d) distinguish city-average ratio of realized to potential ES and city-area fraction with high degree ($\geq$0.5) of realization, respectively, with blue and brown symbol outlines showing eastern and western countries respectively, and solid lines showing best log/power law fits for all countries (associated regression equation y and coefficient of determination R^2 values are also given in each panel). SI Fig. 8 in Paper IV further illustrates results corresponding to those in panel d, but for GDP per capita instead of HDI, and SI Figs. 9-10 in Paper IV illustrate the co-variation with HDI and with GDP per capita, respectively, of the various exponents β and scale factors A included in the Eff expression (Fig. 3 in Paper IV).

Overall, the power law exponent ($\beta d - \beta s$) for relative effectiveness Eff declines (logarithmically) with increasing intercept (Ad/As), meaning that the western countries with the predominantly highest Eff levels at low PD also have the steepest decreases in Eff with increasing PD (Fig. 13c). Nevertheless, the western countries still exhibit mostly higher mean Eff levels than the eastern countries over the whole PD range. Further comparison of PD-average Eff (i.e., mean Eff over the whole considered PD range) with a socio-economic country indicator like the Human Development Index (HDI, Fig. 13d) indicates that the socio-economic conditions accounted for and reflected in HDI correlate particularly well with the effectiveness indicator Eff for area fraction with high ES realization (R^2 = 0.77; compared with R^2 = 0.26 for city-average Eff). Similar results are also obtained by comparing PD-average Eff with GDP per capita (SI Figs. 8-10 in Paper IV). These results indicate that, under growth in HDI (or GDP per capita), cities tend to be more effective in maintaining and enhancing the ES of local climate regulation in low-density city parts, which also tend to be relatively wealthy (Paper I), than on average over the whole city.

5 Discussion

5.1 Nature accessibility and environmental equity

This thesis has identified that, in Stockholm region, the local presence of nature for urban residents relates to their socio-economic status (Paper I), and that future urban trajectories involve trade-offs between energy efficiency and nature availability (Paper II). Paper I uses income relationship with local living environment features as a proxy for feature preferences of urban residents, as people can better afford to choose their desired features the wealthier they are. This assumes that each individual who can afford it will tend to decide to live in the best possible location for him/herself, even though such choices also depend on a variety of other factors than just nature accessibility (e.g., location status, and other types of urban advantages like transportation, local amenities, etc). Nonetheless, preferences of more wealthy people are found to clearly tend toward higher green-blue area presence in their living environment. In parallel, Paper II addresses a strive toward denser, more efficient urban forms, from which a conflict emerges: people want more nature (Paper I) but city efficiency may require more compaction (Paper II). The latter implies higher population densities and lower shares of nature per capita, due to progressive disappearance of nature in growing cities. Green-blue urban areas may thus become increasingly rare in the future (if their maintained presence is not an explicit urban development strategy), and thus increasingly valuable and more unevenly split between richer and poorer parts of the urban population.

Recent work has started to highlight a mechanistic and neural basis of the therapeutic potential of nature (Chang et al., 2021), in addition to previously reported positive relationships between natural areas and beneficial health effects (Lee and Maheswaran, 2011; Tzoulas et al., 2007; World Health Organization 2016). A divide in such health-promoting conditions between richer and poorer parts of urban populations may then become more prevalent in the future, rather than at least a minimum of local natural preservation for all urban habitants. The question of how much nature is needed is still open, for example due to the difficulties of quantifying health responses to varying living environments (Shanahan et al., 2015), and because greening can also lead to paradoxical effects of gentrification (Amorim Maia et al., 2020; Wolch et al., 2014) with progressive exclusion of poorer people. Urban densifying trends for increased energy/resource efficiency also imply possible reduction of ES over urban areas at large, as well as for specific parts of a city's population (see also discussion in the next section). A balance needs to be found between urban energy/resource efficiency and a good, inclusive urban living environment for the whole urban population, which is not a simple problem.

Stockholm is rapidly developing and densifying (RUFS, 2018), but also remains one of the greenest cities in Europe (Fuller and Gaston, 2009; Kabisch et al., 2016), with successive Swedish governments emphasizing the importance of natural areas in urban planning (Sandström, 2002). It is thus interesting that accessibility to green-blue areas, despite their relative abundance compared to other European cities, are also here associated with income. By being rarer, green-blue urban may be even more valued and desirable in other European metropolitan areas (Comber et al., 2008; Kabisch and Haase, 2014; Laurent, 2011). However, although Paper I found that richer parts of the Stockholm region population have a higher presence of nature in their environment, it also showed that no particular population section is entirely deprived of nature in their living environment in this region. Moreover, although Paper II found it likely that future urban development will imply lower local presence of natural areas, the extent of these changes is not easily predicted. The recently released new Stockholm region development plan until 2050 (RUFS, 2018) highlights as a first challenge to 'facilitate population growth while improving the region's environment and the health of its inhabitants'. Such considerations are thus seen as important, and included in current strategy for urban development. However, most attention is focused on green wedges at regional scale, which are important and can be located close to urban areas, but are also essentially natural lands surrounding (and thus outside) Stockholm and other cities in the region.

Studies of the relationships between the built environment and travel times are abundant in urban planning research (Ewing and Cervero, 2010), with probably one of the most iconic works in the field (Newman and Kenworthy, 1989) clearly relating lower transport energy use with increased PD. More recent work (Ewing et al., 2017) suggests that while PD is correlated with per capita travel distances, other variables (e.g., personal income or freeway capacity) may be more important for the latter. Paper II shows increased job accessibility with higher city density (926.10^3 jobs for the lowest density scenario, $1'162.10^3$ jobs for the highest density, increase by $\sim$25%), which could translate in lower energy consumption. However, future changes to job accessibility, e.g. by road traffic congestion, or potential infrastructure changes, were not assessed and could imply different energy consumption results (Tsekeris and Geroliminis, 2013). Similarly, Paper II did not project future socio-economic situations, or changes in transportation modes (e.g. bike, cars, subway, etc), thus subsequent work with robust such projection scenarios is needed to further our understanding. Nevertheless, care needs to be taken not to deplete natural areas in cities for potentially small energy gains. As such, the intermediate development scenario (polycentric) considered in Paper II may currently be the most reasonable choice for balancing these aspects and not excessively converting natural land and degrading urban quality of life. Beyond general quality of life and well-being, green-blue urban areas can also provide other urban benefits in terms of ES discussed in the next section.

5.2 Urban ES framework: spatially linking supply and demand

This thesis has developed a spatial framework and methodology for linking the supply and demand sides of the ES equation. Paper III presents a simplified application of this for the city of Stockholm, showing that account of spatial flows is needed to differentiate between potential and actual ES. Tallis et al. (2008) elegantly summarized this problem: *'The science of ecology made huge advances when it began to consider dispersal and the importance of movement in governing the dynamics of ecological communities. However, the science of ecosystem services has not yet made this transformation, and as a result typically depicts ecosystem services as site-bound on static maps'.* Quantifying actual ES is needed for urban management and planning, for instance to understand who is benefiting from which urban conditions and developments, detect urban sections of insufficient access to ES, and design future development to strategically include urban ES.

By applying the spatial ES methodology to local climate regulation in and across a large set of Eupopean cities, Paper IV could comparatively study and quantify the behavior of ES realization indicators with varying PD. Besides increasing fundamental understanding of realized ES trajectories with changes in PD and more or less related socio-economic measures of growth (HDI or GDP per capita), Paper IV also shows a possible practically relevant and useful quantification contribution to urban planning. Key differences between various cities, countries, and eastern and western sub-regions of Europe could be detected by use of this approach in Paper IV, with important variations in ES demand fulfillment seen between cities with similar PD, indicating better or worse urban forms and land-cover mixes for the studied ES.

Paper IV shows that city differences in average ES effectiveness are larger for PD below $\sim$5'000 people/km^2. However, the city-average indicator of relative ES demand fulfillment Rd/Pd does not distinguish how this fulfillment is attained. For example, similar city-average Rd/Pd can be obtained with an overall moderate ES realization, or with large variations between high and low ES realization within a city. The associated effectiveness measure (relating Rd/Pd to Rs/Ps) shows relatively weak relationship with the socio-economic measures of HDI and GDP per capita, with nonetheless higher values for western countries on average. France and Belgium emerge as negative outliers, using a higher average supply (Rs/Ps) for fulfillment of average demand (Rd/Pd) compared to other western countries. Spain, Sweden and Switzerland emerge as positive outliers, with Spain having lower average supply use for similar demand fulfillment, and Sweden and Switzerland reaching higher demand fulfillment for similar supply use in comparison with other western countries. The area-fraction indicator (area part with Rd/Pd$\geq$0.5) shows improved ES realization efficiency with higher PD, but only for less dense and likely more wealthy parts of a city than on average over the whole city. The high correlation of the associated effectiveness indicator (relating the area part with high demand fulfillment, Rd/Pd$\geq$0.5, to that of high supply use, Rs/Ps$\geq$0.5) with socio-economic measures also indicates that as cities (and countries) get richer, ES demand fulfillment is further enhanced for such selected parts of the city population and their living environment, but not for the whole city.

The data-given differences between cities in eastern and western European countries may depend on insufficient regulations for protecting urban greenery in the former (Haase et al., 2017; Kronenberg, 2015). The higher ES realization found on average for western countries in Paper IV indicates that such protection for ES provision also may be too costly for at least some less wealthy eastern countries of Europe.

The look-up matrix method applied in Papers III and IV is a relatively simple method to evaluate initial potential supply and demand. Further accuracy improvement from such baseline evaluation can be valuable for human-nature ES connectivity assessment. So far, however, few studies have attempted to resolve the problem of spatial dependencies between ES supply and demand (Schirpke et al., 2019b; Schröter et al., 2018). Demand indicators may also be difficult to define, measure and ultimately relate to supply in a meaningful way, depending on the ES considered, with provisioning services being more easily evaluated as they depend on extraction of resources and production measures (Kabisch et al., 2018; Rieb et al., 2017).

Overall, nature's regulating services can be essential for cities, representing a large part of the new concept (or metaphor) of 'nature based solutions' (Escobedo et al., 2019; Frantzeskaki et al., 2019; Keesstra et al., 2018; Raymond et al., 2017), for example for adaptation to climate change. However, although nature in urban regions is important for current and future well-being, these are not the only solutions to such challenges. For example, nature can help in reducing urban temperatures, but engineered solutions, e.g., changing the heat capacity of construction materials or city-scale albedo, can also offer necessary complementary benefits (Hobbie and Grimm, 2020; Oke et al., 2017). Furthermore, providing benefits to humans is also not nature's only purpose and value (Silvertown, 2015).

5.3 Spatial boundaries

Challenges to city sustainability assessments are numerous and include environmental, social, and economic aspects (Shen et al., 2011; Wachsmuth et al., 2016). A problem for spatial analyses concerns the difficulty to delineate urban boundaries, with no clear consensus existing on how to define a city (Arcaute et al., 2015; Batty and Ferguson, 2011). Depending on considerations of density, commuting flows or population cutoff, a large number of definitions and associated delineations can be created (Cottineau et al., 2017). Additionally, the choice of spatial units of analysis has a direct influence on results, and administrative or planning boundaries, which are subjective or political in nature, can lead to arbitrary delineations of varying scale units in a region (Tan and Samsudin, 2017). In this context, Papers I and II use an evenly distributed population dataset covering the considered region, with subsequent network spatial routing considering each populated point in a regular grid covering the region. Paper IV uses city delineations based on the definition of the European statistics office (Eurostat, 2018), which provide some consistency over the large multi-city dataset. Relationships for the ES indicators in Paper IV are further considered versus PD, which is less sensitive to city delineation than total population count. For example, a narrowing of city limits to exclude areas with low population density would increase PD as well as city-average realization of ES supply Rs/Ps and decrease that of demand Rd/Pd, thereby following the main relationships found in Paper IV. Accuracy in any study of course also depends on the quality and resolution of relevant data availability within city boundaries.

6 Conclusion

This thesis has identified and quantified urban population relationships with their living environment, and developed a spatial ES quantification framework for distinction of potential and actually realized ES, with demonstrated applicability in and across a large number of cities. Specific conclusions related to each main objective are outlined below:

Objective A:

– Average income level is positively related to green-blue area accessibility in the Stockholm region. In particular, richer parts of the population, with greater possibilities to choose their living environment, prefer low-density urban areas ($\leq$30% soil imperviousness), close to water and forested areas, and overall higher average level of greenness (measured by NDVI).

– Industrial and commercial areas, and high-density urban zones ($>$30% soil imperviousness) emerge as undesirable for the richer population parts, and prevail at greater degree in the living environments of less wealthy inhabitants. Income level also correlates with ethnicity (in particular population fractions of European and non-European inhabitants), highlighting another dimension of urban segregation in relation to nature proximity.

– The above conclusions are based on analysis of relative landscape area shares (un-weighted by population counts). However, population density also tends to increase with lower income, thus enhancing differences between more and less privileged parts of the urban population also in terms of per-capita share of natural areas (m^2/person).

Objective B:

– Considering present results and plans for future developments in the Stockholm region (RUFS 2050), the region is expected to become denser in the future, with lower natural area share in the living environment relative to the 2010 baseline, and progression tradeoffs between a dense polycentric and a monocentric development.

– Shifts in future job accessibility are smaller than shifts in access to natural areas, in particular between the polycentric and the monocentric development scenario. Care must be taken not to deplete vital natural areas for potentially small efficiency and energy gains, with the polycentric scenario likely representing a balanced middle ground.

– A conflict emerges in that people want nature (objective A conclusion) while city resource efficiency may require compaction, with the poorest parts of the urban population being most impacted by future changes towards the latter if equity issues are not considered.

Objective C:

- Quantification of actual ES realization requires identification of the spatial ES connections from the supply by nature to the human demands. The thesis develops a relatively simple conceptualization, quantification and mapping approach to achieving this.
- In particular, measuring actual ES benefits requires account of the demand (human need) side of the ES service, an aspect so far rarely explored in the ES literature, and included in the spatially explicit quantification approach of this thesis (by use of relatively simple proxies).
- The thesis shows the applicability of the developed quantification approach for two types of urban ES provided by green-blue urban areas: local climate regulation, and storm water regulation.

Objective D:

- The actual realization of the ES of local climate regulation shows consistent power law relationships with city population density, implying that ES demand is progressively less fulfilled while ES supply by green-blue urban areas is progressively more used with increasing PD.
- Cities with similar PD can exhibit large differences, reflecting underlying differences in urban forms and land-cover mixes that determine the benefits provided by green-blue urban areas for the studied ES of local climate regulation.
- Area fraction with high ES realization tends to increase with increasing PD, as well as with growth in HDI or GDP per capita, indicating preferential enhancement of green-blue areas and their ES in low-density, wealthy city parts, while city-average ES realization effectiveness decreases under growth.
- Western and eastern European cities exhibit distinct ES realization relationships with PD, with western cities exhibiting higher levels of city-average ES demand fulfillment, in particular for PD up to 5'000 per km^2, while results become more mixed for greater PD.
- These data-given ES realization relationships with PD can be useful in projecting possible ES developments under various growth scenarios (in terms of PD, HDI, or GDP per capita), as a basis for deciding on needs and measures to improve urban ES provision.

7 Future perspectives

The scientific literature on ES, nature based solutions, and urban sustainability is relatively recent, with many challenges and opportunities for improvements still remaining to address in further research. Research on urban systems needs to consider perspectives from various science fields and should thus be interdisciplinary (involving, e.g., urban planning, ecology, social science, economy, hydrology, climatology, etc) for holistic, integrated urban assessments (Creutzig et al., 2019; Liu et al., 2015; McPhearson et al., 2016; Rieb et al., 2017).

Main questions for ES science of when, where and how much nature can provide ES for human well-being (Rieb et al., 2017) remain to be answered also after the first steps taken in this thesis. Further improvements and developments are needed in spatially explicit ES modeling, to identify beneficiaries, apply relevant spatial human-nature connections, and develop relevant quantification metrics for different ES in urban and other types of regions. Based on such advancements, questions of systems dynamics, feedbacks loops, and formulations and analyses of future scenarios need to be addressed to provide more meaningful and accurate insights, and lead to greater and better incorporation of natural capital and ES in decision-making. Recent research efforts have led to progression in availability of spatially explicit models considering both humans and nature (Martínez-López et al., 2019), available for the larger scientific community to be further applied, tested and developed. Other recent work (Chaplin-Kramer et al., 2019) has also highlighted the challenge of spatially explicit modeling of ES, using conceptual developments with similarities to those in Paper IV with practical implications on global scale.

Concerning nature presence and accessibility in urban regions, further research of general interest should consider mechanistic nature-health links (Chang et al., 2021; Shanahan et al., 2015) and investigation of nature's qualitative contributions (Dillen et al., 2012; Hoffimann et al., 2017). Furthermore, research is also needed on creation and preservation of natural space that can benefit whole cities and not only their richest population parts (Wolch et al., 2014).

Finally, more robust definitions of spatial system boundaries are needed in studies of urban systems. The increased availability and amounts of high-resolution datasets can greatly contribute to moving beyond subjective, coarse-scale, and varying administrative urban system delineations in research, by facilitating finer spatiotemporal resolutions that can reveal small-scale variabilities and their roles and influences on results at and across different urban scales.

Additional co-authored papers

1. Thorslund, J., Jarsjo, J., Jaramillo, F., Jawitz, J.W., Manzoni, S., Basu, N.B., Chalov, S.R., Cohen, M.J., Creed, I.F., **Goldenberg, R.**, Hylin, A., Kalantari, Z., Koussis, A.D., Lyon, S.W., Mazi, K., Mard, J., Persson, K., Pietro, J., Prieto, C., Quin, A., Van Meter, K., Destouni, G., 2017. Wetlands as large-scale nature-based solutions: Status and challenges for research, engineering and management. *Ecological Engineering, Ecological Engineering of Sustainable Landscapes* 108, 489–497. https://doi.org/10.1016/j.ecoleng.2017.07.012
2. Bring, A., **Goldenberg, R.**, Kalantari, Z., Prieto, C., Ma, Y., Jarsjö, J., Destouni, G., 2019. Contrasting Hydroclimatic Model-Data Agreements Over the Nordic-Arctic Region. *Earth's Future* 7, 1270–1282. https://doi.org/10.1029/2019EF001296
3. Kalantari, Z., Santos Ferreira, C.S., Page, J., **Goldenberg, R.**, Olsson, J., Destouni, G., 2019. 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. https://doi.org/10.1016/j.jenvman.2019.05.086
4. Ma, Y., Vigouroux, G., Kalantari, Z., **Goldenberg, R.**, Destouni, G., 2020. Implications of Projected Hydroclimatic Change for Tularemia Outbreaks in High-Risk Areas across Sweden. *International Journal of Environmental Research and Public Health* 17, 6786. https://doi.org/10.3390/ijerph17186786

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Tack tack !

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