Assessing the contribution of nature-based solutions for addressing sustainability challenges in European urban areas

Clara Veerkamp, Aafke Schipper, Frank van Rijn, Martijn Spoon, Milan Loreti and Ton Dassen

Extension of WP3.4. deliverables

June, 2021

This project has been funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 730243

PBL Netherlands Environmental Assessment Agency

Assessing the contribution of nature-based for addressing sustainability challenges solutions in European urban areas

Table of Contents

List of figures

List of tables

Abbreviations

FUA - Functional Urban Areas

GIS – Geographic Information System

HSG - Hydrological Soil Group

IPBES - Intergovernmental Panel on Biodiversity and Ecosystem Services

InVEST - Integrated Valuation of Ecosystem Services and Trade-offs

LULC – Land Cover and Land Use

MAR - Minimum Area Requirements

NBS – Nature-Based Solutions

NGO – Non-Governmental Organisation

NFF - Nature' Future Framework

POF - Potentially Occurring Fraction of species

SCS-CN - Soil Conservation Service Curve Number

SSD - Species Sensitivity Distribution

UHI - Urban Heat Island

WHO - World Health Organisation

Abstract

Nature is increasingly recognized for its potential to effectively address various sustainability challenges due to its capacity to provide multiple benefits to people simultaneously. However, large-scale assessments quantifying the extent to which urban nature can offer relevant solutions to challenges are limited. The aim of this study is to assess current and future contributions of nature-based solutions (NBS) in major European urban areas to address multiple urban sustainability challenges (climate change, loss of biodiversity, human health and well-being). We applied a scenario-based modelling approach and quantified five benefits of NBS. We made use of the InVEST (Integrated Valuation of Ecosystem Service and Trade-offs) tool as well as developed additional GIS-based models, and applied these modules to the current situation of more than 700 European larger urban areas (urban core and associated hinterlands), and to three future scenarios that represent different perspectives on the value of (urban) nature, hence prioritize a different set, amount and location of NBS to be implemented. Results illustrate that existing NBS in European cities have a positive impact on reducing the risk of heat stress and stormwater flooding, lowering atmospheric carbon dioxide, and providing space to people for recreational purposes and habitat to biodiversity. Moreover, results show large variations across European regions and benefits, and demonstrate the vital role of cities' hinterlands in providing benefits to urban dwellers. Enhancing the amount of NBS in densely inhabited urban core areas can further enhance benefit provision.

This study should be considered as a first order magnitude assessments as it required generalisation, the use of proxies and initial estimates and accounts for a limited set of NBS (on publicly-owned land). But, it allows to compare the potential of NBS in different urban contexts and helps to identify potential synergies and trade-offs among benefits and challenges, thus providing a more comprehensive and contextualized approach to evaluate and discuss the value of urban NBS.

1. Introduction

Nature is increasingly recognized for its potential to effectively address various sustainability challenges due to its capacity to provide multiple benefits to people simultaneously (Faivre et al., 2017, Seddon et al., 2020). Especially in urban areas, green and blue infrastructure, such as street trees, vegetated roofs or lakes, are shown to play an important role into enabling resilient and healthy cities (Kabisch et al., 2017, Frantzeskaki et al., 2019, van den Bosch and Sang, 2017, Lafortezza et al., 2018). This has prompted a proliferation of policies and actions for mainstreaming so-called nature-based solutions (NBS) into (urban) planning and decision-making (e.g. New Urban Agenda (UN 2017), Urban agenda for the European Union (EC 2016)).

To consider NBS as a serious alternative to conventional/traditional grey infrastructure, assessments quantifying the multiple benefits of green and blue infrastructure within the urban environment are vital. Although there is a growing body of such assessments (Veerkamp et al., under review), these typically estimate the effectiveness of urban NBS within a specific location (e.g. city, street). Large-scale quantitative assessments are currently limited. Moreover, available assessments are strong in assessing the capacity of urban ecosystems to deliver benefits (supply), while the amount of benefits demanded by the urban population is hardly quantified (Haase et al., 2014, Veerkamp et al., under review). Hence, the extent to which urban NBS can offer relevant solutions to challenges is rarely considered in urban ecosystem assessments (but see Baro et al. (2015), Larondelle and Lauf (2016)), and therefore widely unknown to decision makers.

To position NBS into decision making processes in the context of urban environments, assessments that explore possible future trajectories and discuss specific interventions or solutions which help to achieve more desirable futures might be supportive to underpin current discourses and debates on the future city. To come to a set of narratives, it is important to realize that there are plural perspectives on what is desirable, as people ascribe different values to nature (e.g. depending on their cultural, socio-economic and ecological context) (Díaz et al., 2018). For example, a park can be valued by its potential to retain water during a heavy rainfall event, to provide space where people can relax and meet as well as by its potential to support local biodiversity. The recognition of this plurality of values in (environmental) assessments will better meet the information needs of policymakers and other stakeholders and allow assessments to be used in various contexts (Pereira et al., 2020).

The aim of this study is to assess current and future contributions of NBS in major European urban areas to address multiple urban sustainability challenges. We focus on challenges related to i) climate change, ii) loss of biodiversity, iii) human health and well-being.

Climate change presents one of the greatest challenges to urban societies today where impacts of climate change are often of socio-economic nature (e.g. heat related health effects and damage to building infrastructure), induced by an increased number and intensity of heatwaves, droughts and flooding events (Kovats, 2014, EEA 2020). Urban nature can help to reduce air temperature by providing shade, enhancing cooling through evapotranspiration, and increasing the diffuse reflection of solar radiation by enhancing albedo (Bolund and Hunhammar, 1999). In addition, the porous terrain of vegetated areas allows water to infiltrate into the soil, while vegetation itself takes up and releases water through evapotranspiration, hence reducing overall rainwater runoff (Bolund and Hunhammar, 1999). Additionally, vegetation can lower atmospheric carbon dioxide (CO_2) concentration by fixing carbon during photosynthesis and storing excess carbon as biomass (Nowak et al., 2013). In this assessment we focus on NBS potential to address challenges related to the need to counteract increased urban heat stress and risk of urban flooding, and the need to mitigate increased atmospheric carbon dioxide concentration.

Global biodiversity and associated benefits to people from nature are declining, causing serious consequences to livelihoods, economics and a good quality of life (IPBES, 2019). Urbanization, including the expansion of urban areas and increased demand for energy and natural resource use, poses one of the greatest threats to global biodiversity (Seto et al., 2012, IPBES, 2019, McDonald RI et al., 2018). For example, past urban expansion contributed significantly to habitat loss and fragmentation, and projected urban growth could threaten an additional 290,000km^2 of natural habitat by 2030 (McDonald RI et al., 2018). Yet, urban areas can also be critical for preserving and enhancing local biodiversity by bringing nature back into the cities (Bulkeley, 2021, Ives et al., 2016, Hall et al., 2017). Moreover, urban green and blue areas allow people to interact with the natural environment which may enhance their appreciation of nature and inspire sustainable behaviours, such as willingness to conserve or protect biodiversity (Alcock et al., 2020).

Although over the last decades, urbanization has improved the lives of many people worldwide, urban life-styles take a toll on physical and mental well-being (e.g. mental stress, physical inactivity, cardiovascular and respiratory diseases). Urban green space, such as parks, urban forests and allotment gardens provide various social benefits to urban residents, such as stimulating daily recreation and physical activities, by offering a refuge from the hectic everyday lifestyle and bring residents into contact with nature and encouraging social cohesion (Remme et al., 2021, Langemeyer et al., 2018). In times of societal crisis, these effects may be amplified as for example urban residents have emphasized the need of green space during COVID-19 isolations for solace and respite (Ugolini et al., 2020). Providing equal access to green spaces in cities is a promoted international and European policy strategy to maintain social cohesion and to support health and wellbeing of individuals and communities (e.g. through the UN Sustainable Development Goals (particular SDG 11.7 (UN 2015)), Parma Declaration in the WHO European Region (WHO, 2010), but also see (Stessens et al., 2017)).

To assess current and future contributions of NBS in European cities to address challenges related to climate change, loss of biodiversity and health and well-being, we quantified benefits of i) heat mitigation, ii) carbon sequestration, iii) stormwater regulation and iv) green space availability, as well as v) biodiversity. The work described here builds on the mapping and assessment of NBS in 775 European urban areas, presented in the NATURVATION Deliverable 3.7 (Veerkamp et al., 2020). Here we further expanded this work, and developed additional methods and indicators representative for the actual contribution of NBS to society under multiple scenarios where NBS are mainstreamed. This allowed us to identify potential synergies and trade-offs among benefits and societal challenges, thus providing a more comprehensive and contextualized approach to evaluate and discuss the value of urban NBS. To that end, we used the InVEST (Integrated Valuation of Ecosystem Service and Trade-offs) tool as well as developed additional GIS-based models and applied these modules to major European urban areas under the current situation and three future scenarios that represent different perspectives on the value of (urban) nature, hence prioritize a different set, amount and location of NBS to be implemented.

2. Materials and methods

2.1. Conceptual framework

A widely used framework in numerous global, national and subnational environmental assessments (e.g. Maes et al., 2013, Maes, 2020, TEEB, 2010), is the so-called 'ecosystem service cascade model', explaining how ecosystem services are the specific elements of ecosystems that explicitly contribute to human well-being (Haines-Young and Potschin, 2010). Building on the ecosystem service cascade framework from Haines-Young and Potschin (2010) and variations of that work, we developed a conceptual framework for selecting indicators measuring the benefits of (urban) nature to people (Veerkamp et al., under review) (Figure 1). Thereby we explicitly consider the two complementary components of nature's contributions to people (i.e. benefits): i) people's needs (i.e. demands) and ii) nature's contribution (i.e. supply) (Chaplin-Kramer et al., 2019, Baro et al., 2015, Baro et al., 2016, Geijzendorffer et al., 2015) (Figure 1).

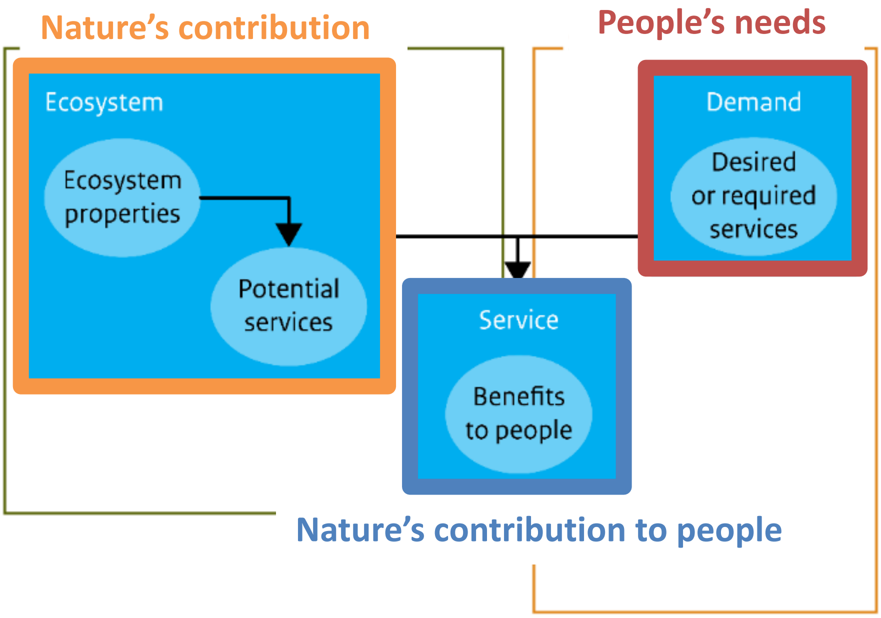


Figure 1: Conceptual framework for assessing (urban) NBS benefits to people.

Nature's contribution is defined by the capacity or potential of urban ecosystems to deliver benefits, indicating possible options available to people for usage (i.e. supply indicator). This indicator is defined by an ecosystem property (i.e. ecological structure, process, function). For example, measured as the potential of vegetation to reduce air temperature by providing shade and increasing evapotranspiration, or the presence of urban green space potentially available to be used by people for daily recreation (Table 1). *People's need* is defined as the amount of benefits required, demanded or desired by society (i.e. demand indicator), e.g. described by desired environmental conditions or quality standards as well as by peoples preferences. For example, potential need is measured as the amount of rainfall that needs to be regulated to prevent stormwater flooding during a peak rainfall event or the temperature reduction required to maintain human thermal comfort (Table 1). *Nature's contribution to people* is defined by the actual benefit used or consumed by people (i.e. benefit indicator). Actual benefits exist only in relation to people's needs, and illustrate the contribution of (urban) nature to mitigate negative felt or experienced challenges (e.g. reduce the risk of exposure to heat stress) as well as a means to meet desired or required conditions or goals (e.g. contribution to cities' carbon emission reduction targets) (Table 1).

Table 2: Overview of selected urban NBS benefits and used indicators.

NBS benefit	Supply / Demand / Benefit Indicator	Indicator (unit)	Description
Heat mitigation	Supply	Heat mitigation index per grid cell (0 - 1)	Contribution of vegetation to reduce air temperature by its' potential to provide shade, increase evapotranspiration and modify thermal properties of the urban fabric (albedo effect)
	Demand	Urban heat Island (UHI) intensity per FUA (°C)	Uncomfortable thermal conditions to people defined by the extent of heat stress measured as the additional summer heat experienced within a city when compared to surrounding areas
	Demand	Heat stress temperature threshold value per FUA (°C)	Risk of exposure to critical temperatures; when temperature is exceeded, mitigation is required to prevent negative health impacts described by national heat stress threshold values (e.g. heat health warning, heat alert)
	Benefit	Reduction of UHI intensity per FUA (°C)	Contribution of vegetation to reduce heat stress during summer defined by the actual cooling of the UHI
	Benefit	Reduced risk of exposure to heat stress per FUA (%)	Relative contribution of urban NBS to reduce the risk of exceeding temperature thresholds over which people perceive heat stress, using national heat health warning levels as a benchmark
Carbon sequestration	Supply	Carbon sequestration per FUA (kg C/year)	Annual amount of carbon sequestrated by trees in the urban living environment.
	Demand	Carbon dioxide emissions per FUA (tons CO_{2eq}/year)	Cities carbon footprint: carbon dioxide emission of the year 2013, (mainly due to per capita purchasing power and consumption patterns)

	Benefit	Carbon mitigation per FUA (%)	Relative contribution of urban NBS to reduce cities annual CO2 emissions, based on the amount of carbon sequestered by trees within the FUA relative to cities carbon footprints
Stormwater regulation	Supply	Potential max. water retention index per grid cell (0-100)	Vegetation and associated groundcover is able to uptake and delay the release of rainwater
	Demand	Rainfall during heavy precipitation event per FUA (m^3)	Amount of rainfall which needs to be regulated to prevent stormwater flooding
	Benefit	Avoided stormwater runoff per FUA (%)	Relative contribution of vegetation to reduce risk of stormwater flooding based on the amount of stormwater retained during a heavy rainfall event compared to when no vegetation is present (i.e. 100% runoff)
Human health and well-being	Supply	Presence of green space within the FUA	Presence of public accessible green areas potentially available to urban residents to relax, recreate or meet other people
	Demand	Health and well-being reference value(s): 1ha within 300m	Having public accessible green space in close proximity to where residents live in support of peoples' health and well-being
	Benefit	Share of population living within 300m distance to publicly accessible urban green spaces (%)	Amount of population having publicly accessible green space (e.g. parks, forest) within walking distance (i.e. 300m)
Biodiversity	/	Potentially occurring fraction of species (POF) (dimensionless)	Proportion of birds and flying insects species for which available green areas meet the required area needs for sustaining a minimum viable population

2.2. Modelling approach

We used the Integrated Valuation of Ecosystem Services and Trade-offs tool (InVEST, version 3.8.7, Sharp et al. (2020)) for heat mitigation and stormwater regulation, and developed additional GIS-based modelling approaches for carbon sequestration, green space availability and urban biodiversity.

2.2.1. Heat mitigation model

The InVEST urban cooling model is designed to quantify the potential of urban nature to mitigate the Urban Heat Island (UHI) effect by providing shade, increasing cooling through evapotranspiration, and modifying the thermal properties of the urban fabric (albedo effect). The model works with a heat mitigation (HM) index, expressed by a value between 0-1, (0) representing low and (1) high mitigation potential (i.e. supply indicator). Key input variables for the model are shade, albedo, crop coefficient and green area occurrence per LULC type (Table 2). For more details on the model see Sharp et al. (2020) and NATURVATION Deliverable 3.7 (Veerkamp et al., 2020). Based on the heat mitigation index (i.e. supply indicator), we estimated the actual contribution of urban vegetation to reduce the risk of exposure to high temperatures (i.e. benefit indicators), defined by the reduction of the UHI effect (°C) and reduced exceedance of heat stress threshold temperatures (%) by using i) a FUA-specific UHI magnitude and ii) threshold temperature values over which people perceive heat stress (i.e. demand indicators).

The UHI describes the additional summer heat experienced within a city when compared to its surrounding area. In this study, the UHI magnitude for each FUA was defined by the air temperature measured during the hottest day in July of 2016 and estimated as the difference between the maximum temperature (presented by the highest value measured within a FUA) and minimum temperature (presented by the lowest value within the FUA). The actual cooling (°C) was then estimated by multiplying the UHI with the average HM index of the FUA.
As there is no unique definition of 'hot days' and 'heat wave', various heat health warning systems, indicating when a safe temperature threshold is exceeded, are applied across Europe (Casanueva et al., 2019). National weather/meteorological institutes are often using different risk levels according to the severity of the heat stress (i.e. maximum temperature, duration) and its impact on human health. In this study, we selected the lower threshold values, varying between +25°C to +40°C, representing the first risk level of heat stress (e.g. yellow risk code, first level warning, class 1, moderate health risk, heat alert) (Kim et al., 2018, Casanueva et al., 2019, Koppe et al., 2004) (see Table A-1 in the Appendix). If no information about a national heat threshold value could be found, we used threshold values of a neighbouring country, expressing a similar or identical climate type (following the Köppen-Geiger climate classification system (Koppen, 1936), and a simplified map of Europe as presented in Peel et al. (2007)).

The contribution of urban vegetation to reduce the risk of being exposed to critical temperatures, using national heat stress threshold values as benchmark, was then calculated as:

$$Heat\ stress\ mitigation\ (\%) = \frac{T_{max}-T_{new}}{T_{max}-T_{alert}} \qquad [Eq.\ 1]$$

Where T_{max} is defined by the maximum temperature (°C) measured within a FUA, representing a situation where no vegetation is present; T_{new} is defined by the new average temperature (°C) within a FUA, when taking urban vegetation into account; and T_{alert} is defined by the country-specific threshold temperature value over which people perceive heat stress (°C).

Table 3: Key input variables for the heat mitigation model

Parameter	Value	Source
LULC	European Urban Atlas Land Use Land Cover Classification	Urban Atlas 2012 — Copernicus Land Monitoring Service
Evapotranspiration	Average evapotranspiration July 2016 per FUA	Global Aridity Index and Potential Evapotranspiration Climate Database
Shade	Average tree cover density per LULC class per FUA	Tree Cover Density (TDC)
Albedo	0.15 or 0.06 (for water)	Veerkamp et al. (2020)
Crop Coefficient	Area-weighted average value based on the composition of each LULC type based on tree cover density and baseline Kc values for certain crops (e.g. trees, turf grass, grass and shrubs) or the soil coefficient for bare soils	Veerkamp et al. (2020)
Green areas	Green urban area, forest	European Urban Atlas LULC
Cooling distance	230m	Aram et al. (2019)
UHI	Difference between maximum and minimum daytime temperature during the hottest day in July 2016, per FUA	ERA5-Land dataset
Heat stress temperature threshold	Country specific heat health warning threshold values, representing the first risk level of heat stress	Table A-1 in Appendix

2.2.2. Carbon sequestration model

We modelled the contribution of urban trees to reduce cities' annual carbon dioxide emissions (i.e. benefit indicator) by estimating annual amount of carbon sequestrated by urban trees (Kton C/FUA/year) (i.e. supply indicator) relative to cities carbon footprints (i.e. demand indicator).

Carbon sequestration rates can vary depending on variables such as tree species composition, age and diameter. Here we retrieved net carbon sequestration rates by urban trees from a large-scale assessment carried out in ten US cities (Nowak et al., 2013), which values have also been applied to European cities (Baro et al., 2015). In the model, first, tree cover density per FUA is estimated as a total area covered by trees (in m^2) per FUA. Then this value is multiplied by the standard carbon sequestration value for tree covered urban areas (i.e. 0.205 kg C/m^2/year) to estimate the total amount of carbon sequestered per FUA. In order to compare this value to cities' carbon footprints, typically expressed in annual CO_2 emission, the carbon sequestration value per FUA is multiplied by the ratio of the molecular weight of carbon dioxide to that of carbon (i.e. 44/12= 3.67) to arrive at CO_2 equivalent ($CO_{2eq.}$).

Annual CO_2 emissions per FUA (Gg $CO_{2eq.}$/year) were constructed by extracting spatially explicit values from a global CO_2 emission dataset, incorporating data for 13,000 cities (Table 3). This datasets estimates CO_2 emissions by incorporating multi-region input-output analyses with national statistics on household spending, per-capita purchasing power and population density (Moran et al., 2018). While such a generic, relatively global approach generally comes with wider uncertainty than a local, more contextual analysis, the method offers the possibility to simultaneously assess a multitude of cities and, due to method consistency, enabling comparison between cities. Then, the annual amount of CO_2 equivalent sequestered was compared to the total amount of CO_2 emitted per city, representing the relative contribution of urban trees to mitigate local carbon dioxide emissions.

Table 4: Key input variables for the carbon sequestration model.

Parameter	**Value**	**Source**
Land Cover	European Urban Atlas Land Use Land Cover Classification	Urban Atlas 2012 — Copernicus Land Monitoring Service
Carbon sequestration rate	0.205 kg C/m2 tree canopy/year	Nowak et al. 2013
Tree canopy coverage	Tree cover density per FUA in %	Urban Atlas
Carbon emission	Annual carbon emission per FUA in Kt C/year (year 2013)	Global Gridded Model of Carbon Footprints (citycarbonfootprints.info)

2.2.3. Stormwater regulation

To estimate stormwater regulation benefits, we used the InVEST Urban Flood Risk Mitigation model (Sharp et al., 2020). This model is designed to estimate the contribution of vegetation to reduce the risk of stormwater flooding, expressed as the amount of stormwater retained during a heavy rainfall event when compared to when no vegetation is present (i.e. 100% water runoff), hence avoiding stormwater runoff.

The retention of stormwater runoff is based on the amount of stormwater infiltrating into the ground determined by the infiltration capabilities of natural urban infrastructures (i.e. supply indicator). Depending on factors such as soil type, and imperviousness, urban landscapes have different capabilities of retaining and delaying storm water runoff, and as such mitigating flooding during heavy rainfall events (i.e. demand indicator).

Avoided stormwater runoff *R* per grid cell *i,* is calculated as a function of runoff *Q* and precipitation *P*, and represents a dimensionless value relative to precipitation volume.

$$R_i = 1 - \frac{Q_{p,i}}{P} \quad [Eq. 2]$$

By further taking into account grid cell area (m^2), runoff retention volume R_{m3} can be expressed in cubic meters (m^3) per grid cell.

$$R_{m^3_i} = R_i \cdot P \cdot grid\ cell.area \cdot 10^{-3} \quad [Eq. 3]$$

Q_p represents a runoff equation based on the Soil Conservation Service Curve number (SCS-CN) method, developed by the USDA (Cronshey, 1986). The SCS-CN method is a simple, widely used and efficient method for determining the approximate amount of runoff from a rainfall event, and has already been applied to the urban context to assess the contribution of urban green space on urban runoff (McPhearson et al., 2013, Yao et al., 2015, Grêt-Regamey et al., 2020). The runoff Q is defined by potential retention, rainfall depth and initial abstraction:

$$Q_{p,i} = \begin{Bmatrix} \frac{(P-\lambda S_{max,\,i})^2}{P+(1-\lambda)S_{max,\,i}} & if \quad P > \lambda \cdot S_{max,i} \\ 0 & otherwise \end{Bmatrix} \quad [Eq. 4]$$

Where P is the design storm depth (mm), and $S_{max,i}$ is the potential maximum retention (mm) per grid cell, for which $\lambda \cdot S_{max}$ is the minimum rainfall depth (e.g. initial abstraction) value (mm) in order for runoff to be initiated:

$$S_{max,\,i} = \frac{25400}{CN_i} - 254 \qquad [Eq. 5]$$

Initial abstraction λ is defined to be a fixed value of 0.2. S_{max} is a function of the curve number *CN,* which depends both on the LULC type as well as a spatially explicit hydrological soil group. Hydrological soil groups are expressed as four different categories, depending on the infiltration properties for each soil type. Here, we used a global gridded dataset of hydrological soil groups (HSGs), allocating soil types into one of eight different hydrological soil groups. While group A to D represent low, moderately low, moderately high, and high runoff potentials respectively, there are four additional groups (dual HSG) characterized by a high runoff potential (e.g. group D) unless drained (Ross et al., 2018). As we did not assume specific drainage scenarios in our models nor scenarios, all additional groups were assumed to be matching group D.

For the LULC map, each land cover type is associated with a specific CN value for each of the four hydrological groups (see 2.2.2 for parametrization). To define a heavy rainfall event, potentially able to cause stormwater flooding, we used the 99.8th percentile of the average daily rainfall per FUA measured between 1950 and 2020 at the centroid urban core. This value corresponds with a rainfall event typically occurring once a year. If no data was available for a specific FUA, we used the average 99.8 percentile of the average daily rainfall of all remaining FUAs.

Table 5: Key input variables for the stormwater regulation model.

Parameter	**Value**	**Source**
LULC	European Urban Atlas Land Use Land Cover Classification	Urban Atlas 2012 — Copernicus Land Monitoring Service
Heavy rainfall event	99.8th percentile of 70 years of rainfall data	ERA5-Land hourly data from 1981 to present (copernicus.eu)
Curve number values	Based on standard runoff CN number and composition of LULC (i.e. imperviousness, woody/grass coverage, bare soil), except for agricultural land, water and wetlands (fixed values)	Cronshey (1986)
Imperviousness	Imperviousness degree (1-100%) per LULC	Imperviousness — Copernicus Land Monitoring Service
Hydrological soil group	Reclassification of hydrological soil groups into four main groups, based on their runoff potential (A= low runoff; D= high runoff)	Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modelling (ornl.gov); (Ross et al., 2018)

2.2.4. Green Space availability

The model is designed to assess the spatial availability of urban green space within a certain defined distance to where urban residents live, hence contributing to public health and well-being. It follows the method as suggested by the World Health Organisation (WHO) Regional Office for Europe (WHO, 2016) and applied in various European cities (Kabisch et al., 2016, Annerstedt van den Bosch et al., 2016). The model estimates the availability of publicly accessible green space (i.e. supply indicator) within a certain distance to where people live (i.e. demand indicator)) and the proportion of the city's population living within a certain distance from a public green space (%) (i.e. benefit indicator).

$$\text{Urban Green Space Indicator} = (N_{ACC} / N_{Total}) \times 100$$

N_{acc} = number of inhabitants living with 300m from nearest urban green space of specified minimum size; N_{Total} = total number of inhabitants within the area of interest; Urban green space indicator = percentage of residents living within 300m from nearest Urban green space of specified minimum size (from EU-WHO)

To assess the spatial green space availability, we first selected specific LULC classes from the Urban Atlas LULC dataset, which represent vegetation and assumed to be publicly accessible, and dissolved classes of the same type if they were in close proximity to each other and only separated by e.g. a bike path, as to not underestimate the total coherent area. Having publicly accessible green space in close proximity/walking distance to where residents live describes peoples‘ demand. Since there is no universally accepted guideline on the minimum size of green space and maximum distance to define accessibility/availability (Stessens et al., 2017), we considered the recommended threshold values from the WHO, namely as having at least 1 hectare green space within walking distance (i.e. five minutes' walk), which corresponds to 300m linear distance (WHO, 2016).

To calculate the total share of citizens with green space available within walking distance (i.e. 300m), we computed the distance to the nearest urban green space within the FUA measured as the Euclidean distance between the place of residence and the boundary of any adjacent green LULC class within reach. Buffer zones (using the 'buffer analysis' function in ArcMap) of 300m were created around each population cell and the population within distance of green space as well as the available green space per citizen within these buffers were summed up.

Table 6: Key input variables for the green space availability model.

Variables	**Value**	**Source**
LULC	Publicly accessible green space	Urban Atlas 2012 — Copernicus Land Monitoring Service
Population	Population density per grid cell	GHS resident population grid — European Environment Agency (europa.eu)
Distance-size threshold value	1ha, 300m	WHO 2016

2.2.5 Urban biodiversity

Although biodiversity in cities is dependent on a complex interplay of factors (McKinney, 2008), there is increasing evidence that the area, connectivity and vegetation structure of green spaces are key variables for its prosperity (Beninde et al., 2015). Across a range of species, it has been shown that both area and connectivity promote biodiversity in cities (Beninde et al., 2015, Drinnan, 2005, Lepczyk et al., 2017, Magle et al., 2009, Shanahan et al., 2011, Sushinsky et al., 2013). However, patch size and connectivity requirements vary considerably among species and taxonomic groups (Donaldson et al., 2017, Lepczyk et al., 2017, Pe'er et al., 2014). We propose an indicator that takes into account this variability by calculating the proportion of species (between 0 and 1) for which (connected) area requirements are being met.

Available area

The area available for a given species can be calculated based on the so-called effective mesh size (m_{eff}). This represents the average amount of habitat accessible to an individual that is randomly placed within a landscape, given a certain movement distance, and accounting for both within- and between-patch connectivity (Spanowicz and Jaeger, 2019). It is calculated as:

$$m_{eff} = A_{total} \cdot \sum_{i=1}^{m} \left[\frac{A_{Gi}}{A_{total}}\right]^2 = \frac{1}{A_{total}} \sum_{i=1}^{m} A_{Gi}^2 \qquad \text{[Eq.6]}$$

where *m* = the number of groups of connected habitat patches inside a defined landscape, A_{total} = the total area of the landscape, and A_{Gi} = size of each of the m groups of patches (where i = 1, 2, 3, …, m). A group of patches is defined by the patches being closer to each other than the maximum movement distance. Maximum movement distance is highly context-dependent, as it differs between species, so-called landscape matrices (the urban fabric). For this assessment, we focused on flying animals (birds and airborne insects), for which it is reasonable to assume a linear movement distance for calculating connectivity. We took two tentative linear movement distances, i.e., 100m and 1000m, as first-tier estimates. We considered all (semi-)natural land cover within the city boundaries as potential habitat (i.e., parks, (semi-)natural grasslands and forests)) (Table 6).

Required area

The area required for sustaining a minimum viable population depends on various species traits, including body mass and trophic level (i.e., a small herbivore needs considerably less space than a large carnivore). For our indicator, we retrieved species-specific minimum area requirements (MAR) for birds and flying insects from the database published by Pe'er et al. (2014). If there were multiple MAR values for a single species, we took the average. If MAR values were reported as a range rather than a single value, we took the midpoint of the range. We then log-transformed the values and established a species sensitivity distribution (SSD) assuming a logistic function (Figure 2). We merged birds and insects in the SSD because the means and variances of the log-transformed MAR values were not significantly different between the two species groups (Levene's test p-value of 0.99; independent samples t-test p-value of 0.76).

Comparing available and required area

For our indicator, we compared the available and required area to evaluate the extent to which the network of urban green in the city meets the needs of the species. For each FUA, we first calculated the effective mesh size for the two selected movement distances (100m and 1000m) (Table 6). We then compared each effective mesh size value with the distribution of MAR values (as shown in Figure 2) in order to determine the proportion of species for with the available area is equal to or larger than the required area:

$$POF = \frac{1}{1+e^{-x}} \qquad \text{[Eq.7]}$$

with

$$x = \frac{\log(m_{eff})-\alpha}{\beta} \qquad \text{[Eq.8]}$$

Where POF = potentially occurring fraction of species (between 0 and 1) and α and β are the mean and standard deviation of the species sensitivity distribution (Figure 2), with α = 0.76 and β = 1.37.

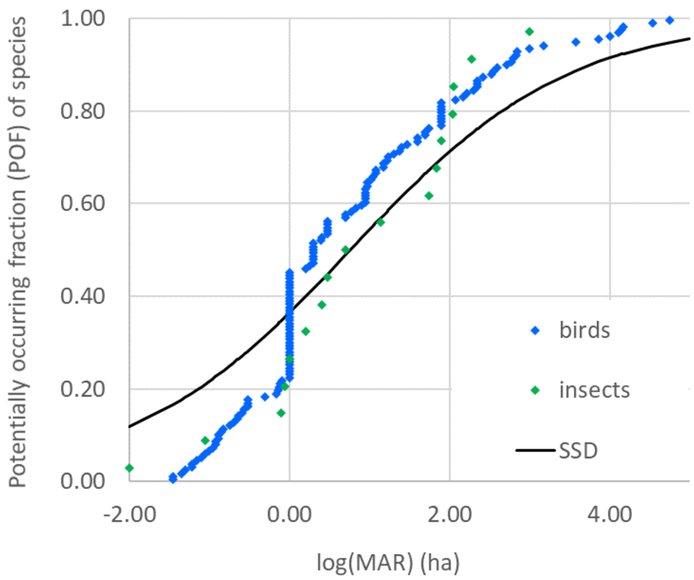


Figure 2: Species sensitivity distribution (SSD) for minimum area requirements (log_{10}-transformed) based on bird and flying insect species.

Table 7: Key input variables for the urban biodiversity model.

Variables	Value	Source
LULC	Semi-natural green space	Urban Atlas 2012 — Copernicus Land Monitoring Service
Movement distances	100m, 1000m	
Minimum area requirements (MAR)	Minimum area requirements for birds and flying insects	Pe'er et al. (2014)

2.3. Model parameterization

2.3.1. Study area and spatially explicit input data

We applied the InVEST model and the GIS-based models to each of the Functional Urban Areas (FUAs), using spatially explicit input data on relevant input variables. A FUA represents a city with more than 100,000 inhabitants including its commuting zone. The FUAs cover the EU27 plus Great Britain, EFTA countries (i.e. Iceland, Liechtenstein, Norway and Switzerland), West Balkan and Turkey. The basic data requirements per FUA are a map showing its geographical location and territory and a land use/land cover (LULC) map (Table 7). We obtained high-resolution LULC data for the FUAs from the European Urban Atlas. This dataset distinguishes among 27 different LULC classes. Per model, additional global and European data is required (Table 7). Due to data availability and calculation capacity, the amount of FUAs can vary between the different models (minimum 703 FUA to maximum 778 FUAs). For example, for the green space availability model, population data for Turkey and Serbia could not be obtained, while for the biodiversity model, the amount of semi-natural habitat could not be calculated for two larger FUAs because of an extensively large dataset and limited computation capacity.

Table 8: Spatially explicitly input data.

Data Name	**Spatial and temporal resolution**	**Source**	**Used in which model**
European Urban Atlas LULC	20m x 20m; reference year 2012	Urban Atlas 2012 — Copernicus Land Monitoring Service	All
Global Aridity Index and Potential Evapotranspiration Climate Database	30 arc-seconds/ 1km at the equator; reference year 2016	Global Aridity Index and Potential Evapotranspiration (ET0) Climate Database v2 (figshare.com)	Heat mitigation model, stormwater regulation model
ERA5-Land dataset	9km x 9km; reference year 2016	ERA5-Land hourly data from 1981 to present (copernicus.eu)	Heat mitigation model, stormwater regulation model
Tree Cover Density (TDC)	20m x 20m; reference year 2015	Tree Cover Density — Copernicus Land Monitoring Service	Heat mitigation model; carbon sequestration model
Gridded Global Model of Carbon Footprints (GGMCF)	250m x 250m; reference year 2013	Global Gridded Model of Carbon Footprints (citycarbonfootprints.info)	Carbon sequestration model

Imperviousness Density (IMD)	10m x 10m; reference year 2018	Imperviousness — Copernicus Land Monitoring Service	Stormwater regulation model
Hydrological Soil Map	250m x 250m; reference year 2018	Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modelling (ornl.gov); (Ross et al., 2018)	Stormwater regulation model
Population	100m x 100m, reference year 2016; EU29	GHS resident population grid — European Environment Agency (europa.eu)	Green space availability model

2.3.2. Model parametrization

The heat mitigation model requires values for shade, albedo, crop coefficient and green areas per LULC type (see Deliverable 3.7 for the parametrization of these values, and Table B-1 in the Appendix). The average tree cover density (i.e. shade value) for each LULC was also used for the calculation of total carbon sequestration per FUA. To that end, we multiplied the FUA-specific shade value per LULC with an average carbon sequestration rate per area of tree coverage (i.e. 100% tree coverage), which were retrieved from Nowak et al. 2013 (Table B-4 in the Appendix). The stormwater regulation model requires CN values per LULC per hydrological soil group. FUA-specific runoff CN values were estimated based on the composition of each LULC type (i.e. imperviousness and perviousness), and their respective runoff coefficients (Cronshey, 1986). To that end, we estimated the average imperviousness per LULC class per city, using zonal statics and an assumption on remaining land cover (e.g. trees, grass, bare soil). For example, if an urban LULC has an imperviousness density of 60%, we calculated the CN as 0.6 times the baseline runoff CN number of imperviousness, plus 0.4 times the baseline value for the remaining assumed coverage. In case of urban fabric (e.g. discontinuous urban fabric), we assumed the remaining area would be covered by a combination of trees and grass. For agricultural land, water and wetlands, we adopted baseline CN values from Cronshey (1986) (Table B-2 & B-3 in Appendix). To assess the availability of green space we selected ‘green urban areas’, ‘forest’, ‘herbaceous vegetation’ (e.g. natural grassland, moors) and ‘open space with little or no vegetation’ (e.g. beaches, dunes, bare rocks) as publicly available LULC classes (Table B-5 in the Appendix). For the biodiversity model, the key parameter is the presence of semi-natural green areas. We selected ‘green urban areas’, ‘forest’, and ‘herbaceous vegetation’ as semi-natural LULC classes (Table B-6 in the Appendix).

2.4. Scenario Development

2.3.1. Urban NBS narratives

We developed three narratives on the future city in which NBS are central, while giving recognition to different values that people have or strive for, in relation to nature. Each narrative counts for a different vision on the future urban environment where NBS are mainstreamed in urban planning and design in such a way that they optimally contribute to diminish or solve the different challenges that cities are facing.

We used the Nature Futures Framework (NFF) as a starting point to envision positive futures for cities in Europe. The NFF was developed by the scenarios and models expert group of the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) as a strategy to formulate scenarios centered on our relationship(s) with nature, which would help inform decision-making across multiple scales (Pereira et al., 2020). It captures three different perspectives of how people relate to and thus value nature: i) Nature for Nature, where nature has value in and of itself, emphasizing the intrinsic value of nature, ii) Nature for Society, where nature is primarily valued for the benefits or uses people derive from it, emphasizing the instrumental value to nature, and iii) Nature as Culture, where people are seen as an integral part of nature, emphasizing the relational value to nature (Figure 3) (Pereira et al., 2020). Multiple values can be assigned to the same natural entity (e.g. a park can be valued by its potential to retain water (instrumental value) as well as supporting biodiversity (intrinsic value)).

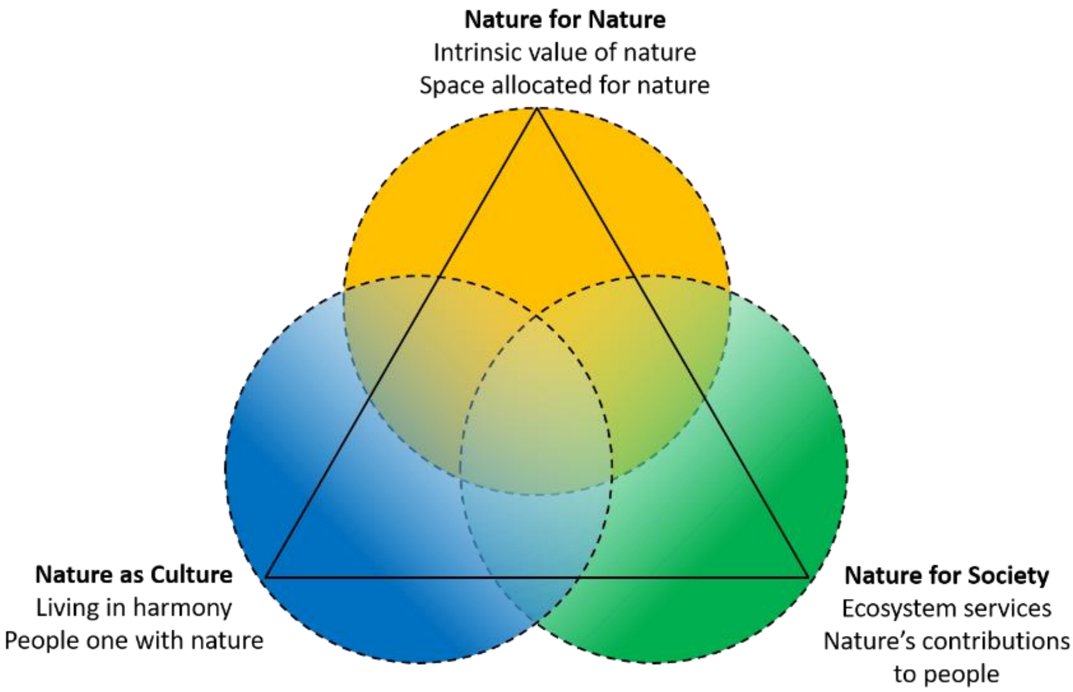


Figure 3: Conceptual framework of the Nature's Future Framework, developed by the IPBES community, with a list of some possible synonyms for the value perspectives that are used by various actors (Pereira et al., 2020).

To ensure that the narratives are informed by views from key stakeholders, a workshop was held on April 7, 2021 and attended by 29 participants representing various organizations, research institutes and groups working on urban NBS initiatives (see Appendix C for the list of participants and outcomes of the workshop). Ideas and visions from stakeholders were collected and used as input to develop the narratives.

Nature for Nature

In this perspective, nature has a value in and of itself, and the preservation of nature's diversity and functions is of primary importance, emphasizing the intrinsic value of nature (Pereira et al., 2020). Hence, a prerequisite of implementing urban NBS is to maintain and enhance (urban) biodiversity. This is achieved by bringing nature back into the city, for example by i) creating additional adequate space for nature and reintroducing certain key species (e.g. 'flagship species', such as certain birds and butterflies to raise support for biodiversity conservation), ii) increasing the connectivity among urban ecosystems and between urban and rural areas (e.g. creating 'stepping stones', ecological corridors), and iii) ecological or biodiversity-friendly management of green and blue space, to support a diverse 'wild' nature (quality).

Nature for Society

In this perspective, nature is primarily valued for the benefits or uses people derive from it, and which could lead to an optimization of multiple uses of nature (Pereira et al., 2020). This perspective emphasizes the instrumental value of nature and (urban) nature is used as a tool to enhance benefits that people want, need or desire, such as the need to address certain felt threats to current or future living environments. The value of urban nature is thus directly connected to what people experience or will experience as a threat and where nature can potentially help to mitigate this threat. Key societal challenges are closely related to impacts of climate change including stormwater flooding, heat, drought and atmospheric carbon dioxide concentrations. To optimize NBS' multiple benefits to address climate change challenges, nature is integrated into the city where people most need it, by i) implementing small-scale initiatives (e.g. planting trees along streets to create additional shade, greening parking lots to enhance water retention potential), ii) connecting green features to grey infrastructure (e.g. combining grey and green solutions such as constructed wetlands, green roofs or walls); iii) greening of public and private land (e.g. developing public green space as well as de-paving private gardens), and iv) management of green and blue space to optimize multiple desired benefits.

Nature as Culture

In this perspective, humans are perceived as an integral part of nature, and therefore what is valued is the reciprocal character of the people-nature relationship (Pereira et al., 2020). Hence, implementing (urban) NBS creates space for people and nature to reconnect and affiliate with nature and in that way support human health and well-being. This is achieved by creating 'attractive' nature within living environments by, for example i) increasing the amount of public accessible green space within a city to all urban dwellers (and thus providing equal access to nature contributes to social inclusion and social justice), ii) reinforcing identity of an urban environment (e.g. integration of cultural important aspect, creating opportunity to engage with nature) and iii) tactical urbanism, allowing temporary changes to the build environments to support neighbourhoods and city gathering (e.g. transforming streets or parking lots into green places intended to create room for meeting neighbours or learn about nature).

2.3.2. Scenario implementation

The three narratives were then used to design quantitative scenarios allowing for a model-based assessment of the value of nature in the selected European urban areas. According to each perspective, scenarios prioritize a different set, amount and location of NBS to be implemented when compared to the current situation (i.e. reference) (Table 8). To transfer the narratives into scenarios that can be used in the GIS-based modelling, we converted current LULC classes and LULC properties (e.g. shade, crop coefficient, impervious surface, green area values) in such a way that the situation most closely represents the future urban area as it is imagined in the narrative. We assume changes within the core city only, while the cities' hinterland, often consisting of agricultural land, forests, wetlands, airports, port areas and water areas, to remain unchanged (Table A-1 to A-6 in the Appendix).

Table 9: Overview of the three urban NBS scenarios.

Scenario name	NBS	Action
Nature for Nature	Semi-natural green areas (i.e. forests, grasslands) and parks	Preservation of existing green space (parks, urban forest, grasslands); creating additional green space in low density populated areas, by transformation of 'low' and 'very low urban fabric', 'mineral extraction sites', 'construction sites', 'unused land' and 'sports fields' into new semi-natural green areas.
Nature for Society	Trees, forests, parks, permeable surfaces	Implementation of additional trees along streets, increase of tree density and permeable surfaces in the urban fabric, parks and forests; 'construction sites' and 'unused land' are transformed into green residential areas, 'mineral extraction and dump sites' into parks, and 'herbaceous vegetation' into forests.
Nature as Culture	Parks	Creating additional public parks by transforming 'fast transit roads and associated land', 'mineral extraction and dump sites', 'construction sites', 'land without current use' and 'sports and leisure facilities' into public parks.

In the **Nature for Nature** scenario, we assumed the preservation of existing semi-natural green areas (i.e. forest, grasslands, parks) and created additional space for urban nature within the city, especially in low density populated areas. To implement this scenario, we converted certain LULC classes into semi-natural green areas, assuming a coverage of 50% trees and 50% grass, but publicly accessible. We converted low and very low-density urban fabrics into semi-natural green areas (hence densification of population within city). Moreover, we converted 'mineral extraction and dump sites', 'construction sites' and 'land without current use' into 'semi-natural green areas' (creating green stepping stones within the city) and the green areas within the 'sport and leisure facilities' are managed in such a way that it supports local biodiversity, hence counted as semi-natural green areas in this scenario.

In the **Nature for Society** scenario, we assumed the implementation of additional urban nature, including increase of permeable surfaces (e.g. green roofs on buildings, grass strips along roads or green parking lots) and planting of extra trees close to where people most benefit from it (e.g. within residential areas, along streets, within parks). Moreover, we assumed the creation of new green residential areas on former construction sites and unused land, convert extraction sites into parks (brownfield redevelopment), and placed additional green areas within the city where possible (e.g. transforming grassland into urban forests).

We simulated the implementation of additional trees within the city by increasing the shade values per LULC to the 95 percentile of the LULC-specific shade values across all cities. We used the 95 percentile to represent an ambitious but realistic increase in trees. If the reference value of a FUA specific LULC type was higher than the scenario value of that specific LULC, we kept the reference value. To simulate the increase of permeable surfaces, we used the 5 percentile of the LULC specific impervious values across all cities. In addition, we changed selected LULC classes into 'greener' LULC classes (resulting in changes in shade and impervious values). We converted 'construction sites' and 'land without current use' into 'very low-density urban fabric' (assuming new residential areas) and herbaceous vegetation' into new forest areas, and 'mineral extraction sites' into new green urban areas (parks), representing a higher shade and lower impervious value, and counted as semi-natural, publicly accessible green areas.

In the **Nature as Culture** scenario, we assumed a large-scale implementation of additional urban parks which can be used by urban dwellers to meet, relax, or enjoy. To implement this scenario, we changed certain LULC classes into new 'urban green areas', representing parks which are publicly accessible. We transformed 'fast transit roads and associated land', into public parks as well as 'mineral extraction and dump sites', 'construction sites', 'land without current use' and 'sports and leisure facilities' into public parks.

2.5. Analysis of the results

We estimated averages of four benefits provided per FUA for the reference and the three NBS scenarios, as i) Heat stress mitigation (%): Relative contribution of urban NBS to reduce the risk of exceeding temperature thresholds over which people perceive heat stress, using national heat health warning levels as a benchmark; ii) avoided stormwater runoff: amount of avoided aboveground stormwater runoff (m^3/km^2) during a heavy rainfall event, based on the natural infrastructure's capacity (i.g. soil permeability) to retain water in relation to the amount of rainfall; iii) Carbon dioxide mitigation (%): Relative contribution of urban NBS to reduce cities annual CO_2 emissions, based on the amount of carbon sequestered by trees within the FUA relative to cities carbon footprints iv) Green space availability (%): Share of population living within 300m distance to publicly accessible urban green spaces (of at least 1ha); and v) Biodiversity: Potentially occurring fraction of species

(POF), measuring the proportion of birds and flying insects populations which could potentially survive in the urban area based on the availability of semi-natural habitat within 100m and 1000m distance.

To assess future contributions of urban NBS, we then compared the relative change of the four benefits between the current situation/reference and the three future green scenarios anddescribing that change as a percentage of the reference value:

% change = (% Scenario) – (% Reference) / (% Reference)

3. Results

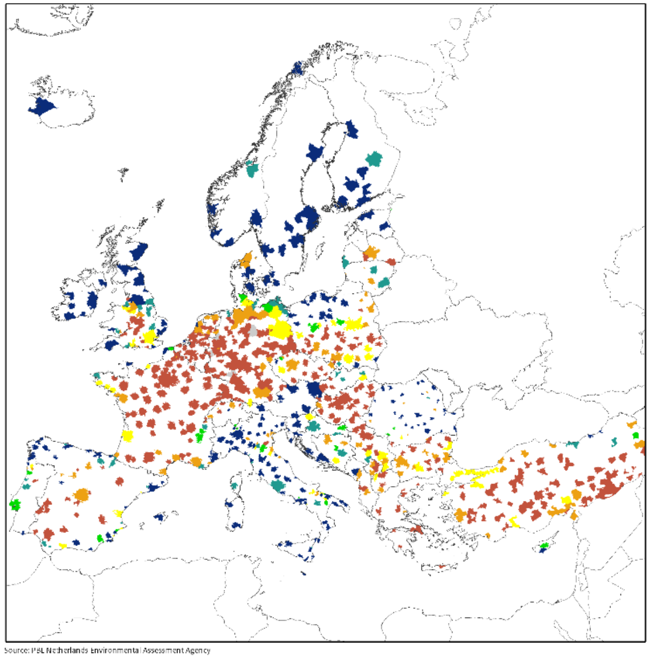
3.1. Reference

Models were implemented to quantity and map four of the five benefits across the European urban areas, and average benefits provided are presented in Table 9 and Figures 4, 5 & 6. The maps are also presented on the NATURVATION website.

Table 10: NBS benefits quantified for the reference.

NBS benefits	Indicator	average value	FUAs' included
Heat stress mitigation	Reduced risk of exceeding heat stress temperature thresholds (%)	25	775/565
Avoided stormwater runoff	Amount of water retained during heavy rainfall event (1 year stormwater event) (m3/km2)	$28 * 10^3$	769
Carbon dioxide mitigation	Amount of carbon sequestered relative to cities carbon footprint (%)	15	767
Green space availability	Share of population living within 300m distance to publicly accessible green space of at least 1ha (%)	62	695
Urban biodiversity	Potential occurring fraction of species (POF) at 100m to 1000m distance	0.82 – 0.87	778

During the hottest days in July 2016, 73% of 775 FUAs would exceed **temperature** thresholds over which heat-health warnings may occur, if no vegetation was present. With the current amount and location of urban NBS, the risk of exceedance is reduced by 25% across the FUAs with heat warnings (i.e. 565). 34 FUAs even experience no heat warning anymore, meaning that the risk of exposure to critical temperatures is avoided by urban NBS, particular in the UK (e.g. Liverpool, Cambridge), Spain (e.g. Avilés, Pamplona) and Italy (e.g. Rom, Modena). Moreover, urban NBS can also contribute in reducing the risk of **stormwater flooding**. For 769 FUA, an average of 69 % of precipitation is being retained during heavy rainfall events compared to when no natural infrastructure is present. As such, 28 * $10^3 m^3/km^2$ of stormwater is currently kept from running off. As for the cities with the highest amount of avoided stormwater runoff (> 50 * $10^3 m^3/km^2$), located in France (e.g. Cannes, Nice) and Italy (e.g. Massa, Genova, Savonna) (Figure 4), they represent cities with a combination of high runoff retention and high amounts of rainfall. Due to a combination of low runoff retention and low rainfall, cities with the lowest amount of runoff retention (< 17 * $10^3 m^3/km^2$) are predominantly located in the Netherlands (e.g. Lelystad, Amsterdam, Rotterdam, Leeuwarden) and Belgium (e.g. Oostende) (Figure 4). In terms of **carbon** sequestration benefits, cities annual CO_2 emissions are reduced by an average of 15%. Nearly 80% of all FUAs have a very low carbon dioxide mitigation potential (i.e. 0-20% reduction of annual CO_2 emission), especially for cities in the UK, Turkey and The Netherlands (Figure 5). The lowest values are estimated for two FUAs in Turkey (Viranşehir 0.11%; Van 0.13%) and Gouda in the Netherlands (0.21%) (Figure 5). Ten FUAs (1.3% of total number FUAs) sequester even more carbon then their cities annually emit, particular cities in Latvia (Liepāja, Daugavpils, Jelgava), Sweden (Umeå) and Finland (Kuopio). The high mitigation values correspond to large forested areas in each cities' hinterland, leading to high carbon sequestration rates. For example, in Liepāja and Umeå annual CO_2 emission is fully sequestered by trees within the entire FUA boundaries (339% and 243% respectively). When accounting for trees within the core area only, carbon dioxide mitigation values are still relatively high, but significantly less compared to the entire FUA area (i.e. to 19% and 73% respectively) (Appendix D – Figure D1). As for **accessibility to green**, 62% of the European population is living withing a 300m distance to parks, beaches, forest and grassland areas of a minimum size of 1 hectare. In 86 FUAs (12%) more than 80% of the urban dwellers living within 300m distance to green space. The highest values have been estimated for urban areas in Finland (e.g. Kuopio, Jyväskylä, Lahti, Oulu) and Sweden (e.g. Göteborg). For nearly 10% of the FUAs, availability of green space is below 40%, and the lowest availability of green space to urban dwellers was estimated for cities in Bulgaria (Pazardzhik:17%, Yambol: 25%), Romania (Roman: 20%, Târgu Jiu: 24%) and Italy (Trapani: 23%, Cerignola: 26%). In terms **of biodiversity**, an average POF of 0.82 (100m) to 0.87 (1000m) is estimated across European cities, meaning that the current amount of semi-natural habitat present in the urban landscape is sufficient to support at least 80% of the bird and flying insect species. 67% to 83% of all FUAs included (total 778) have a high POF (>0.8) at a 100m and 1000m distance respectively. The highest POFs are estimated in northern European countries (Figure 6), particular in Sweden (Umea: 0.98; Upsala 0.97), Finland (Oulu, Kuopio, Tampere: 0.97) and Norway (Trondheim, Oslo, Kristiansand: 0.97). 20% of the FUAs had a low POF (0 to 0.4), particular in the UK, Netherlands, Belgium, North Germany, Denmark (Figure 6). The lowest values are estimate for the Italian cities of Barletta (0.13 to 0.20 for 100m and 1000m) and Capri (0.17 to 0.31 for 100m to 1000m) and the Belgian city Oostende (0.20 to 0.31 for 100m to 1000m).



Heat Stress mitigation per FUA

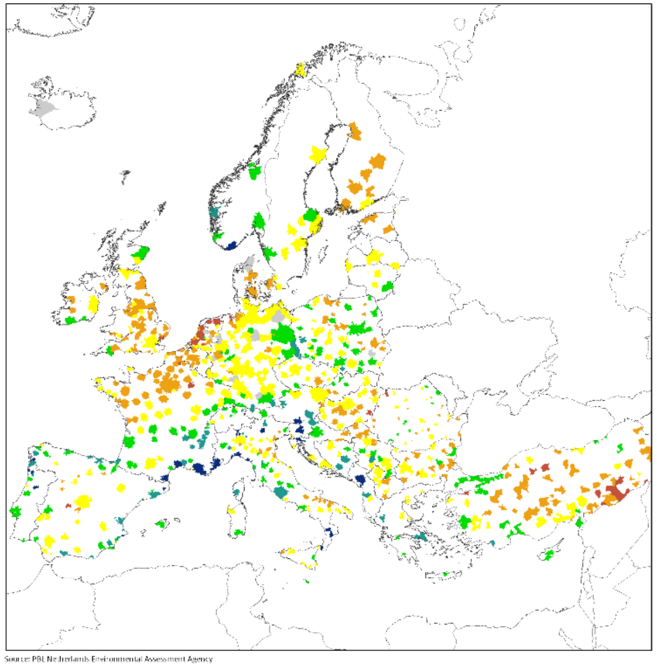
Reference scenario

Heat Stress mitigation in %

- No Heat Stress warming
- 80 - 100
- 60 - 80
- 40 - 60
- 20 - 40
- 0 - 20
- No data

Summary EU average (all FUA)

Scenario	Heat mitigation index	Stress mitigation
Reference	0.37	25.0%
Nature for Society	0.45	29.3%
Nature for Culture	0.42	27.9%
Nature for Nature	0.44	28.6%



Avoided Stormwater per FUA

Reference scenario

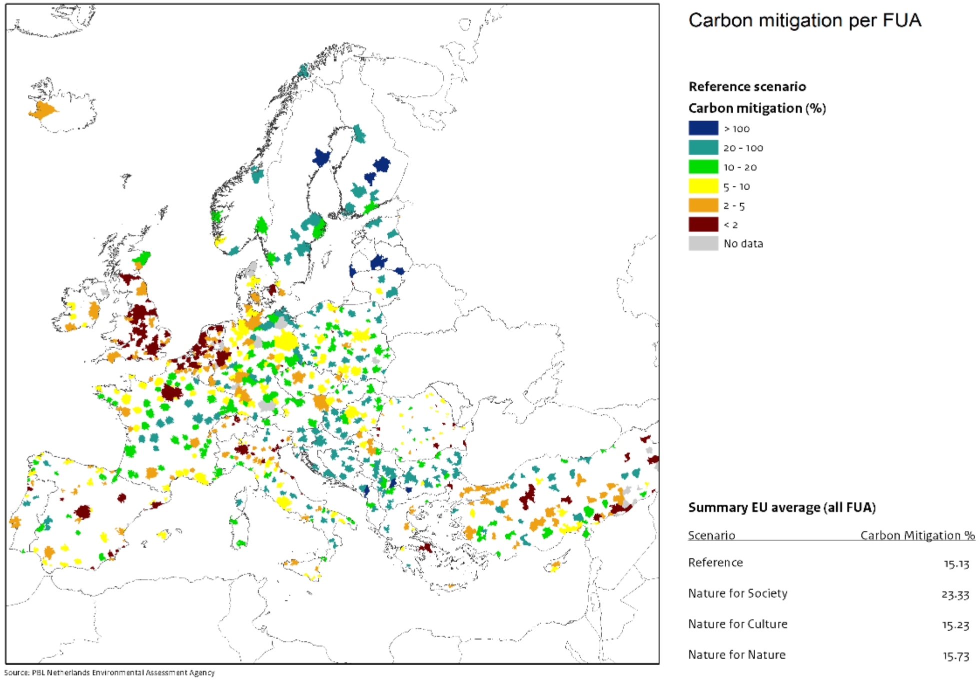
Avoided stormwater in m3 per km2

- > 40000
- 35000 - 40000
- 30000 - 35000
- 25000 - 30000
- 20000 - 25000
- < 20000
- No data

Summary EU (all FUA)

Scenario	EU average runoff retention index	EU average of avoided stormwater in m3 per km2
Reference	0.689	28037
Nature for Society	0.700	28544
Nature for Culture	0.690	28076
Nature for Nature	0.693	28205

Figure 4: Spatial distribution of average heat stress mitigation (%) an avoided stormwater runoff (m3/km2) per FUA in the current situation (i.e. reference).



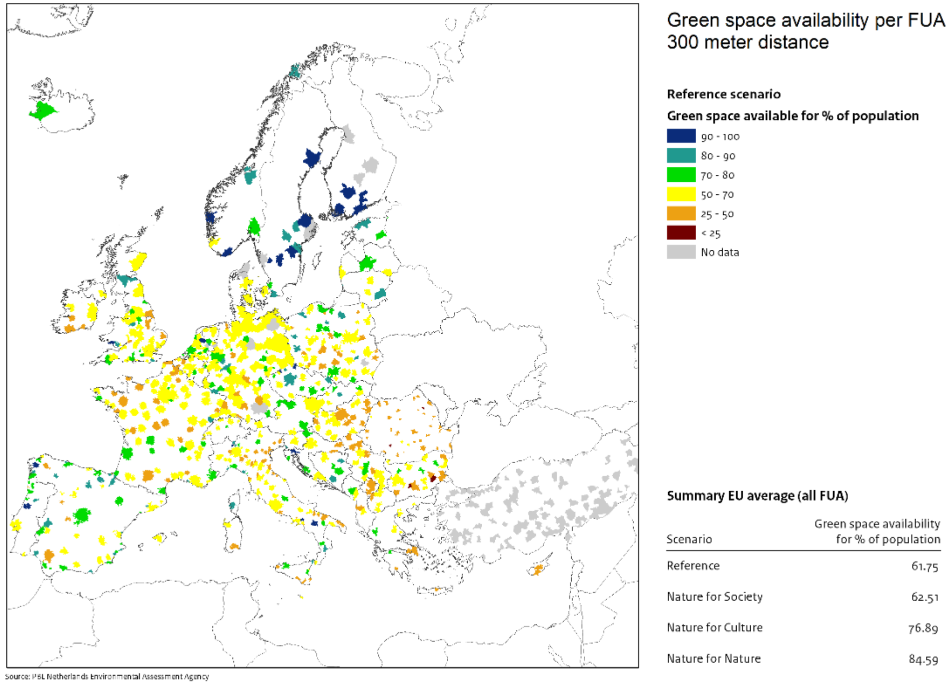
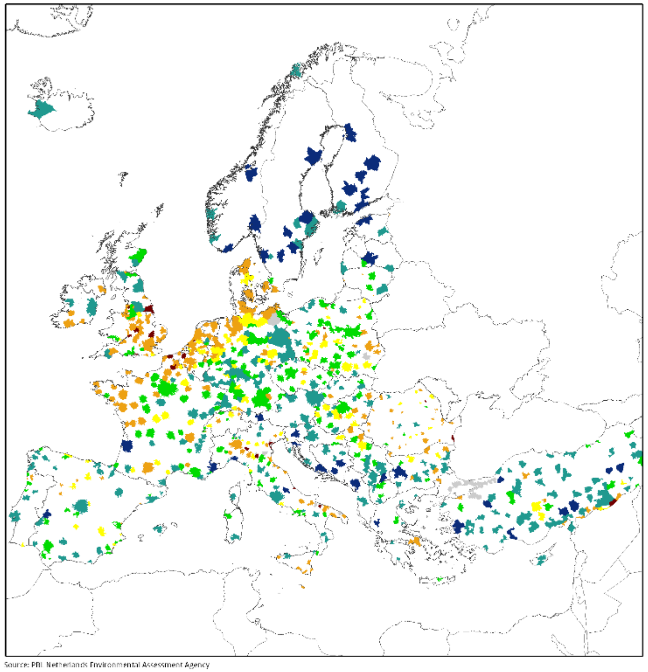


Figure 5: Spatial distribution of carbon dioxide mitigation (%) and green space availability (%) per FUA in the current situation (i.e. reference).



Biodiversity in POF per FUA
100 meter distance

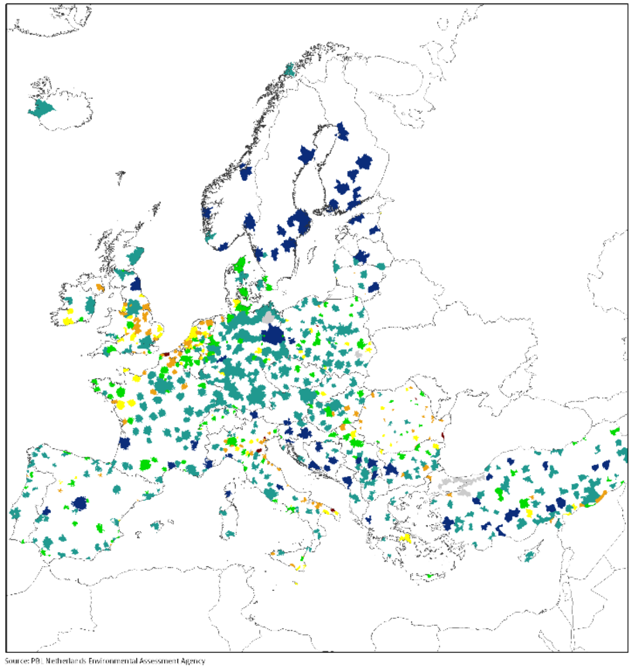
Reference scenario

Potentially Occurring Fraction of species

- > 0.95
- 0.90 - 0.95
- 0.85 - 0.90
- 0.80 - 0.85
- 0.50 - 0.80
- < 0.50
- No data

Summary EU average (all FUA)

Scenario	100m	1000m
Reference	0.82	0.87
Nature for Society	0.82	0.88
Nature for Culture	0.84	0.89
Nature for Nature	0.84	0.90



Biodiversity in POF per FUA
1000 meter distance

Reference scenario

Potentially Occurring Fraction of species

- > 0.95
- 0.90 - 0.95
- 0.85 - 0.90
- 0.80 - 0.85
- 0.50 - 0.80
- < 0.50
- No data

Summary EU average (all FUA)

Scenario	100m	1000m
Reference	0.82	0.87
Nature for Society	0.82	0.88
Nature for Culture	0.84	0.89
Nature for Nature	0.84	0.90

Figure 6: Spatial distribution of the potentially occurring fraction of species (POF) at 100m and 1000m distance per FUA in the current situation (i.e. reference).

3.2. Urban NBS scenarios

Implementing additional NBS within the urban areas increased all four benefit provisions across the three NBS scenarios when compared to the reference, although the differences between the scenarios are minimal (Figure 7).

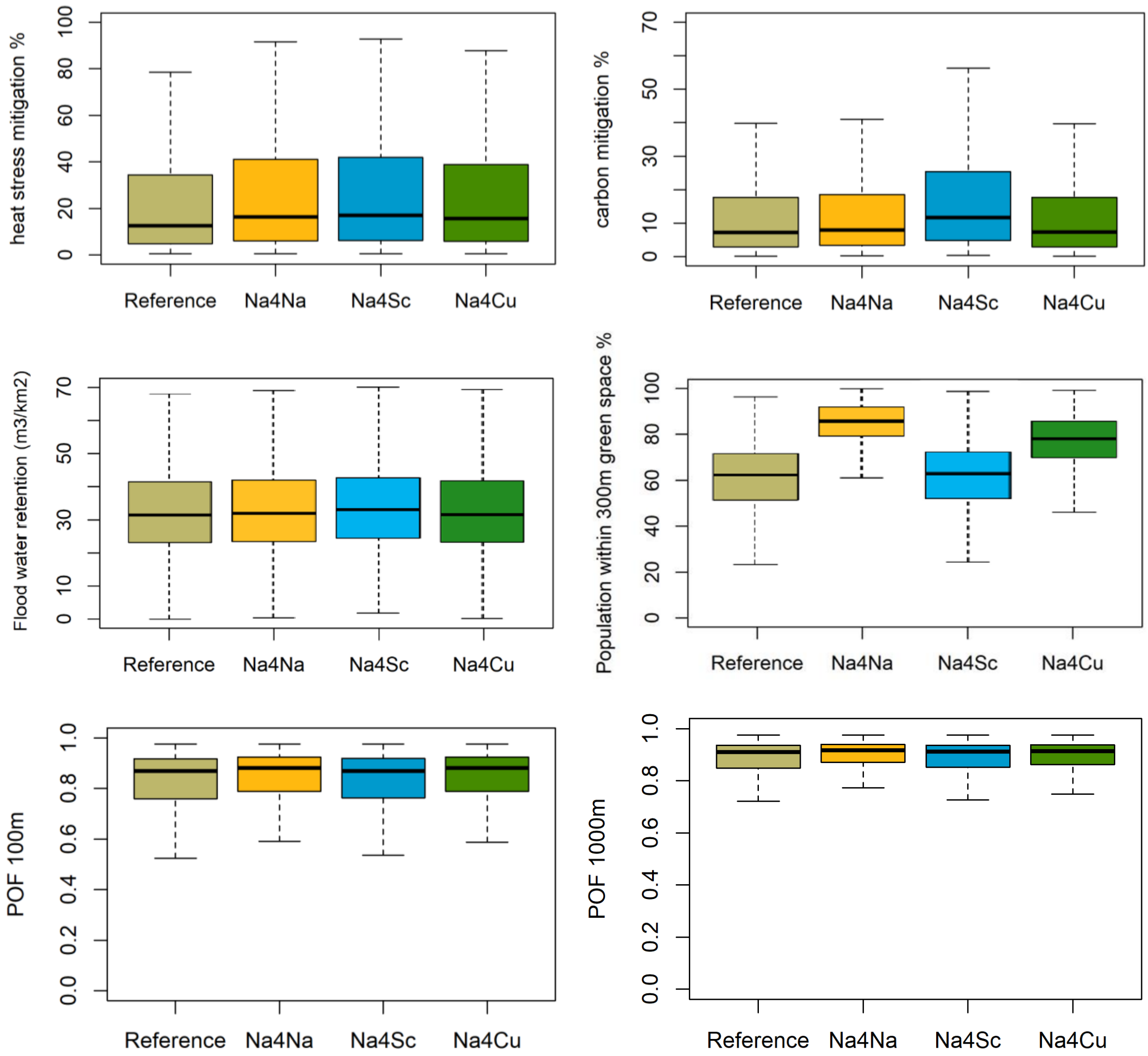


Figure 7: Heat stress mitigation, avoided stormwater runoff, carbon dioxide mitigation, green space availability and biodiversity across the FUAs in the current situation and the three NBS scenarios. Boxplots represent median (black line), interquartile range (boxes) and range (minimum – maximum; whiskers represent the minimum and maximum values within 1.5 times the interquartile range).

However, when comparing the relative changes of benefit provisioning across the different scenario, significant differences are identified. The **Nature for Society** scenario is characterized by the largest increase in heat mitigation (+4.27%), carbon mitigation (+8.2%) and stormwater runoff mitigation (+1.8%) when compared to the other scenarios. In this scenario, 48 FUAs have now temperatures below the threshold, thus no heat stress warning. In terms of carbon dioxide mitigation, 30 FUAs now mitigate more than 100% of their annual carbon emission (3.9% of all FUAs) and more than 14% of the FUAs have a medium or high carbon mitigation potential. Although biodiversity increases in this scenario as well, it is the smallest increase when compared among the three NBS scenarios (i.e. no increase for 100m and 1% increase for 1000m). The **Nature for Nature** scenario is characterized by the largest rise in biodiversity (measured by the POF) through the increase of habitats/refuges for different birds and flying insect species (2.4% and 3.4% for 100m and 1000m respectively). More than 70% (at 100m distance) and 90% (at 1000m distance) of the FUAs have a high POF (>0.8) in this scenario. But also heat stress mitigation benefits increase in this scenario (+3.54%) which is close to the value of Nature for Society. Moreover, the Nature for Nature scenario also creates additional space to be used by people, and estimates the highest increase in the availability of green space to people when compared to the reference (+23%), and 85% of the population lives within 300m distance to urban green space. The **Nature for Culture** scenario shows the 2^{nd} highest increase in the availability of green space to people when compared to the reference scenario, with 77% of the population living within 300m distance to urban green space. In terms of biodiversity, the Nature for Culture scenario also shows the 2^{nd} highest increase in POF, coming in just 1% short of the Nature for Nature scenario.

4. Discussion and Conclusion

This study demonstrates a first order magnitude assessment of current and future contributions of urban NBS to address multiple urban sustainability challenges in major European urban areas, by the application of a scenario-based modelling approach. The work described here builds on the previous European-scale NBS assessment (Veerkamp et al., 2020), but further developed methods, indicators and scenarios. To that end, we used two existing models (i.e. InVEST) and developed three additional GIS-based models to account for a total of five benefits of urban NBS in the assessment. We applied the InVEST modelling framework because it is open access and relatively simple to parametrize, as well as is developed on the latest scientific insights. As we could not find existing suitable models for urban carbon sequestration, green space availability and biodiversity, we developed additional GIS-based models based on standard quantitative relationships and values we found in peer-reviewed literature and/or other urban NBS assessments. An advantage of this approach is that our assessment was able to account for the quantification of multiple benefits of urban NBS across a large-scale environment (more than 700 European cities).

The use of InVEST and our GIS-based modelling on the scale of over 700 FUAs in Europe, however, required generalisation, assumptions and the use of proxies and initial estimates. For example, we estimated carbon sequestration rates based on the urban tree canopy coverage, applying standard sequestration rates for urban trees from literature. However, sequestration rates may differ among tree species and the inclusion of other types of vegetation (e.g. shrubs, grass) was forgone in our assessment. Moreover, we did not refine carbon sequestration rates to local environmental conditions such as the length of the growing season, green space and soil management or age of vegetation (Baro et al., 2015, Velasco et al., 2016), hence our assessment approach might be prone to uncertainties. Moreover, there are variations in cities' carbon emission values depending on which datasets or model used for the assessment. In this study, we used a global dataset (from the GGMCF model), which exclusively focuses on subnational resident consumption, income and expenditure patterns. While this method allows for the creation of a gridded carbon footprint map based on spatial population data, certain assumptions and data uncertainties affect the results (e.g. homogenous consumption patterns per region, even distribution of direct emission from households, possible allocation and aggregation errors). As such, the model was subjected to a sensitivity analysis with rather generous uncertainty margins (Moran et al., 2018). While other global datasets exist, such as the Global Human Settlement Layer (GHSL), expressing carbon footprint values of many global cities by sector and inhabitant, they do not provide a spatially gridded emission map, and as such are less likely to fit the extent and/or amount of the FUA's selected in this assessment. However, despite the uncertainties in the approach and data used for the carbon sequestration model, our results are in line with Baro et al. (2015). In this study, carbon mitigation values are estimated for five European cities and when compared with our assessment, results are shown to be within the same order of magnitude (see Appendix D Figure D-2), hence supporting the confidence in our approach and estimated results.

Another example of a generalisation in our approach is the assessment of green space availability, which focuses on the quantitative distribution of green space in relation to the associated population, as it does not account for the actual use/accessibility of urban green space or barriers to use certain spaces. For example, we considered the WHO guidelines (i.e. 1ha of green within 300m) to measure availability, however different guidelines are used across EU countries (Stessens et al., 2017) as well as different distances are associated with specific age groups (e.g. elderly might profit the most from a close park whereas for younger people, distance might matter less due to superior physical fitness). Additionally, we ignored attractiveness (e.g. level of noise, facilities, safety, habitat type) and quality (e.g. healthy vegetation) of green space as well different preferences among social groups, influencing the actual use of the green space for example for recreation, relaxation or meeting other people. Also, further differentiation of green space in terms of structure and habitat type as well as accounting for small-scale green space (e.g. garden, courtyard, street trees) could add meaningful insights into green space availability, as well as into urban biodiversity. However, this was simply not possible using European datasets (such as the Urban Atlas) within the technical practicability (i.e. model running time, data storage capacity). Moreover, the urban biodiversity model applied in this assessment has focused on a few species alone (i.e. birds and flying insects; due to data availability), which is a simplification of the actual biodiversity present in cities.

Moreover, our assessment focused on a limited set of green NBS on public-owned land (trees, parks, forests, permeable surfaces), and did not account for blue NBS (e.g. water bodies) and NBS implemented on private land (e.g. green roofs, gardens), which have shown to provide substantial benefits as well (Nutsford et al., 2016, Camps-Calvet et al., 2016). For example, the InVEST stormwater regulation model, cannot account for green roofs, which are however relevant stormwater management practices to retain/delay large amounts of rainwater runoff (Shafique et al., 2018).

Another issue regarding the model approach is that, while the InVEST models overall show great flexibility in tailoring key parameters to the area of interest (e.g. considering data availability, context), users are limited in their ability to modify key parameters. For example when following the latest findings in literature (e.g. the initial abstraction value is a set value in the stormwater regulation model, however a recent study suggests a lowered value (Krajewski et al., 2020)) actual implementation into the model depends entirely on the developers. The online forum of the Natural Capital project (https://community.naturalcapitalproject.org/), however, is a valuable platform to get in contact with the developers of the model and to make suggestions for further improvements.

For the development of the scenarios, we applied generic change rules to all FUAs to reflect possible changes in each scenario. We did not tailor the scenarios to the local context, but based them on generic narratives which have been informed by key stakeholders and capture important values and approaches on (urban) nature (e.g. NFF framework). The magnitude of the relative changes between the reference and the three NBS scenarios are relatively small. This is explained by the fact that we have made changes exclusively to the densely populated urban core area where we also focused on public-owned land only. Private land (e.g. gardens, building roofs) and surrounding less density populated hinterlands (commonly covered by agriculture and/or forest areas, commuting zone) remain unchanged in the scenarios. Cities' hinterlands often describe the biggest share of the total FUA area, and our results demonstrate that these essential providers of benefits to urban dwellers (e.g. carbon sequestration).

Given this approach, our study provides tentative estimates of the contributions of urban NBS to address urban sustainability challenges. But it gives first overall estimates of the benefits of NBS for the urbanised land of Europe, where approximately 75% of the European population is living. Additionally, it allows to compare the potential of NBS in different urban contexts at European scale (e.g. which cities have the most potential benefit from NBS in relation to climate change) and helps to identify potential synergies and trade-offs among benefits and challenges, thus providing a more comprehensive and contextualized approach to evaluate and discuss the value of urban NBS. Moreover, it might support city governments, companies and organisations debating and deciding on NBS in the urban planning and design phases by providing science-based insights. Other, more-detailed reports such as the NBS handbook for practitioners (EC 2021), or assessment reports of the Joint Research Centre MAES project (Maes, 2019, Maes J. et al., 2016) can then be used to further guide the assessment of NBS, accounting for the local context and conditions.

In conclusion, this study demonstrates a first order magnitude assessment which shows that existing NBS in European cities and their associated hinterlands have a positive impact on climate change adaptation and mitigation, people's health and well-being and biodiversity conservation. Concerning climate change adaptation, we estimated that the risk of exceeding (local) temperature threshold at which heat-health warnings may occur, is reduced by an average of 25% during the hottest day in July. The amount of urban areas experiencing heat-health warning is reduced by nearly 5% due to trees' capacity to cool the air and providing shade. Moreover, our analysis showed that vegetation and permeable surfaces within the city are able to reduce the risk of stormwater flooding and nearly 70% of the precipitation during a heavy rainfall is retained. In relation to climate change mitigation, we estimated that on average NBS offset 15% of Europe cities' annual CO2 emissions due to trees capacity to sequester carbon. We found that on average 61% of a FUAs population lives withing close proximity to urban green space, potentially stimulating daily recreation and physical activities, and bring residents into contact with nature. Green space also provide habitats for biodiversity, and we estimated that 85% of the representative birds and flying insect population (as a proxy of biodiversity) could potentially survive in urban areas. Moreover, the results demonstrate large variation across European regions and benefits. Generally speaking, highest beneficial contribution of NBS are estimated for Scandinavian and Baltic regions, while urban areas in the UK, Netherlands, Belgium, and Romania are estimated with lowest overall benefit provision. This spatial pattern is partly explained by the cities' hinterlands, often covered by (semi-)natural land, hence essential providers of benefits to urban dwellers, while at the same time often being under pressure by ongoing urban expansion and development. Enhancing the amount of NBS in densely inhabited urban core areas can further enhance benefit when compared to the current situation. Our results further demonstrate that there are different strategies to mainstream NBS in planning and design of core cities, for example, increasing tree cover densities is shown to be most beneficial for heat stress and climate mitigation, while (re)connecting green areas and creating urban parks particular enhance biodiversity and health and well-being benefits.

Acknowledgement

We would like to thank all the participants of the Workshop "*Assessing the potential of urban nature - Mapping and quantifying the benefits of current and future urban NBS*" (April 2021) who gave us very valuable insights for improving our assessment work and developing the urban NBS narratives. Moreover, we are also very grateful to Dr. Alexandra Marques (PBL) for discussing with us the conceptual framework and selected indicators, as well as would like to thank Prof. Wouter Botzen (Vrije Universiteit Amsterdam) for providing feedback on the report.

References

ALCOCK, I., WHITE, M. P., PAHL, S., DUARTE-DAVIDSON, R. & FLEMING, L. E. 2020. Associations between pro-environmental behaviour and neighbourhood nature, nature visit frequency and nature appreciation: Evidence from a nationally representative survey in England. *Environment international,* 136**,** 105441.

ANNERSTEDT VAN DEN BOSCH, M., MUDU, P., USCILA, V., BARRDAHL, M., KULINKINA, A., STAATSEN, B., SWART, W., KRUIZE, H., ZURLYTE, I. & EGOROV, A. I. 2016. Development of an urban green space indicator and the public health rationale. *Scandinavian journal of public health,* 44**,** 159-167.

ARAM, F., GARCÍA, E. H., SOLGI, E. & MANSOURNIA, S. 2019. Urban green space cooling effect in cities. *Heliyon,* 5**,** e01339.

BARO, F., HAASE, D., GOMEZ-BAGGETHUN, E. & FRANTZESKAKI, N. 2015. Mismatches between ecosystem services supply and demand in urban areas: A quantitative assessment in five European cities. *Ecological Indicators,* 55**,** 146-158.

BARO, F., PALOMO, I., ZULIAN, G., VIZCAINO, P., HAASE, D. & GOMEZ-BAGGETHUN, E. 2016. Mapping ecosystem service capacity, flow and demand for landscape and urban planning: A case study in the Barcelona metropolitan region. *Land Use Policy,* 57**,** 405-417.

BENINDE, J., VEITH, M. & HOCHKIRCH, A. 2015. Biodiversity in cities needs space: a meta-analysis of factors determining intra-urban biodiversity variation. *Ecology letters,* 18**,** 581-592.

BOLUND, P. & HUNHAMMAR, S. 1999. Ecosystem services in urban areas. *Ecological economics,* 29**,** 293-301.
BULKELEY, H., KOK M., XIE, L. 2021. Realising the Urban Opportunity: Cities and Post-2020 Biodiversity Governance. The Hague, The Netherlands: PBL Netherlands Environmental Assessment Agency
CAMPS-CALVET, M., LANGEMEYER, J., CALVET-MIR, L. & GÓMEZ-BAGGETHUN, E. 2016. Ecosystem services provided by urban gardens in Barcelona, Spain: Insights for policy and planning. *Environmental Science & Policy,* 62**,** 14-23.
CASANUEVA, A., BURGSTALL, A., KOTLARSKI, S., MESSERI, A., MORABITO, M., FLOURIS, A. D., NYBO, L., SPIRIG, C. & SCHWIERZ, C. 2019. Overview of existing heat-health warning systems in Europe. *International journal of environmental research and public health,* 16**,** 2657.
CHAPLIN-KRAMER, R., SHARP, R. P., WEIL, C., BENNETT, E. M., PASCUAL, U., ARKEMA, K. K., BRAUMAN, K. A., BRYANT, B. P., GUERRY, A. D. & HADDAD, N. M. 2019. Global modeling of nature's contributions to people. *Science,* 366**,** 255-258.
CRONSHEY, R. 1986. Urban hydrology for small watersheds TR-55. US Dept. of Agriculture, Soil Conservation Service, Engineering Division.
DÍAZ, S., PASCUAL, U., STENSEKE, M., MARTÍN-LÓPEZ, B., WATSON, R. T., MOLNÁR, Z., HILL, R., CHAN, K. M., BASTE, I. A. & BRAUMAN, K. A. 2018. Assessing nature's contributions to people. *Science,* 359**,** 270-272.
DONALDSON, L., WILSON, R. J. & MACLEAN, I. M. 2017. Old concepts, new challenges: adapting landscape-scale conservation to the twenty-first century. *Biodiversity and conservation,* 26**,** 527-552.
DRINNAN, I. N. 2005. The search for fragmentation thresholds in a southern Sydney suburb. *Biological conservation,* 124**,** 339-349.
EC (EUROPEAN COMMISSION) 2016. Urban Agenda for EU 'Pact of Amsterdam'. Agreed at the Informal Meeting of EU Ministers Responsible for Urban Matters on 30 May 2016 in Amsterdam, Netherlands, Dutch Presidency of the Council of the European Union
EC (EUROPEAN COMMISSION) 2021. Evaluating the Impact of Nature-based Solutions: A Handbook for Practioners. *In:* ADINA DUMITRU & WENDLING, L. (eds.). Brussels: European Commission, Directorate-General for Research and Innovation, Directorate C - Healthy Planet, Unit C3-Climate and Planetary Boundaries.
EEA (EUROPEAN ENVIRONMENT AGENCY) 2020. Urban adapatation in Europe: How cities and towns responds to climate change European Environment Agency (EEA).
FAIVRE, N., FRITZ, M., FREITAS, T., DE BOISSEZON, B. & VANDEWOESTIJNE, S. 2017. Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. *Environmental research,* 159**,** 509-518.
FRANTZESKAKI, N., MCPHEARSON, T., COLLIER, M. J., KENDAL, D., BULKELEY, H., DUMITRU, A., WALSH, C., NOBLE, K., VAN WYK, E. & ORDÓÑEZ, C. 2019. Nature-based solutions for urban climate change adaptation: linking science, policy, and practice communities for evidence-based decision-making. *BioScience,* 69**,** 455-466.
GEIJZENDORFFER, I. R., MARTÍN-LÓPEZ, B. & ROCHE, P. K. 2015. Improving the identification of mismatches in ecosystem services assessments. *Ecological Indicators,* 52**,** 320-331.
GRÊT-REGAMEY, A., GALLEGUILLOS-TORRES, M., DISSEGNA, A. & WEIBEL, B. 2020. How urban densification influences ecosystem services—a comparison between a temperate and a tropical city. *Environmental Research Letters,* 15**,** 075001.
HAASE, D., LARONDELLE, N., ANDERSSON, E., ARTMANN, M., BORGSTRÖM, S., BREUSTE, J., GOMEZ-BAGGETHUN, E., GREN, Å., HAMSTEAD, Z. & HANSEN, R. 2014. A quantitative review of urban ecosystem service assessments: concepts, models, and implementation. *Ambio,* 43**,** 413-433.
HAINES-YOUNG, R. H. & POTSCHIN, M. P. 2010. The links between biodiversity, ecosystem services and human well-being. *In:* D.G. RAFFAELLI & FRID, C. L. J. (eds.) *Ecosystem Ecology: a new synthesis, .* Cambridge University Press.

HALL, D. M., CAMILO, G. R., TONIETTO, R. K., OLLERTON, J., AHRNÉ, K., ARDUSER, M., ASCHER, J. S., BALDOCK, K. C., FOWLER, R. & FRANKIE, G. 2017. The city as a refuge for insect pollinators. *Conservation Biology,* 31**,** 24-29.

IPBES 2019. Summary for policymakers of the global assessment on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecoystem Services. *In:* S. DÍAZ, J. S., E. S. BRONDÍZIO E.S., H. T. NGO, M. GUÈZE, J. AGARD, A. ARNETH, P. BALVANERA, K. A. BRAUMAN, S. H. M. BUTCHART, K. M. A. CHAN, L. A. GARIBALDI, K. ICHII, J. LIU, S. M. SUBRAMANIAN, G. F. MIDGLEY, P. MILOSLAVICH, Z. MOLNÁR, D. OBURA, A. PFAFF, S. POLASKY, A. PURVIS, J. RAZZAQUE, B. REYERS, R. ROY CHOWDHURY, Y. J. SHIN, I. J. VISSEREN-HAMAKERS, K. J. WILLIS, AND C. N. ZAYAS (ed.). Bonn, Germany: IPBES Secretariat.

IVES, C. D., LENTINI, P. E., THRELFALL, C. G., IKIN, K., SHANAHAN, D. F., GARRARD, G. E., BEKESSY, S. A., FULLER, R. A., MUMAW, L. & RAYNER, L. 2016. Cities are hotspots for threatened species. *Global Ecology and Biogeography,* 25**,** 117-126.

KABISCH, N., KORN, H., STADLER, J. & BONN, A. 2017. *Nature-based solutions to climate change adaptation in urban areas: Linkages between science, policy and practice*, Springer Nature.

KABISCH, N., STROHBACH, M., HAASE, D. & KRONENBERG, J. 2016. Urban green space availability in European cities. *Ecological indicators,* 70**,** 586-596.

KIM, S., SINCLAIR, V. A., RÄISÄNEN, J. & RUUHELA, R. 2018. Heat waves in Finland: Present and projected summertime extreme temperatures and their associated circulation patterns. *International Journal of Climatology,* 38**,** 1393-1408.

KOPPE, C., SARI KOVATS, R., MENNE, B., JENDRITZKY, G., WETTERDIENST, D. & ORGANIZATION, W. H. 2004. Heat-waves: risks and responses.

KOPPEN, W. 1936. Das Geographische System der Klimate. *Handbuch der Klimatologie***,** 46.

KOVATS, R. S., VALENTINI, R., BOUWER, L.M., GEOERGOPOULOU, E., JACOB, D., MARTIN, E., ROUSEVELL, M., AND F.J., SOUSANNA 2014. **Europe**. *In:* FIELD, C. B., BARROS, V. R., MACH, K. & MASTRANDREA, M. (eds.) *Climate change 2014: impacts, adaptation, and vulnerability.* Cambridge University Press Cambridge and New York.

KRAJEWSKI, A., SIKORSKA-SENONER, A. E., HEJDUK, A. & HEJDUK, L. 2020. Variability of the Initial Abstraction Ratio in an urban and an agroforested catchment. *Water,* 12**,** 415.

LAFORTEZZA, R., CHEN, J., VAN DEN BOSCH, C. K. & RANDRUP, T. B. 2018. Nature-based solutions for resilient landscapes and cities. *Environmental research,* 165**,** 431-441.

LANGEMEYER, J., CAMPS-CALVET, M., CALVET-MIR, L., BARTHEL, S. & GÓMEZ-BAGGETHUN, E. 2018. Stewardship of urban ecosystem services: Understanding the value (s) of urban gardens in Barcelona. *Landscape and Urban Planning,* 170**,** 79-89.

LARONDELLE, N. & LAUF, S. 2016. Balancing demand and supply of multiple urban ecosystem services on different spatial scales. *Ecosystem Services,* 22**,** 18-31.

LEPCZYK, C. A., ARONSON, M. F., EVANS, K. L., GODDARD, M. A., LERMAN, S. B. & MACIVOR, J. S. 2017. Biodiversity in the city: fundamental questions for understanding the ecology of urban green spaces for biodiversity conservation. *BioScience,* 67**,** 799-807.

MAES, J., TELLER, A., ERHARD, M., LIQUETE, C., BRAAT, L., BERRY, P., EGOH, B., PUYDARRIEUX, P., FIORINA, C. & SANTOS, F. 2013. Mapping and Assessment of Ecosystems and their Services. *An analytical framework for ecosystem assessments under action,* 5**,** 1-58.

MAES, J., TELLER, A., ERHARD, M., CONDE, S., VALLECILLO RODRIGUEZ, S., BARREDO CANO, J.I., PARACCHINI, M., ABDUL MALAK, D., TROMBETTI, M., VIGIAK, O., ZULIAN, G., ADDAMO, A., GRIZZETTI, B., SOMMA, F., HAGYO, A., VOGT, P., POLCE, C., JONES, A., MARIN, A., IVITS, E., MAURI, A., REGA, C., CZUCZ, B., CECCHERINI, G., PISONI, E., CEGLAR, A., DE PALMA, P., CERRANI, I., MERONI, M., CAUDULLO, G., LUGATO, E., VOGT, J., SPINONI, J., CAMMALLERI, C., BASTRUP-BIRK, A., SAN-MIGUEL-AYANZ, J., SAN ROMÁN, S., KRISTENSEN, P., CHRISTIANSEN, T., ZAL, N., DE ROO, A., DE JESUS CARDOSO, A., PISTOCCHI, A., DEL BARRIO ALVARELLOS, I., TSIAMIS, K., GERVASINI, E., DERIU, I., LA NOTTE, A., ABAD VIÑAS, R., VIZZARRI, M., CAMIA, A., ROBERT, N., KAKOULAKI, G., GARCIA BENDITO, E., PANAGOS, P., BALLABIO, C., SCARPA, S., MONTANARELLA, L., ORGIAZZI, A., FERNANDEZ UGALDE, O. AND SANTOS-MARTÍN, F., 2020.

Mapping and Assessment of Ecosystems and their Services: An EU ecosystem assessment. *EUR 30161 EN.* Luxembourg.
MAES, J., ZULIAN, G., GUENTHER, S., THIJSSEN, M. AND RAYNAL, J., 2019. Enhancing resilience of urban ecosystems through green infrastructure (EnRoute). *EUR 29630 EN.* Luxembourg: JRC.
MAES J., ZULIAN G., THIJSSEN M., CASTELL C., BARO F., FERREIRA A., MELO J., GARRET C. & DAVID N., A. C., GENELETTI D., CORTINOVIS C., ZWIERZCHOWSKA I., LOURO ALVES F., SOUTO CRUZ C., BLASI C., ALÓS ORTÍ M., ATTORE F., AZELLA M., CAPORTORTI G., COPIZ R., FUSARO L., MANES F., MARANDO F., MARCHETTI M., MOLLO B., SALVATORI E., ZAVATTERO L., ZINGARI P., GIARRATANO M., BIANCHI E., DUPRÈ E., BARTON D., STANGE E., PEREZ-SOBA M., VAN EUPEN M., VERWEIJ P., DE VRIES A., KRUSE H., POLCE C., CUGNY-SEGUIN M., ERHARD M., NICOLAU R., FONSECA A., FRITZ M., TELLER A., 2016. Mapping and Assessment of Ecosystems and their Services: Urban ecosystems 4th Report, Final May 2016. *JRC101639.* JRC.
MAGLE, S. B., THEOBALD, D. M. & CROOKS, K. R. 2009. A comparison of metrics predicting landscape connectivity for a highly interactive species along an urban gradient in Colorado, USA. *Landscape ecology,* 24**,** 267-280.
MCDONALD RI, C. M. L., HAMANN M, SIMKIN R, WALSH B, ASCENSÃO F, BARTON M, CROSSMAN , K, E. M., ELMQVIST T, GONZALEZ A, GUNERALP B, HAASE D, HILLEL O, HUANG K, MADDOX & D, M. A., PAQUE J, PEREIRA HM, PIERCE JR, WELLER R, SETO KC, TAN MMJ, ZITER C, CHAPLIN-KRAMER B, MACMANUS K AND SHARP R 2018. Nature in the Urban Century: a global assessment of where and how to conserve nature for biodiversity and human wellbeing. The Nature Conservancy.
MCKINNEY, M. L. 2008. Effects of urbanization on species richness: a review of plants and animals. *Urban ecosystems,* 11**,** 161-176.
MCPHEARSON, T., KREMER, P. & HAMSTEAD, Z. A. 2013. Mapping ecosystem services in New York City: Applying a social–ecological approach in urban vacant land. *Ecosystem Services,* 5**,** 11-26.
MORAN, D., KANEMOTO, K., JIBORN, M., WOOD, R., TÖBBEN, J. & SETO, K. C. 2018. Carbon footprints of 13 000 cities. *Environmental Research Letters,* 13**,** 064041.
NATIONS, U. 2017. New Urban Agenda. *In:* 2015, R. A. B. T. G. A. O. S. (ed.).
NOWAK, D. J., GREENFIELD, E. J., HOEHN, R. E. & LAPOINT, E. 2013. Carbon storage and sequestration by trees in urban and community areas of the United States. *Environmental pollution,* 178**,** 229-236.
NUTSFORD, D., PEARSON, A. L., KINGHAM, S. & REITSMA, F. 2016. Residential exposure to visible blue space (but not green space) associated with lower psychological distress in a capital city. *Health & place,* 39**,** 70-78.
PE'ER, G., TSIANOU, M. A., FRANZ, K. W., MATSINOS, Y. G., MAZARIS, A. D., STORCH, D., KOPSOVA, L., VERBOOM, J., BAGUETTE, M. & STEVENS, V. M. 2014. Toward better application of minimum area requirements in conservation planning. *Biological Conservation,* 170**,** 92-102.
PEEL, M. C., FINLAYSON, B. L. & MCMAHON, T. A. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and earth system sciences,* 11**,** 1633-1644.
PEREIRA, L. M., DAVIES, K. K., DEN BELDER, E., FERRIER, S., KARLSSON-VINKHUYZEN, S., KIM, H., KUIPER, J. J., OKAYASU, S., PALOMO, M. G. & PEREIRA, H. M. 2020. Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework. *People and Nature,* 2**,** 1172-1195.
REMME, R. P., FRUMKIN, H., GUERRY, A. D., KING, A. C., MANDLE, L., SARABU, C., BRATMAN, G. N., GILES-CORTI, B., HAMEL, P. & HAN, B. 2021. An ecosystem service perspective on urban nature, physical activity, and health. *Proceedings of the National Academy of Sciences,* 118.
ROSS, C., PRIHODKO, L., ANCHANG, J., KUMAR, S., JI, W. & HANAN, N. 2018. Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modeling. *ORNL DAAC*.
SEDDON, N., CHAUSSON, A., BERRY, P., GIRARDIN, C. A., SMITH, A. & TURNER, B. 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B,* 375**,** 20190120.

SETO, K. C., GÜNERALP, B. & HUTYRA, L. R. 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences,* 109**,** 16083-16088.
SHAFIQUE, M., KIM, R. & RAFIQ, M. 2018. Green roof benefits, opportunities and challenges–A review. *Renewable and Sustainable Energy Reviews,* 90**,** 757-773.
SHANAHAN, D. F., MILLER, C., POSSINGHAM, H. P. & FULLER, R. A. 2011. The influence of patch area and connectivity on avian communities in urban revegetation. *Biological Conservation,* 144**,** 722-729.
SHARP, R., DOUGLASS, J., WOLNY, S., ARKEMA, K., BERNHARDT, J., BIERBOWER, W., CHAUMONT, N., DENU, D., FISHER, D., GLOWINSKI, K., GRIFFIN, R., GUANNEL, G., GUERRY, A., JOHNSON, J., HAMEL, P., KENNEDY, C., , KIM, C. K., LACAYO, M., LONSDORF, E., MANDLE, L., ROGERS, L., SILVER, J., , TOFT, J., VERUTES, G., VOGL, A. L., WOOD, S. & WYATT, K. 2020. InVEST 3.8.7 User's Guide.
SPANOWICZ, A. G. & JAEGER, J. A. 2019. Measuring landscape connectivity: on the importance of within-patch connectivity. *Landscape Ecology,* 34**,** 2261-2278.
STESSENS, P., KHAN, A. Z., HUYSMANS, M. & CANTERS, F. 2017. Analysing urban green space accessibility and quality: A GIS-based model as spatial decision support for urban ecosystem services in Brussels. *Ecosystem Services,* 28**,** 328-340.
SUSHINSKY, J. R., RHODES, J. R., POSSINGHAM, H. P., GILL, T. K. & FULLER, R. A. 2013. How should we grow cities to minimize their biodiversity impacts? *Global change biology,* 19**,** 401-410.
TEEB 2010. The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A synthesis of the approach, conclusions and recommendations of TEEB.
UGOLINI, F., MASSETTI, L., CALAZA-MARTÍNEZ, P., CARIÑANOS, P., DOBBS, C., OSTOIĆ, S. K., MARIN, A. M., PEARLMUTTER, D., SAARONI, H. & ŠAULIENĖ, I. 2020. Effects of the COVID-19 pandemic on the use and perceptions of urban green space: An international exploratory study. *Urban forestry & urban greening,* 56**,** 126888.
UN (UNITED NATIONS) 2015. Transforming our world: the 2030 agenda for sustainable development. New York. New York: United Nations.
VAN DEN BOSCH, M. & SANG, Å. O. 2017. Urban natural environments as nature-based solutions for improved public health–A systematic review of reviews. *Environmental research,* 158**,** 373-384.
VEERKAMP, C., SCHIPPER, A., HEDLUND K., L., T., , NORDIN A. & HANSON HI. under review. Ecosystem services provided by urban green and blue infrastructure: a review of assessment methods.
VEERKAMP, C., SPOON, M., VAN RIJN, F., LORETI, M., DASSEN, T., SCHIPPER, A., BOKE-OLEN, N., CORTINOVIS, C., HEDLUND, K. & OLSSON, P. 2020. Assessing the potential of nature-based solutions in European cities for adressing climate change challenges. *NATURVATION project deliverable 3.7* PBL Netherlands Enviornmental Assessment Agency & Lund University
VELASCO, E., ROTH, M., NORFORD, L. & MOLINA, L. T. 2016. Does urban vegetation enhance carbon sequestration? *Landscape and urban planning,* 148**,** 99-107.
WHO 2010. Parma declaration on Environment and Health. Fitfth Ministrial Conference on Environment and Health "Potecting children's health in a changing envirnoment" *In:* EUROPE, W. R. O. F. (ed.). Copenhagen, Denmark.
WHO 2016. Urban green space and health. Copenhagen: WHO Regional Office for Europe.
YAO, L., CHEN, L., WEI, W. & SUN, R. 2015. Potential reduction in urban runoff by green spaces in Beijing: A scenario analysis. *Urban Forestry & Urban Greening,* 14**,** 300-308.

Appendix

Appendix A: European heat stress level

Table A-1: European heat warning thresholds/alert levels.

Country	Threshold temperature (°C)	heat health warning / alert level	Reference
Albania	26	no information on heat health warning systems; value from Greece (same climate zone Köppen-Geiger)	WHO 2004[1]
Austria	35.01	perceived temperature over at least 3 days	Casanueva et al. 2019[2]
Bosnia and Herzegovina	29	no information on heat health warning systems; value from Czech Republic same climate zone Köppen-Geiger)	WHO 2004
Belgium	25	maximum temperature over at least 5 days (= heatwave definition); yellow heat alert code	KMI - Legenda Hitte (meteo.be)
Bulgaria	29	no information on heat health warning systems; value from Czech Republic same climate zone Köppen -Geiger)	WHO 2004
Switzerland	28	yellow heat alert code = moderate health risk (based on Temperature in combination with 'Taupunkt' or relative humidity within code yellow)	Hitzetage, Frosttage und andere Indikatoren - MeteoSchweiz (admin.ch)
Cyprus	33.7	threshold temperature mortality risk	Heaviside et al. 2016[3]
Czech Republic	29	maximum temperature for Hot Weather Warning and medium heat stress.	Urban et al. 2017[4]

[1] WHO (2004) Heat-waves: risks and responses. https://www.euro.who.int/__data/assets/pdf_file/0008/96965/E82629.pdf

[2] CASANUEVA, et al. (2019) Overview of existing heat-health warning systems in Europe. International journal of environmental research and public health, 16, 2657.

[3] Heaviside et al. (2016) Heat-related mortality in Cyprus for current and future climate scenarios. Science of Total Environment, 569-570. https://doi.org/10.1016/j.scitotenv.2016.06.138

[4] Urban et al. (2017) Impacts of the 2015 heat waves on mortality in the Czech Republic – A comparison with Previous Heat Waves. In. J. Environ. Res. Public Health. 14. https://doi.org/10.3390/ijerph14121562

Germany	26	perceived temperature; level 2 (= moderate health effects)	Casanueva et al. 2019; Wetter und Klima - Deutscher Wetterdienst - Leistungen - Thermischer Gefahrenindex (dwd.de)
Denmark	28	maximum temperature for at least 3 days	Følg en hedebølge med DMI
Estonia	30	maximum temperature, 'dangerous heatwave event'	VITO 2019[5]
Spain	36	maximum temperature at least one day, average across regions; level 1/yellow code	Casanueva et al. 2019
Finland	27	maximum temperature; 1st risk level of heat warning (hot conditions)	Kim et al. 2017[6]; VITO 2019
France	28	City specific ; 28 deg (= smallest Tmax in study for potential heat health risks in France)	Casanueva et al. 2019; Pascal et al. 2005[7]
Greece	26	average across regions;	Casanueva et al. 2019
Croatia	35	maximum temperature; but some regions deviate from the threshold value.	https://climate-adapt.eea.europa.eu/observatory/policy-context/country-profiles/croatia
Hungary	25.01	mean temperature; yellow code	Casanueva et al. 2019
Ireland	30	no information on heat health warning systems; value from UK (same climate zone Köppen- Geiger)	WHO 2004
Iceland	27	no information on heat health warning systems; value from Finland (same climate zone Köppen - Geiger)	WHO 2004
Italy	34.4	maximum temperature; average across regions and months;	VITO 2019
Kosovo	30	follows value of Serbia	
Lithuania	30	maximum temperature, 'dangerous heatwave event'	VITO 2019
Luxembourg	25	no information on heat health warning systems; value from Belgium (same climate zone Köppen - Geiger)	WHO 2004

[5] VITO (2019) C3S_422_Lot2 SIS European Health. Spells extra documentation. Copernicus Climate Change Service (C3S). Document Title (copernicus-climate.eu)

[6] Kim et al. (2017). Heat waves in Finland: Present and projected summertime extreme temperatures and their associated circulation patterns. International Journal of Climatology, 38, 1393-1408. https://doi.org/10.1002/joc.5253

[7] Pascal et al. (2005) France's heat health watch warning system. International Journal of Biometeorology. 50, 144-153. https://doi.org/10.1007/s00484-005-0003-x

Latvia	27	maximum temperature for at least 2 days	Pfeifer et al. 2020[8]
Montenegro	35	maximum temperature	WHO 2004
Macedonia	29	City and month Specific (Increasing heat index), here use value from Czech Republic (same climate zone Köppen-Geiger)	WHO 2011[9]
Malta	40	maximum temperature	WHO 2004
Netherlands	27.01	maximum temperature for at least 4 days; yellow code	Casanueava et al. 2019; KNMI - KNMI waarschuwingen
Norway	27	no heat health warning systems; value from Finland (same climate zone Köppen-Geiger)	WHO 2004
Poland	30	maximum temperature for at least 3 days	https://klimada.mos.gov.pl/wp-content/uploads/2013/11/SPA-2020.pdf
Portugal	32.01	for at least 2 days (heatwave definition), code yellow; some regions have threshold value of 35.	Casanueva et al. 2019; https://www.dgs.pt/directrizes-da-dgs/normas-e-circulares-normativas/norma-n-0072015-de-29042015-pdf.aspx
Romania	35	maximum temperature	Casanueava et al. 2019
Serbia	30	maximum temperature	http://www.meteoalarm.rs/eng/talasi.pdf
Sweden	30	maximum temperature for 2-4days; heat warning class 1	Casanueva et al. 2019;
Slovenia	31.01	maximum temperature; yellow code	Casanueava et al. 2019
Slovakia	29	no heat health warning systems; value from Czech Republic (same climate zone Köppen-Geiger)	WHO 2004
Turkey	27	maximum temperature with min. 40 percent humidity	WHO 2004
United Kingdom	30	maximum temperature for 2 days, average as region-specific ; level 1	Casanueva et al. 2019, VITO 2019

[8] Pfeifer et al. (2020) Evaluating Mortality Response Associated with Two Different Nordic Heat Warning Systems in Riga, Latvia. In. J. Environ. Res. Public Health. 17, 21. https://doi.org/10.3390/ijerph17217719

[9] WHO (2011) Heat-Health Action Plan. To prevent the heat waves consequences on the health population in the former Yugoslav Republic of Macedonia. Brosura 1 Sredeno Final.indd (who.int)

Appendix B: Model parameter values

Heat mitigation

Table B-1: Heat mitigation parameter values for the reference and the three scenarios. If no value are shown for the scenario (blank space), then there is no change when compared to the reference scenario, and values from the reference are still valid.

		Green area (for heat mitigation) (1 = yes)				Shade (%)				Crop coefficient (Kc)			
Code	**Urban Atlas LULC classes**	**Reference**	**Nature for Nature**	**Nature for Society**	**Nature as Culture**	**Reference**	**Nature for Nature**	**Nature for Society**	**Nature as Culture**	**Reference**	**Nature for Nature**	**Nature for Society**	**Nature as Culture**
11100	Continuous Urban Fabric (Soil sealing >80%)					Estimated per FUA based on city specific tree densities		9 (= 95th percentile]		(shade * 1.37[10])		new shade * 1.37	
11210	Discontinuous Dense Urban Fabric (S.L. 50% - 80%)							20		(shade * 1.37)		new shade * 1.37	
11220	Discontinuous Medium Density Urban Fabric (S.L. 30% - 50%)							25		(shade * 1.37)		new shade * 1.37	
11230	Discontinuous Low Density Urban Fabric (S.L. 10% - 30%)		1				50	30		(shade * 1.37)	(50 * 1.37) + (50* 0.85	new shade * 1.37	

[10] Average Kc of different forest types assuming 100% tree coverage (i.e. coniferous forest, broad-leaved forest, mix forest) (Allen et al. 1998 Nistor et al 2015 and 2016)

11240	Discontinuous Very Low Density Urban Fabric (S.L. <10%)		1				50	32		(shade * 1.37)	(50 * 1.37) + (50* 0.85	new shade * 1.37	
11300	Isolated structures							28		(shade * 1.37)		new shade * 1.37	
12100	Industrial, commercial, public military and private units							12		(shade * 1.37)		new shade * 1.37	
12210	Fast transit roads and associated land				1			20	‘green urban areas’ reference shade	(shade * 1.37)		new shade * 1.37	green urban area reference (shade * 1.37) + ((1-shade)* 0.85)
12220	Other roads and associated land							25		(shade * 1.37)		new shade * 1.37	
12230	Railway and associated land									(shade * 1.37)			
12300	Port areas									(shade * 1.37)			
12400	Airports									(shade * 1.37)			

13100	Mineral extraction and dump sites		1	1	1		50	50 [= green urban areas]	green urban areas' reference shade	(shade * 1.37) + ((1-shade)*0.3[11])	(50 * 1.37) + (50* 0.85)	new (shade * 1.37) + ((1-shade)* 0.85)	green urban area reference (shade * 1.37) + ((1-shade)* 0.85)
13300	Construction sites		1	x	1		50	32 [=very low density urban fabric]	green urban areas' reference shade	(shade * 1.37) + ((1-shade)*0.3[7])	(50 * 1.37) + (50* 0.85)	new shade * 1.37	green urban area reference (shade * 1.37) + ((1-shade)* 0.85)
13400	Land without current use		1	x	1		50	32 [=very low density urban fabric]	green urban areas' reference shade	(shade * 1.37)	(50 * 1.37) + (50* 0.85)	new shade * 1.37	green urban area reference (shade * 1.37) + ((1-shade)* 0.85)
14100	Green urban areas	1	1	1	1			50		(shade * 1.37) + ((1-shade) * 0.85[6])		new (shade * 1.37) + ((1-shade)* 0.85)	
14200	Sports and leisure facilities		1		1		50	31	green urban areas'	(shade * 1.37) + ((1-	(50 * 1.37) +	shade * 1.37	green urban area

[11] Average Kc for bare soil (Allen et al. 1998)

									reference shade	shade) * 0.85[6])	(50* 0.85)		reference (shade * 1.37) + ((1-shade)* 0.85)
21000	Arable land (annual crops)									1.08[12]			
22000	Permanent crops									0.89[13]			
23000	Pastures									0.85[6]			
24000	Complex and mixed cultivation patterns									1.11[14]			
25000	Orchards									0.85[15]			
31000	Forest	1	1	1	1			82		(Shade *1.37)		new shade * 1.37	
32000	Herbaceous vegetation associations	x	1	1	1			82 [= forest]		(shade * 1.37) + ((1-shade) * 0.75)		new shade * 1.37	
33000	Open spaces with little or no vegetation									0.3[7]			
40000	Wetlands									1.20[16]			
50000	Water									0.65[17]			

[12] Average Kc for various annual crop types (i.e. wheat, barley, oats, maize, hay, clover, rye grass), (Allen et al. 1998)
[13] Average Kc for various permanent crop types (i.e. apple trees, olive, berries, grapes, hops)(Allen et al. 1998)
[14] Average Kc for arable land, permanent crops and trees
[15] Average Kc for fruit trees (i.e. apple, cherries, pear, olive, berries, grapes)(Allen et al. 1998)
[16] Average Kc for wetland in temperate climate (Allen et al. 1998)
[17] Average kc for water (Allen et al. 1998)

Stormwater regulation

Table B-2: Baseline runoff CN numbers per LULC Class (adapted from USDA 1986).

Code	LULC Class	A	B	C	D	USDA cover type
						FIXED VALUES
21000	Arable land (annual crops)	72	81	88	91	Agricultural land, straight row – poor condition
22000	Permanent crops	72	81	88	91	Agricultural land, straight row – poor condition
23000	Pastures	49	69	79	94	Agricultural land, pastures – fair condition
24000	Complex and mixed cultivation patterns	72	81	88	91	Agricultural land, straight row – poor condition
25000	Orchards	43	65	76	82	Wood-Grass combination (orchard or tree farm) – fair condition
33000	Open spaces with little or no veget.	68	79	86	89	Open Space – poor condition
40000	Wetlands	0	0	0	0	Retains all rainfall (0)
50000	Water	0	0	0	0	Retains all rainfall (0)
FLEXIBLE VALUES: % Impervious + (1- % impervious) = % Wood/Grass						
11100	Continuous Urban Fabric (Soil sealing >80%)	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	Composite CNs for 1) Impervious areas (incl. paved parking lots, roofs, driveways, streets, roads etc.) and 2) woods-grass combination (incl. 50% woods and 50% grass cover), fair conditions
11210	Discontinuous Dense Urban Fabric (S.L. 50% - 80%)	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
11220	Discontinuous Medium Density Urban Fabric (S.L. 30% - 50%)	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
11230	Discontinuous Low Density Urban Fabric (S.L. 10% - 30%)	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
11240	Discontinuous Very Low Density Urban Fabric (S.L. <10%)	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
11300	Isolated structures	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	

12100	Industrial, commercial, public, military and private units	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 *+ (1-x) * 82	
12210	Fast transit roads and associated land	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
12220	Other roads and associated land	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
31000	Forest	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
12300	Port areas	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
12400	Airports	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
13400	Land without current use	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
14100	Green urban areas	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
14200	Sports and leisure facilities	x * 98 + (1-x) * 43	x * 98 + (1-x) * 65	x * 98 + (1-x) * 76	x * 98 + (1-x) * 82	
FLEXIBLE VALUES: % Impervious + (1- %impervious) = % Bare Soil						
12230	Railway and associated land	x * 98 + (1-x) * 77	x * 98 + (1-x) * 86	x * 98 + (1-x) * 91	x * 98 + (1-x) * 94	Composite CNs for 1) Impervious areas (incl. paved parking lots, roofs, driveways, streets, roads etc.) and 2) bare soil
13100	Mineral extraction and dump sites	x * 98 + (1-x) * 77	x * 98 + (1-x) * 86	x * 98 + (1-x) * 91	x * 98 + (1-x) * 94	
13300	Construction sites	x * 98 + (1-x) * 77	x * 98 + (1-x) * 86	x * 98 + (1-x) * 91	x * 98 + (1-x) * 94	

FLEXIBLE VALUES: % Impervious + (1- %impervious) = % Shrub[18]						
32000	Herbaceous vegetation associations	x * 98 + (1-x) * 55[19]	x * 98 + (1-x) * 72	x * 98 + (1-x) * 81	x * 98 + (1-x) * 86	Herbaceous – mixture of grass, weeds, and low-growing brush

Table B-3: Stormwater regulation parameter values for the reference and the three scenarios. If no value are shown for the scenario (blank space), then there is no change when compared to the reference scenario, and values from the reference are still valid.

		impervious surface (%)			
Code	**Urban Atlas LULC classes**	**Reference**	**Nature for Nature**	**Nature for Society**	**Nature as Culture**
11100	Continuous Urban Fabric (Soil sealing >80%)	Estimated per city based on city specific impervious surface coverage		41 [5th percentile]	
11210	Discontinuous Dense Urban Fabric (S.L. 50% - 80%)			24.28 [5th percentile]	
11220	Discontinuous Medium Density Urban Fabric (S.L. 30% - 50%)			12 [5th percentile]	
11230	Discontinuous Low Density Urban Fabric (S.L. 10% - 30%)		no impervious (i.e. 50% 'Woods" + 50% Open Space - Good Condition)	8 [5th percentile]	
11240	Discontinuous Very Low Density Urban Fabric (S.L. <10%)		no impervious (i.e. 50% 'Woods" + 50% Open Space - Good Condition)	3 [5th percentile]	
11300	Isolated structures			1 [5th percentile]	
12100	Industrial, commercial, public military and private units			31 [5th percentile]	
12210	Fast transit roads and associated land			34[20]	[= impervious value green urban area from reference]
12220	Other roads and associated land			14 [5th percentile]	
12230	Railway and associated land				

[18] As there is no value for soil group A, we used the CN value from ' Desert Shrub - Fair Condition' which show similar CN values for other soil type groups
[19] As there is no value for soil group A, we used the CN value from ' Desert Shrub - Fair Condition' which show similar CN values for other soil type groups
[20] Based on the average change of urban fabric and industry (because of resolution problem calculating the imperviousness of roads)

12300	Port areas				
12400	Airports				
13100	Mineral extraction and dump sites		no impervious (i.e. 50% 'Woods" + 50% Open Space - Good Condition)	4 [= 5^{th} percentile green urban areas]	[= impervious value green urban area from reference]
13300	Construction sites		no impervious (i.e. 50% 'Woods" + 50% Open Space - Good Condition)	3 [= 5^{th} percentile very low density urban fabric]	[= impervious value green urban area from reference]
13400	Land without current use		no impervious (i.e. 50% 'Woods" + 50% Open Space - Good Condition)	3 [= 5^{th} percentile very low density urban fabric]	[= impervious value green urban area from reference]
14100	Green urban areas			4 [5^{th} percentile]	
14200	Sports and leisure facilities		no impervious (i.e. 50% 'Woods" + 50% Open Space - Good Condition)	6 [5^{th} percentile]	[= impervious value green urban area from reference]
21000	Arable land (annual crops)	Fixed Values			
22000	Permanent crops				
23000	Pastures				
24000	Complex and mixed cultivation patterns				
25000	Orchards				
31000	Forest	Estimated per city based on city specific impervious surface coverage		0 [5^{th} percentile]	
32000	Herbaceous vegetation associations			0 [5^{th} percentile forest]	
33000	Open spaces with little or no vegetation	Fixed Values			
40000	Wetlands				
50000	Water				

Carbon sequestration

Table B-4: Carbon sequestration parameter values for the references and the three scenarios. If no value are shown for the scenario (blank space), then there is no change when compared to the reference scenario, and values from the reference are still valid. Equation: (shade value) *(standard carbon sequestration value per 100% tree cover density retrieved from Nowak et al. 2013).

		carbon sequestration kg C/m2/year trees (shade * 0.205)			
Code	**Urban Atlas LULC classes**	**Reference**	**Nature for Nature**	**Nature for Society**	**Nature as Culture**
11100	Continuous Urban Fabric (Soil sealing >80%)	shade *0.205		new shade *0.205	
11210	Discontinuous Dense Urban Fabric (S.L. 50% - 80%)	shade *0.205			
11220	Discontinuous Medium Density Urban Fabric (S.L. 30% - 50%)	shade *0.205			
11230	Discontinuous Low Density Urban Fabric (S.L. 10% - 30%)	shade *0.205	50 *0.205		
11240	Discontinuous Very Low Density Urban Fabric (S.L. <10%)	shade *0.205	50 *0.205		
11300	Isolated structures	shade *0.205			
12100	Industrial, commercial, public military and private units	shade *0.205			
12210	Fast transit roads and associated land	shade *0.205			shade *0.205 [reference shade value urban green space]
12220	Other roads and associated land	shade *0.205			
12230	Railway and associated land	shade *0.205			
12300	Port areas	shade *0.205			
12400	Airports	shade *0.205			
13100	Mineral extraction and dump sites	shade *0.205	50 *0.205	new shade *0.205 [= green urban areas]	shade *0.205 [reference shade value urban green space]

13300	Construction sites	shade *0.205	50 *0.205	new shade * 0.205 [= very low density urban fabric]	shade *0.205 [reference shade value urban green space]
13400	Land without current use	shade *0.205	50 *0.205	new shade * 0.205 [= very low density urban fabric]	shade *0.205 [reference shade value urban green space]
14100	Green urban areas	shade *0.205		new shade *0.205	
14200	Sports and leisure facilities	shade *0.205	50 *0.205	new shade *0.205	shade *0.205 [reference shade value urban green space]
21000	Arable land (annual crops)	shade *0.205			
22000	Permanent crops	shade *0.205			
23000	Pastures	shade *0.205			
24000	Complex and mixed cultivation patterns	shade *0.205			
25000	Orchards	shade *0.205			
31000	Forest	shade *0.205		new shade *0.205	
32000	Herbaceous vegetation associations	shade *0.205		new shade *0.205 [= forest value]	
33000	Open spaces with little or no vegetation	shade *0.205			
40000	Wetlands	shade *0.205			
50000	Water	0			

Green space availability

Table B-5: Green space availability parameter values for the references and the three scenarios. If no value are shown for the scenario (blank space), then there is no change when compared to the reference scenario, and values from the reference are still valid.

		public accessible green areas (1 = yes)			
Code	**Urban Atlas LULC classes**	**Reference**	**Nature for Nature**	**Nature for Society**	**Nature as Culture**
11100	Continuous Urban Fabric (Soil sealing >80%)				

11210	Discontinuous Dense Urban Fabric (S.L. 50% - 80%)				
11220	Discontinuous Medium Density Urban Fabric (S.L. 30% - 50%)				
11230	Discontinuous Low Density Urban Fabric (S.L. 10% - 30%)		1		
11240	Discontinuous Very Low Density Urban Fabric (S.L. <10%)		1		
11300	Isolated structures				
12100	Industrial, commercial, public military and private units				
12210	Fast transit roads and associated land				1
12220	Other roads and associated land				
12230	Railway and associated land				
12300	Port areas				
12400	Airports				
13100	Mineral extraction and dump sites		1	1	1
13300	Construction sites		1		1
13400	Land without current use		1		1
14100	Green urban areas	1	1	1	1
14200	Sports and leisure facilities		1		1
21000	Arable land (annual crops)				
22000	Permanent crops				
23000	Pastures				
24000	Complex and mixed cultivation patterns				
25000	Orchards				
31000	Forest	1	1	1	1
32000	Herbaceous vegetation associations	1	1	1	1
33000	Open spaces with little or no vegetation	1	1	1	1
40000	Wetlands				
50000	Water				

Urban biodiversity

Table B-6: Urban biodiversity parameter values for the references and the three scenarios. If no value are shown for the scenario (blank space), then there is no change when compared to the reference scenario, and values from the reference are still valid.

		suitable urban green area for biodiversity (1 = yes)			
Code	Urban Atlas LULC classes	Reference	Nature for Nature	Nature for Society	Nature as Culture
11100	Continuous Urban Fabric (Soil sealing >80%)				
11210	Discontinuous Dense Urban Fabric (S.L. 50% - 80%)				
11220	Discontinuous Medium Density Urban Fabric (S.L. 30% - 50%)				
11230	Discontinuous Low Density Urban Fabric (S.L. 10% - 30%)		1		
11240	Discontinuous Very Low Density Urban Fabric (S.L. <10%)		1		
11300	Isolated structures				
12100	Industrial, commercial, public military and private units				
12210	Fast transit roads and associated land				1
12220	Other roads and associated land				
12230	Railway and associated land				
12300	Port areas				
12400	Airports				
13100	Mineral extraction and dump sites		1	1	1
13300	Construction sites		1		1
13400	Land without current use		1		1
14100	Green urban areas	1	1	1	1
14200	Sports and leisure facilities		1		1
21000	Arable land (annual crops)				
22000	Permanent crops				
23000	Pastures				
24000	Complex and mixed cultivation patterns				
25000	Orchards				
31000	Forest	1	1	1	1
32000	Herbaceous vegetation associations	1	1	1	1
33000	Open spaces with little or no vegetation				
40000	Wetlands				
50000	Water				

Appendix C: Scenario workshop (April 2021)

List of Participants

Canddie Magdelenat - WWF Cities team, France

Jennifer Lenhart - WWF Cities team, global

Jeet Mistry - WWF Cities team, Sweden

John-Rob Pool - Cities4Forests, World Resources Institute

Roberto Rinalidi - European Committee of the Regions

Russell Galt - Urban Alliance, IUCN

Aleksandra Kazmierczak - European Environment Agency

Rob Carr - Environment Agency UK

Gregg Brill - Pacific Institute

Julie Delcroix - DG Research and Innovation

Sofie Vandewoestijne – European Commission, REA (Research Executive Agency), Brussel

Christophe Codun - European Commission, REA (Research Executive Agency), Brussel

Federica Marando - Joint Research Centre, Italy

Joachim Maes – Joint Research Centre, Italy

Pieter Botha - ICLEI, working as global coordinator for CitiesWithNature

Bettina Wilk - ICLEI Europe Brussel Office, coordinator of NetworkNature

Nikara Mahadeo - ICLEI CBS South Africa

Ingrid Coetzee - ICLEI Cities Biodiversity Center

Samantha McCraine - Science Based Targets Network

Nico Bos- Dutch Ministry for Agriculture Food and Nature

Isabelle Vreeke - Dutch Ministry for Agriculture Food and Nature

NATURVATION TEAM:

Harriet Bulkeley – University of Durham

Ton Dassen PBL Netherlands Environmental Assessment Agency

Clara Veerkamp - PBL Netherlands Environmental Assessment Agency

Milan Loreti - PBL Netherlands Environmental Assessment Agency

Frank van Rijn – PBL Netherlands Environmental Assessment Agency

Katarina Hedlund – Lund University

Chiara Cortinovis - Lund University

Peter Olsson - Lund University

Outcomes of the breakout sessions

Nature for Nature

"In which nature has value in and of itself, and the preservation of nature's diversity and function is a primary importance" (NFF)

- Key to this perspective is the emphasize of the intrinsic value to nature, hence to maintain and enhance future (urban) biodiversity (as key challenge to be addressed)
- "Supporting biodiversity as a prerequisite of implementing (urban) NBS" – *Bettina Wilke (ICLEI Europe Brussel Office)*
- Approach: **Bringing nature back into the city** by
    - creating new habitat. Creating adequate habitat inside the city boundaries allows biodiversity to follow – *Rob Carr (UK Environment Agency)*; Allow the introduction of 'real' nature to the city, and give space to nature's capacity to keep care of itself (which will also avoid potential risks (e.g. pests, pollen, maintenance)) – *Katarina Hedlund (University of Lund)*; But also reintroduce 'flagship species' to the city (e.g. birds, butterflies) – *Bettina Wilk (ICLEI Europe Brussel Office)*; Creating new space for biodiversity in cities as an opportunity for cities to contribute to EU biodiversity targets (e.g. no net loss of biodiversity by restoration of brownfields, increase vegetation/tree coverage within city) - *Joachim Maes (JRC).* Cities can be an important habitat for biodiversity, e.g. green in cities can act as a refuge to certain species (e.g. bees) especially when rural hinterlands are degraded of intensively managed – *Russel Galt (International Union for Conservancy of Nature).* When arguing for biodiversity in cities, we need to communicate that some additional needs can also met with urban NBS it does not mean acting against other, more pressing social issues (e.g. social housing important issue espeically in the Global South) – *Nikara Mahadeo (ICLEI CBS South Africa)*
    - increasing connectivity within the city and between urban and rural areas – *Rob Carr (UK Environment Agency)*; Create 'stepping stones' as 'low hanging fruits' to get started e.g. corridors and connections among different NBS and areas (e.g. (extensive) green roofs, green road side verges, green transport corridors, brownfield redevelopment) - *Bettina Wilk (ICLEI Europe Brussel Office)*
    - ecological/biodiversity-friendly management of green and blue space to support diverse, 'wild' nature (quality). "Nature can be a bit messy" and careful management is needed e.g.

artificial maintenance can also be counterproductive while 'real' nature will reap most benefits, but it needs to be communicated to citizens to allow real nature to be introduced – *Pieter Botha (ICLEI/Cities with nature)*; Management and maintenance of urban NBS will also create possibilities of job creations– *Canddie Magdelenant (WWF France), Jeet Mistry (WWF Cities team)*

Nature for Society

"*In which nature is primarily valued for the benefits or uses people derive from it, and which could lead to an optimization of multiple uses of nature*" (NFF)

- Key to this perspective is the emphasize of the instrumental value of nature, hence using nature as a tool to enhance benefits that people want, need or desire e.g. need to address certain felt threats to current or future living environments.
- "If NBS are connected to actual events that people experience/will experience as a threat, it might help seeing the potential of NBS"- *Samantha McCraine (Science Based Targets Network)*
- Key societal challenges where urban NBS can offer a solution to are:
    - Stormwater flooding: retain water during both fluvial and pluvial rain events avoid cities from flooding - *John Rob Pool (Cities4Forests), Samantha McCraine (Science Based Target Network), Federica Marando (JRC)*
    - Heat mitigation: using natures capacity to cool air temperatures during summer (heat) – *Chiara Cortinovis (University of Lund)*
    - Droughts (especially in Southern Europe, Turkey), which can also be amplified by water needs of vegetation during drought season (trade-offs) - *Samantha McCraine (Science Based Target Network), Jennifer Lenhart (WWF Cities Team)*
    - Air pollution - *Federica Marando (JRC);* But contribution of urban NBS to it questionable/limited - *Chiara Cortinovis (University of Lund);* The same counts for the contribution of urban NBS to climate change mitigation (i.e. carbon storage and sequestration). Urban vegetation captures atmospheric carbon hence contribute to combating global warming, but "delicate topic" - *Pieter Botha (ICLEI/Cities with Nature*); On the one hand yes it might bring private and public initiatives together to contribute to towards a common goal (i.e. reduction of atmospheric carbon concentration, "carbon tokens" – *Rob Carr (UK Environment Agency*); While on the other hand the contribution of urban vegetation to reduce CO_2 is low/questionable - *Chiara Cortinovis (University of Lund*); E.g. urban environments are continuously changing while carbon should ideally stay stored for long-term - *Pieter Botha (ICLEI / Cities with Nature*).
- Approach: **optimize multiple benefits to address key societal challenges (e.g. climate change challenges – heat, flood, drought) by integrating nature into the city where people most need it,** for example by
    - Implementation of small-scale initiatives such as greening streets (e.g. trees along the street, raingardens along roads) and greening parking lots (e.g. permeable surfaces, trees) or making parking lots smaller or even convert into green areas (e.g. pocket parks). Examples like these ('low hanging fruits') will yield the highest and fastest results (e.g. additional shade to cool down the city, enhanced water infiltration to take away from roads/buildings) to showcase urban decision makers to include urban NBS in planning and decision making – *Samantha McCraine (Science Based Targets Network)*

- Green infrastructure connected to grey: Allow combination of grey and green solutions (i.e. hybrid) to optimize benefit provision – *Jeet Mistry (WWF Sweden)* (e.g. constructed wetlands, green buildings)
- Greening of public and private land: "Land use and spatial change are key drivers for adaptation to climate change and being ambitious is important" – *Aleksandra Kazmierczak (EEA)*; Importance to not only implement NBS on public land, but there is also a great potential on private land (e.g. green buildings, de-paving gardens) – *Samantha McCraine (Science Based Targets Network), Harriet Bulkeley (Durham University), Aleksandra Kazmierczak (EEA)*; "What people do in their own garden can also have a big impact" - *Bettina Wilk (ICLEI Europe Brussels Office).* Creating understanding of importance NBS to people, including the need to better communicate and share (science) results among citizens, policy makers etc. – *Russelt Galt (International Union for the Conservancy of Nature), Bettina Wilk (ICLEI Europe Brussels Office)*;
- Management of green space to optimize benefits desired: amount and quality of specific NBS is really relevant, e.g. different size and conditions have the potential to deliver different benefits – *Federica Marando (JRC)*

Nature as Culture

"*in which humans are perceived as an integral part of nature, and therefore what is valued is the reciprocal character of the people-nature relationship*" (NFF)

- Key to this perspective is the emphasize of the relational value of nature, hence creating space for people and nature to reconnect and affiliate with nature and in that way support human health and well-being
- "Especially since the COVID-19 crisis, many governments have shifted their views more and more towards inclusive urban nature, as nature is seen as vital to citizens well-being" – *Rob Carr (UK Environment Agency*)
- Approach: **Having 'attractive' nature within the living environment**
  - Increase public accessible green space. Providing equal access to nature' contributes to social inclusion and social justice; Especially in Global South, providing equal access to nature is a great challenge – *Jennifer Lenhart (WWF Cities Team)*, but also during the COVID-19 crisis in Europe. When implementing NBS, risk of inequality & equity issues should be looked at – *Pieter Botha (ICLEI / Cities with Nature)*
  - Reinforcing identity of an urban environment. Integration of culture important aspect in order to make urban NBS successful – *Russel Galt (International Union for the Conservation of Nature);* Maintenance of green spaces creates also opportunities for local community to engage with nature again, and to learn about the worth of nature as well as how to manage it sustainably – *Samantha McCraine (Science Based Targets Network)*, *Jennifer Lennart (WWF Cities Team);* Potential of NBS can be very different among different countries (e.g. different risk and trade-offs, preferences, safety concerns), which need to be considered when selecting NBS – *Pieter Botha (ICLEI/Cities with Nature), Samantha McCraine (Sciene Based Targets Network), Jennifer Lenhart (WWF Cities Team)*
  - Tactical urbanism. Short term actions e.g. low-cost, temporary changes to the built environment e.g. by transforming streets or parking lots into green places intended to

improve local neighbourhoods and city gathering for long-term changes (more green space for people) – *Jennifer Lenhart (WWF Cities Team)*

Appendix D: Carbon mitigation values

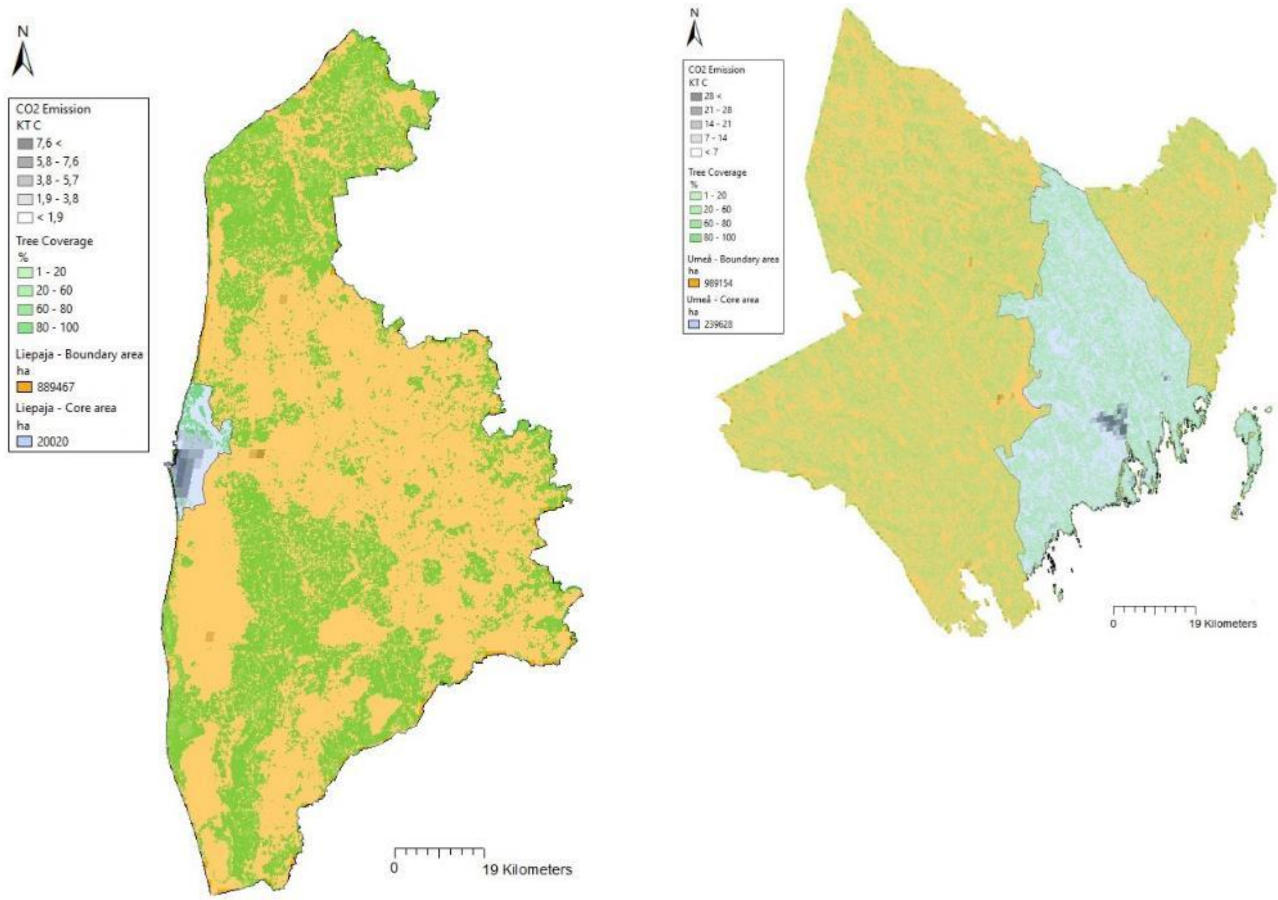


Figure D-1: Tree coverage and CO_2 emissions in the core area (blue) compared to boundary area (yellow), taken Liepāja (Lithuania) and Umea (Sweden) as an example.

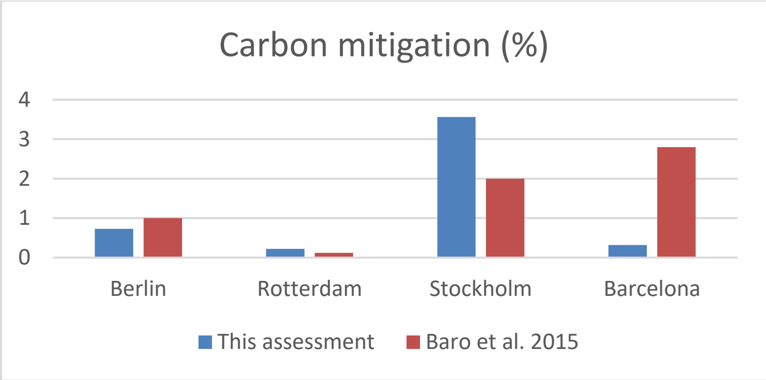


Figure D-2: Carbon mitigation values (%) estimated for four urban core cities in this assessment compared to Baro et al. 2015.