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Title:

Mismatches between ecosystem services supply and demand in urban areas: A quantitative assessment in five European cities

ORIGINAL RESEARCH PAPER

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Abstract

Assessing mismatches between ecosystem service (ES) supply and demand in urban areas can provide relevant insights for enhancing human well-being in cities. This paper provides a novel methodological approach to assess regulating ES mismatches on the basis of environmental quality standards and policy goals. Environmental quality standards indicate the relationship between environmental quality and human well-being. Thus, they can be used as a common minimum threshold value to determine whether the difference between ES supply and demand is problematic for human well-being. The methodological approach includes three main steps: (1) selection of environmental quality standards, (2) definition and quantification of ES supply and demand indicators, and (3) identification and assessment of ES mismatches on the basis of environmental quality standards considering certain additional criteria. While ES supply indicators estimate the flow of an ES actually used or delivered, ES demand indicators express the amount of regulation needed in relation to the standard. The approach is applied to a case study consisting of five European cities: Barcelona, Berlin, Stockholm, Rotterdam and Salzburg, considering three regulating ES which are relevant in urban areas: air purification, global climate regulation and urban temperature regulation. The results show that levels of ES supply and demand are highly heterogeneous across the five studied cities and across the environmental quality standards considered. The assessment shows that ES supply contributes very moderately in relation to the compliance with the EQS in most part of the identified mismatches. Therefore, this research suggests that regulating ES supplied by urban green infrastructure are expected to play only a minor or complementary role to other urban policies intended to abate air pollution and greenhouse gas emissions at the city scale. The approach has revealed to be appropriate for the regulating ES air purification and global climate regulation, for which well-established standards or targets are available at the city level. Yet, its applicability to the ES urban temperature regulation has proved more problematic due to scale and user dependent constraints.

Keywords: Air purification; Assessment; Global climate regulation; Green infrastructure; Human well-being; Urban temperature regulation.

1. Introduction

Green infrastructure (GI) has been defined as a "network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services (ES). It incorporates green spaces (or blue if aquatic ecosystems are concerned) and other physical features in terrestrial (including coastal) and marine areas" (EC, 2013:3). In urban areas, GI elements may include parks, urban forests, allotments, street trees, green roofs, etc. (Landscape Institute, 2009). Relevant ES delivered by GI in cities include, for instance, air purification, urban temperature regulation, runoff mitigation, noise reduction and recreation (Bolund and Hunhammar, 1999; Gómez-Baggethun and Barton, 2013; Gómez-Baggethun et al., 2013).

An increasing body of literature highlights the contribution of GI and ES in enhancing environmental quality (e.g., air quality) in cities, hence fostering a better quality of life and well-being for the urban population (e.g., Nowak, 2006; Tzoulas et al., 2007; Escobedo et al., 2011; Pataki et al., 2011). Some studies even argue that urban policies based on the planning and management of GI can be comparable in terms of effectiveness or efficacy to other policies based on technological measures (e.g., Escobedo et al., 2008; 2010). Yet, the assessment of the current (and potential) contribution of urban GI through ES supply as a means to meeting desired or required environmental quality conditions and goals at the city scale remains largely unexplored.

The main objective of the paper is hence the exploration of the possible contribution of ES supply to meet environmental quality standards and policy goals (hereafter referred as EQS) in urban areas. The underlying assumption derived from this objective is that EQS are to be met exclusively through ES supply. Conceptually, this hypothesis can be framed as the assessment of mismatches between ES supply and demand. This research argues that ES demand, defined here as the amount of service required or desired by society (Villamagna et al., 2013), can be expressed in relation to EQS because these provide a threshold value to determine whether the difference between ES supply and demand is problematic for human well-being. The assessment examines ES mismatches of three regulating ES which are relevant in urban areas (Gómez-Baggethun and Barton, 2013): air purification, urban temperature regulation and global climate regulation (through carbon sequestration). The methodological approach includes three main steps: (1) selection of EQS, (2) definition and quantification of ES supply and demand indicators, and (3) identification and assessment of ES mismatches on the basis of EQS considering certain additional criteria. While ES supply indicators estimate the flow or amount of an ES actually delivered (e.g., air pollutants removed by urban vegetation), ES demand indicators estimate the amount of inputs needing regulation (e.g., air pollutant concentrations) in relation to the corresponding EQS (e.g., air quality standards). The approach is applied to a case study consisting of five European cities: Barcelona, Berlin, Stockholm, Rotterdam and Salzburg. Based on the obtained results, the actual and potential contribution of urban GI to address mismatches between ES supply and demand at the city scale is discussed, as well as the advantages and limitations of using EQS to assess these mismatches.

2. Materials and methods

2.1. Conceptual framework

Recently developed conceptual frameworks in the ES literature call for a distinction between ES *capacity*, *flow* and *demand* as the main components of the ES delivery process (Villamagna et al., 2013; Burkhard et al., 2014; Schröter et al., 2012; 2014; Guerra et al., 2014). Capacity is defined as the ES potential (i.e., hypothetical maximum yield) and flow as the actual supply or use of ES experienced by people. ES demand, however, has been approached differently depending on the authors. Burkhard et al. (2014:5) define demand for ES as the "services currently consumed or used in a particular area over a given time period, not considering where ES actually are provided". Alternatively, ES demand has been described as "the amount of a service required or desired by society" (Villamagna et al., 2013:115) or "the expression of the individual agents' preferences for specific attributes of the service" (Schröter et al., 2014:541). In this paper, ES supply is conceptualized as ES flows (Hein et al., 2006) and ES demand as the required level of ES delivery by society (Villamagna et al., 2013). ES mismatches occur when the demand for ES is not totally met by the supply within a defined spatial and time scale. Thus, ES mismatches express the existence of an unsatisfied or remaining demand (Geijzendorffer et al., 2015).

According to the framework developed by Villamagna et al. (2013), the supply of regulating ES contribute to the maintenance of environmental quality within socially acceptable ranges only until a certain level of ecological pressure (e.g., air pollution). Beyond this level, ES supply cannot sustain a good environmental quality and ES demand should be considered as not totally met. Under this approach, estimating regulating ES demand requires hence information about two main elements: (1) desired conditions (i.e., good environmental quality); and (2) inputs needing regulation (i.e., ecological pressures). In line with Paetzold et al. (2010), this paper considers that EQS can be used as a threshold of desired conditions in relation to the demand for regulating ES. In general terms, EQS rely on scientific evidence and/or expert knowledge concerning the relationship between environmental quality and human well-being with the underlying aim to secure or enhance the latter (e.g., EEA, 2013a). Thus, the methodological approach considered here assumes that EQS can provide a common minimum threshold value to assess regulating ES mismatches across different contexts (in this case study, different European cities). For example, World Health Organization (WHO) air quality guidelines (WHO, 2005) can be used to provide a minimum threshold to assess the mismatch between supply and demand of the ES air purification. A city where air pollution levels exceed WHO reference values reflects a mismatch in which air purification demand exceeds the current local supply. Yet, this situation does not necessarily imply that the EQS is to be achieved solely by ES supply.

2.2. Selection of environmental quality standards

Based on a non-exhaustive examination of European-context regulatory frameworks, relevant EQS were identified for the three ES assessed in this study (**Table 1**). EQS for ES air purification were derived from the European Union (EU) air quality Directive (EU, 2008) and WHO air quality guidelines (WHO, 2005). Reference values for ground-level concentrations of air pollutants are generally more stringent in the WHO standards, but only the EU standards are legally binding for the case study cities, hence the inclusion of both standards in the assessment was considered pertinent. The focus was limited to the following air pollutants: (1) particulate matter with a diameter of 10 µm or less (PM_{10}); (2) nitrogen dioxide (NO_2); and (3) tropospheric ozone (O_3), considered three of the most problematic air pollutants in terms of exposure to concentrations above the EU and WHO reference levels in Europe for its urban population (EEA, 2013a).

The ES global climate regulation is generally assumed to be demanded at global scale (Burkhard et al., 2012), yet city specific GHG emission reduction and offset targets can be considered as a desired condition at lower scales. Following the EU 20-20-20 targets (EC, 2008), many municipal authorities have signed up to the 'Covenant of Mayors' initiative[1], voluntarily committing themselves to reduce their GHG emissions by at least 20% until 2020 (see **Table 1** for specific reduction targets of the case study cities).

No explicit EQS were found in relation to urban temperature regulation at the European regulatory level, probably because human health vulnerability to temperature extremes depends on a complex interaction between different factors such as age, health status, socio-economic circumstances (e.g., housing) and regional adaptation (Kovats and Hajat, 2008; Fischer and Schär, 2010). However, general critical temperature thresholds for health impacts in Europe have been estimated based on the spatial and temporal variance in excess mortality during recent heatwaves[2] episodes (Fischer and Schär, 2010). According to this research, the consecutive occurrence of days with maximum temperature above 35ºC ('hot days') and nights with minimum temperature above 20ºC ('tropical nights') has been found to explain the correlation with excess mortality. These values match well with specific temperature thresholds officially allocated to cities like Barcelona (Tobias et al., 2012), but are likely overestimated for Northern cities like Stockholm (Roklöv and Forsberg, 2008) due to

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[1] See www.covenantofmayors.eu

[2] Fischer and Schär (2010) define a heatwave "to be a spell of at least six consecutive days with maximum temperatures exceeding the local 90th percentile of the control period (1961-1990)".

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regional adaptation factors. In any case, the impacts of heatwaves on human health are particularly strong in cities, both in Northern and Southern latitudes, due to the exacerbating effect of the urban heat island (UHI) (EEA, 2012).

Table 1

EQS selected to assess mismatches between ES supply and demand

<table>
<tr><th>ES</th><th>EQS</th></tr>
<tr><td>Air purification</td><td>
EU Air Quality Directive (EU, 2008) and WHO air quality guidelines (WHO, 2005) reference values:
<table>
<tr><th>Pollutant</th><th>EU</th><th>WHO</th></tr>
<tr><td>PM$_{10}$</td><td>40 µg m^{-3} (Year)</td><td>20 µg m^{-3} (Year)</td></tr>
<tr><td>NO$_2$</td><td>40 µg m^{-3} (Year)</td><td>40 µg m^{-3} (Year)</td></tr>
<tr><td>O$_3$</td><td>120 µg m^{-3} (8-hour)</td><td>100 µg m^{-3} (8-hour)</td></tr>
</table>
</td></tr>
<tr><td>Global climate regulation</td><td>
Covenant of Mayors' GHG emission reduction targets for each case study city are:

Barcelona: 23% by 2020 (baseline year 2008)
Berlin: 40% by 2020 (baseline year 1990)
Stockholm: 45% by 2020 (baseline year 1990)
Rotterdam: 50% by 2025 (baseline year 1990)
Salzburg: No explicit target found (assuming 20% by 2020, baseline year 1990)

</td></tr>
<tr><td>Urban temperature regulation</td><td>
Heatwave thresholds: consecutive occurrence of hot days (T-max > 35ºC) and tropical nights (T-min > 20 ºC) (Fischer and Schär, 2010).
</td></tr>
</table>

Notes: Air quality policy targets correspond to the EU and WHO values set for the protection of human health (in brackets the averaging period applicable for each limit). EU's reference value for O$_3$ is subject to 25 days of allowed exceedances per year averaged over three years. See EEA (2013a) for more details. GHG emission reduction targets for each case study city are based on local Sustainable Energy Action Plans (see www.covenantofmayors.eu and Table 3).

2.3. Defining indicators of ES supply

ES supply was measured directly as the amount of a service delivered or experienced by people (van Oudenhoven et al., 2012; Villamagna et al., 2013). The indicators for ES supply were selected based on methods and data availability (see **Table 2**). For this analysis only terrestrial ecosystems were considered, omitting blue infrastructure elements (sea, lakes, ponds, rivers, etc.) which can also be important sources of ES supply in the urban context (Bolund and Hunhammar, 1999), especially in case study cities such as Stockholm, Rotterdam and Barcelona. The use of tools specifically designed for quantifying ES delivered by terrestrial vegetation (e.g., i-Tree Eco model) prevented a more complete assessment of urban ecosystems (i.e., including blue infrastructure).

The supply of the ES air purification was quantified using estimated air pollution removal of PM_{10}, NO_2, and O_3 by urban green space. Uptake rates were quantified using the dry deposition model of i-Tree Eco tool (Nowak et al., 2006; 2008; Hirabayashi et al., 2012). Data required for each city included hourly air pollution concentration, percentage of tree canopy cover (both deciduous and evergreen) and meteorological data. For Barcelona and Berlin air pollution removal rates were taken from Baró et al. (2014) corresponding to year 2008, and Aevermann (pers. comm., 2013) for year 2011, respectively. Air pollution concentration data from Salzburg, Stockholm and Rotterdam monitoring stations were obtained from the AirBase database v.7 (EEA, 2013b) for the year 2011. Meteorological data were retrieved from the US National Climatic Data Centre for the same year. Percentages of evergreen and deciduous tree canopy cover for these three cities were estimated using i-Tree Canopy tool[3] which allows photo-interpretation of urban land covers from Google Maps aerial imagery using a random sampling location process. A sample of 500 survey points were photo-interpreted for each city based on a categorization of three cover classes: 1) deciduous tree; 2) evergreen tree and 3) non-tree cover. This method likely underestimates the amount of air purification supplied since it accounts for tree canopy but not for shrubs or herbaceous vegetation which can also supply this ES (Nowak et al., 2006).

Carbon storage and annual CO_2 sequestration rates performed by urban GI were used as indicators to measure the supply of the ES global climate regulation (Nowak and Crane, 2002; Strohbach and Haase, 2012; Nowak et al., 2013; Schröter et al., 2014). Barcelona's estimates were based on the i-Tree Eco assessment performed in 2008 using field measurements of urban forest structure, allometric equations to predict above-ground biomass and adjusted urban tree growth and decomposition rates (Baró et al., 2014). Due to limited resources for fieldwork data collection in the other case study cities, carbon storage and sequestration indicators were estimated based on the assessment carried out by Nowak et al. (2013) using urban field data from 28 cities and 6 states in United States (US), where carbon storage per square meter of tree cover averaged 7.69 kg C m^{-2} (SE = 1.36), gross carbon sequestration rate averaged 0.277 kg C m^{-2} $year^{-1}$ (SE = 0.045), and net carbon sequestration rate averaged 0.205 kg C m^{-2} $year^{-1}$ (SE = 0.041). Percentage of tree canopy cover was estimated using the i-Tree Canopy tool as described above (for Berlin, 1,000 points were photo-interpreted due to its larger area). Although these rates can vary depending on variables such as tree diameter distribution or

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[3] see www.itreetools.org/canopy/index.php

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species composition in each city, the indicator estimates should be accurate as they are based on local tree cover values (Nowak et al., 2013). Further, empirical studies carried out in European cities obtained similar values (e.g., Strohbach and Haase, 2012 estimated an average carbon storage rate of 6.82 ± 1.42 kg C m^{-2} of canopy cover in Leipzig, Germany). Because tree growth (and hence CO_2 sequestration) vary depending on the local environmental conditions, sequestration rates were refined using the length of the growing season as a proxy, following the formula (Nowak, pers. comm., 2013):

$$C' = \frac{C-GS}{174} \qquad (1)$$

Where

C' = average (gross or net) carbon sequestration rate (kg C/m^2 tree cover year)
C = US average (gross or net) carbon sequestration rate (kg C/m^2 tree cover year) (Nowak et al. 2013)
GS = length of the growing season (days)

Average length of the growing season in each case study city was based on phenological data for the period 1969-1998 (Chmielewski and Rötzer, 2001). Reported trends in plant phenology in Europe and USA indicate a similar lengthening of the growing season in the last decades associated to global warming (Linderholm, 2006), thus used lengths should be considered a first-order estimate. Carbon sequestration rates were converted to CO_2 after applying the conversion factor 1 g C = 3.67 g CO_2.

The supply of the ES urban temperature regulation by green space can provide important benefits to city inhabitants by mitigating heat stress (Stone et al., 2010) and reducing UHI effects and increased temperatures resulting from climate change (Gill et al., 2007). Vegetation delivers this service mainly through the evapotranspiration process and the shading effect (basically from trees). Bowler et al. (2010) systematically reviewed the empirical evidence of this ES showing that, on average, the temperature within an urban park would be around 1 ºC cooler than a non-green site in the day. Other urban GI elements such as urban forests and green roofs also show evidence of lower air temperatures compared to treeless areas and roofs without vegetation respectively (Oberndorfer et al., 2007; Breuste et al., 2013). Tree shade area was used as a proxy indicator to quantify the supply of this service. It was estimated as tree canopy cover area using i-Tree canopy tool as described above, assuming that the cooling effect is provided mainly below tree canopy (Bowler et al., 2010).

Table 2

ES supply indicators and associated quantification methods and references.

ES	Indicators	Quantification method	Sources / References
Air purification	PM_{10} removal (kg ha^{-1} year^{-1}) NO_2 removal (kg ha^{-1} year^{-1}) O_3 removal (kg ha^{-1} year^{-1})	i-Tree Eco dry deposition model based on tree canopy cover, air pollution and meteorological data	i-Tree Canopy (www.itreetools.org) AirBase v.7 (EEA, 2013b). Year 2011 Nowak et al. (2006); Baró et al. (2014); Aevermann et al. (2015, submitted)
Global climate regulation	CO_2 sequestration (t ha^{-1} year^{-1}) Carbon storage (t ha^{-1})	Estimates from i-Tree assessments based on tree canopy cover and length of growing season	i-Tree Canopy (www.itreetools.org) Nowak et al. (2013); Baró et al. (2014)
Urban temperature regulation	Tree shade area (%)	Cooling effect of trees based on empirical data and tree canopy cover area estimates	i-Tree Canopy (www.itreetools.org) Bowler et al. (2010); Breuste et al. (2013)

2.4. Defining indicators of ES demand

Due to the different approaches to ES demand, a variety of indicators can be defined to measure it. One way is to consider population density in combination with average or desired consumption rates (Burkhard et al., 2012; Kroll et al., 2012). ES demand can also be measured by the socio-cultural preferences directly expressed by people in interviews and questionnaire surveys (Martín-López et al., 2014) or through monetary valuation (de Groot et al., 2012). Following the conceptual framework described above, in this paper ES demand indicators express the amount or concentration of inputs (i.e., ecological pressures) needing regulation with regard to the corresponding EQS (i.e., the desired environmental conditions which secure human well-being) (Villamagna et al., 2013; Burkhard et al., 2014). **Table 3** shows the selected indicators for ES demand.

Indicators for the ES air purification were estimated on the basis of air pollution levels in each city in relation to the desired level expressed by air quality standards (Burkhard et al. 2014). These indicators express the remaining air pollution as they already include the impact of ES supply (Guerra et al., 2014 call it as "ES mitigated impact"). Annual mean concentrations for PM_{10} and NO_2 from the available traffic monitoring stations (which express the highest demand) in each case study city were extracted from the AirBase database v.7 (EEA, 2013b) using values corresponding to year 2011. O_3 levels were expressed as the twenty-sixth highest value in each city based on daily maximum 8-hour averages since the current European air quality threshold includes 25 days of allowed exceedances (EEA, 2013a).

Demand indicators for the ES global climate regulation were estimated on the basis of annual GHG emissions as expressed in carbon dioxide equivalent (CO_2-eq) per hectare and per capita (Burkhard et al., 2014). Total emissions for each case study city were obtained from local Sustainable Energy Action Plans (SEAPs) and other municipal policy reports (see **Table 3** for references) corresponding to the GHG reduction target baseline year (1990 for Berlin, Stockholm and Rotterdam, 2008 for Barcelona and 2010 for Salzburg because 1990 data was not available).

Finally, demand for the ES urban temperature regulation was estimated using heatwave risk as indicator. Following Fischer and Schär (2010), heatwave risk was quantified as the number of combined tropical nights (> 20ºC) and hot days (>35ºC) projected for the period 2071-2100 in Europe. This scenario was developed at a European scale and it does not take into account the UHI effect that exacerbates heatwave risk in cities (EEA, 2012). Thus, the consideration of this future scenario can roughly express a more realistic current situation of heatwave risk in the case study cities, where the UHI can reach a maximum intensity of 8°C (e.g., Moreno-Garcia, 1994 for Barcelona).

Table 3

Demand ES indicators and associated quantification methods and references.

ES	Indicators	Quantification method	Sources / References
Air purification	PM_{10} annual mean concentration (µg m^{-3}) NO_2 annual mean concentration (µg m^{-3}) 26th highest O_3 value based on daily max 8-hour averages (µg m^{-3})	Statistical data review	AirBase v.7 (EEA, 2013b) - Year 2011
Global climate regulation	Annual CO_2-eq emissions per ha. (t ha^{-1} $year^{-1}$) Annual CO_2-eq emissions per capita (t $capita^{-1}$ $year^{-1}$)	Literature review on municipal GHG emissions and census data	Barcelona: PECQ. 2011. The energy, climate change and air quality plan of Barcelona 2011-2020. Base year 2008. Berlin: Environmental Agency of the Senate of Berlin. Base year 1990. Stockholm: Stockholm action plan for climate and energy 2010–2020. Base year 1990. Rotterdam: CDP Cities 2012 Global Report. Base year 1990. Salzburg: Energiebericht 2010 Smart City Salzburg. Base year 2010.
Urban temperature regulation	Heat wave risk (# days)	Combined tropical nights (>20ºC) and hot days (>35ºC) expected 2071-2100	Fischer and Schär (2010) EEA (2012)

2.5. Criteria for identifying and assessing ES mismatches

The assessment of matches and mismatches between ES supply and demand usually requires demand to be assessed in the same units as supply in order to obtain a budget or ratio indicating ES undersupply, neutral balance or oversupply (Paetzold et al., 2010; Burkhard et al., 2012; Kroll et al., 2012). However, because of the EQS-based approach considered in this paper, the assessment of mismatches was determined by the following criteria: (1) in the case of non-compliance with the limit or target values stipulated by the EQS, the demand for the corresponding ES was considered to be not totally met by the current supply at the city scale, thus an ES mismatch was identified. On the contrary, in the case of standard compliance, the demand was considered to be currently met by the supply and no ES mismatch was expected at the city level; (2) due to the ES-based assumption considered here, it was also important to assess the contribution or impact of ES supply in relation to the compliance with the EQS, especially in the case of exceedance of limit or target values. In this way, informed decisions can be taken on the feasibility of increasing ES supply (e.g., increase tree canopy cover in the city) as an effective measure to address a given mismatch.

In the case of air purification, an ES mismatch between supply and demand was identified if, despite air purification delivered by urban trees, air pollution levels exceeded EU and/or WHO air quality reference values. The ES contribution to the compliance with the standards was estimated as the average air quality improvement due to air purification by urban trees from i-Tree Eco dry deposition model results (Nowak et al., 2006; Hirabayashi et al., 2012). The estimation of this variable involved considering the mixing layer height[4] in each case city area, which was derived from radiosonde data of the closest station available in the NOAA/ESRL Radiosonde Database[5]. A "substantial mismatch" was identified if the ES contribution (air quality improvement) was lower than 10% in relation to the EQS exceedance. A "moderate mismatch" was identified if this contribution was higher than 10%. This mismatch analysis could not be done for EQS exceedances of O_3 because the standards are based on daily max 8-hour averages whereas air quality improvements are based on annual averages. The criterion to assess an ES mismatch for the ES global climate regulation was defined as the deficit of urban ecological carbon sinks to contribute substantially to CO_2-eq reduction targets in each city. An ES contribution lower than 10% in relation to the reduction target was considered as a "substantial mismatch". A "moderate mismatch" was identified when the contribution was higher than 10%, but lower than 100%. Finally, the uncertainty and complexity related to the impact of the ES urban temperature regulation supply at the wider city scale (Bowler et al., 2010) implies that the heatwave risk cannot be consistently compared to the cooling effect provided by GI on the basis of the heatwave thresholds at the city scale. Therefore, the mismatch assessment of this ES was excluded from the analysis.

2.6. Case study cities

The paper builds on five case study cities distributed along a north-south and east-west gradient across Europe: Barcelona, Berlin, Stockholm, Rotterdam, and Salzburg (**Fig. 1**). The cities vary in their population size, urban form, climate patterns and socio-economic characteristics (**Fig. 1**, **Table 4**), making them representative for a broad range of medium-to-large size European cities. Most of these cities have ambitious strategic plans to enhance GI and ES in the coming years (e.g., Barcelona Green

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[4] The mixing height can be defined as "the height of the layer adjacent to the ground over which pollutants or any constituents emitted within this layer or entrained into it become vertically dispersed by convection or mechanical turbulence within a time scale of about an hour" (Seibert et al., 2000).

[5] See http://esrl.noaa.gov/raobs/

Infrastructure and Biodiversity Plan 2020, Barcelona City Council, 2013). Furthermore, these are all case study cities of the URBES project (Urban Biodiversity and Ecosystem Services[6]).

The spatial scope of this analysis is the municipal or core city area (Urban Audit, 2009). An intrinsic limitation must be acknowledged when using administrative boundaries in urban ES assessments because cities are, to a large extent, influenced by ES provided beyond these boundaries, namely from the larger suburbanized and rural hinterland (Larondelle and Haase, 2013). However, the focus on the administrative areas responded to the following motivations: (1) the analysis includes indicators for which required datasets were only available at the administrative level; (2) urban policies related to green space are usually limited to city's municipal boundaries (e.g., Barcelona's green infrastructure and biodiversity plan 2020, Barcelona City Council, 2013), hence recommendations for future policies are more likely to be applicable when addressed at this spatial scale; (3) the administrative area of the case study cities corresponds well with the dense urban core of their metropolitan areas (Larondelle and Haase, 2013; Larondelle et al., 2014).

Barcelona is the capital city of the region of Catalonia and Spain's second-largest city in terms of population. The city is characterized by a compact urban form together with a very high population density (see **Table 4**). Approximately a quarter of the municipal area consists of green space (parks, gardens, urban forests, etc.), most of which corresponds to the urban park of Montjuïc and the peri-urban forest area of Collserola. Barcelona has also a relatively high proportion of street trees compared to other European cities (Pauleit et al., 2002). Berlin is the capital city and the most populous city of Germany, located at the core centre of the Berlin-Brandenburg metropolitan region. Green space amounts to one third of the city's area, including large urban parks such as Tiergarten located at the city centre and larger areas of forest and water ecosystems located at the outskirts of the municipal area. The former Tempelhof airport has recently been converted into an urban park, providing new opportunities to benefit from green space to a large number of city inhabitants (Kabisch and Haase, 2014). Stockholm, awarded the first European Green Capital in 2010 by the European Commission[7], is the capital of Sweden and the country's most populated municipality. The amount of green and blue space is very relevant in Stockholm (on third of the city's areas is covered by parks, forest and other green assets and 12% by water bodies). Rotterdam is the second largest city of the Netherlands and has the largest seaport of Europe in terms of cargo volume and traffic (CRRSC, 2009). Blue space covers almost a quarter of the total city's area, mainly corresponding to the lowest course of the river Nieuwe Maas. The city is considered one of the greenest large cities of the Netherlands, having a total of 117

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[6] www.urbesproject.org

[7] http://ec.europa.eu/environment/europeangreencapital/

public parks and 747,000 trees (Frantzeskaki and Tilie, 2014). Salzburg is the fourth largest city of Austria and the capital city of the federal state of Salzburg. Almost a half of the municipal area is covered by green space, including a relevant share of forest and agricultural land which is legally protected by the City Council (Voigt et al., 2014).

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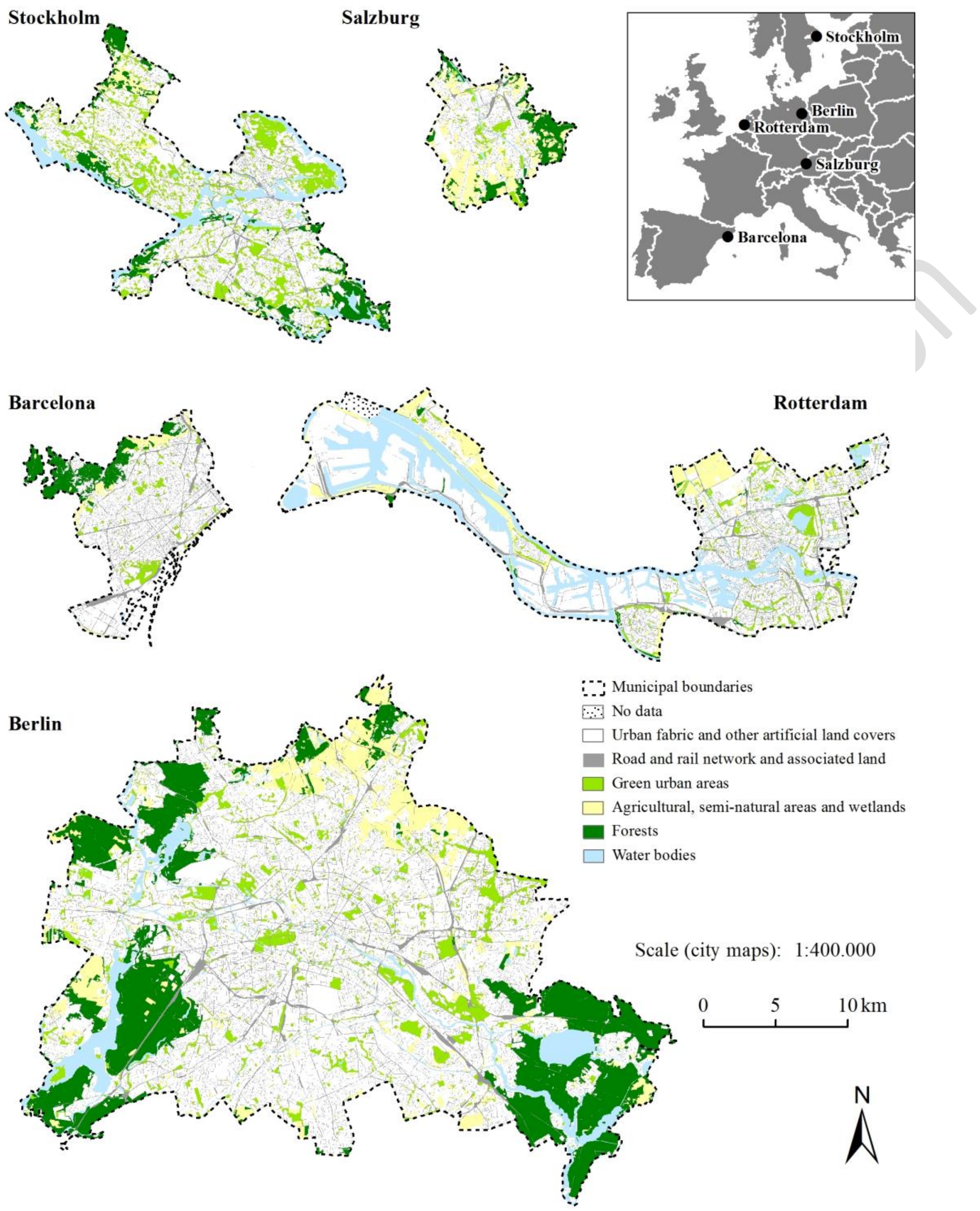

Fig. 1. Location of case study cities and distribution of green space covers. Source: own elaboration based on Natural Earth data (www.naturalearthdata.com) and Urban Atlas (EEA, 2010). Administrative boundaries: Catalan Cartographic Institute (www.icc.cat); Senate Department for Urban Development and the Environment (www.stadtentwicklung.berlin.de/ geoinformation/); Stockholm City Council (www.stockholm.se); Centraal Bureau voor de Statistiek – Statistics Netherlands (www.cbs.nl); Salzburg Geoinformation System (SAGIS) (www.salzburg.gv.at/sagis/).

Table 4

Main characteristics of the case study cities.

	Barcelona	Berlin	Stockholm	Rotterdam	Salzburg	Sources / References
Location in Europe	South-West	Central	North	North-West	Central	-
Physical geography	Coastal / River delta	Inland plains/River	Coastal/Lake outlet	Coastal/River delta	Inland/Foothill of the Alps	-
Population (#)	1,615,908	3,431,675	810,120	582,951	147,169	Urban audit 2009 (reference year 2008)
Population projection in 2050[1] (#)	1,672,112	3,460,046	1,648,000	621,780	161,589	Own trend calculations based on National Census, except for Barcelona (Catalan Statistical Institute – IDESCAT).
Total area (km^2)	101.6	891.1	215.8	277.4	65.7	Municipal boundaries (various sources)
Population density (inhab. km^{-2})	15,905	3,851	3,754	2,101	2,240	Urban audit 2009 (reference year 2008)
Gross Domestic Product (PPS inhab.$^{-1}$)	30,800	24,400	41,000	36,500	38,100	Urban audit 2009 (for NUTS3 region, reference years 2007-2010)
Green urban area (m^2 inhab.$^{-1}$)	3.00	16.91	43.88	23.12	25.86	Urban Atlas (EEA, 2010); Urban audit 2009
Development of green space 1990 – 2006 (ha)	-0.02	1,083	106	16	3	Kabisch and Haase (2013)
Number of private cars registered (# 100 inhab.$^{-1}$)	38.13	28.56	36.98	34.13	N/A	Urban audit 2009 (reference year 2008)
Average temperature of warmest month (ºC)	25.5	19.5	18.5	N/A	18.6	Urban audit 2009 (reference year 2008)

[1] Except for Barcelona (highest population projection for 2021)

3. Results

3.1. ES supply and demand across the case study cities

The quantification results of ES supply and demand indicators are partly shown in **Fig. 2**. The complete set of indicator results is presented in **Table A1** (supply) and **Table A2** (demand) of the Appendix.

Supply of the ES air purification showed the highest values in Berlin, almost doubling the average removal rate for the five case study cities when the three air pollutants are considered. The results for Barcelona and Stockholm displayed comparatively intermediate values, with a total supply of nearly 30 kg removed air pollutants per hectare annually in both cases. Rotterdam and Salzburg were characterized by the lowest values of air purification supply whatever the air pollutant considered. For example, Salzburg's O_3 removal rate was negligible compared to Berlin's (0.12 to almost 22 kg ha^{-1} $year^{-1}$) even though both cities have a relevant share of green space. PM_{10} was the air pollutant comparatively most removed in all the cities, except in Berlin where O_3 removal was slightly higher. Inversely, NO_2 was the pollutant with lowest removal rates in all case study cities, except in Salzburg where the lowest value was found for O_3. Demand indicators for the ES air purification showed different patterns compared to supply across the different case study cities. For example, NO_2 annual mean concentration levels were higher than PM_{10} values in all cities whereas supply indicators showed the opposite condition. It must be noted that PM_{10} and NO_2 have the same EU limit value (40 µg m^{-3} for annual mean concentration), thus demand indicators are comparable for this standard. The highest values for both pollutants were found in Barcelona (32.76 µg m^{-3} for PM_{10} and 53.78 µg m^{-3} for NO_2), while PM_{10} was lowest in Salzburg (23.86 µg m^{-3}) and NO_2 in Stockholm (38.50 µg m^{-3}). Results for O_3 were not comparable with NO_2 and PM_{10} values because concentrations (and standards) are based on daily max 8-hour averages. Berlin (with 116.14 µg m^{-3}) and Salzburg (with 111.63 µg m^{-3}) showed the highest values for O_3. In contrast, the lowest values of O_3 were displayed by Rotterdam (84.74 µg m^{-3}) and Barcelona (89.60 µg m^{-3}).

Regarding global climate regulation supply, CO_2 sequestration indicators ranged from 1.05 t annually sequestered per hectare in Rotterdam to 3.66 t ha^{-1} $year^{-1}$ in Berlin. In the same way, carbon storage values ranged from 9.38 t ha^{-1} in Rotterdam to 32.84 t ha^{-1} in Berlin. Although Stockholm's average growing season is the shortest compared to the other cities, net CO_2 sequestration and carbon storage values were second-ranked after Berlin's. The demand side of global climate regulation showed a different picture: CO_2-eq emissions per hectare were remarkably highest in Rotterdam (865.2 t ha^{-1}

year^{-1}), most likely because of the impact of seaport activities on city's GHG emissions. On the other hand, the lowest value was found for Salzburg (86.6 t ha^{-1} year^{-1}). However, CO_2-eq emissions per capita were lowest in Barcelona (2.51 t capita^{-1} year^{-1}), reflecting the comparatively elevated population density of the Mediterranean city. Supply and demand indicators for this ES could be straightforwardly compared using annual net CO_2 sequestration and CO_2-eq emission rates per hectare as a common unit. Results showed that demand values are approximately two orders of magnitude larger than supply.

Supply indicators for urban temperature regulation revealed also a considerable heterogeneity among case study cities. The highest tree cooling area values were found in Berlin (42.70%) and Stockholm (37.50%). Rotterdam was distinctly the case study city with the lowest share of tree cooling area (12.20%). The demand for urban temperature regulation using heatwave risk as a proxy reflected clearly the different climate zones where the case study cities are located. The results for Barcelona showed a very high number of expected hot days and tropical nights (> 50), while heatwave risk in Stockholm is expected to be minimum (0-2 days). The values for Berlin, Rotterdam and Salzburg were higher than Stockholm's, but substantially far from Barcelona's (2-6 days).

In summary, both supply and demand indicators differed notably among the five case study cities. In most cases, Rotterdam showed the lowest supply values, followed by Barcelona or Salzburg. In contrast, the results for Berlin and, to a lesser extent, Stockholm indicated a relatively high supply of the three regulating ES analyzed. More heterogeneous results were found for demand indicators across the different cities. Barcelona and Rotterdam were clearly characterized by a high demand for urban temperature and global climate regulation respectively. Demand for air purification showed comparatively minor differences across cities. See also exemplary **Fig. 3** showing results for Barcelona compared to case study cities averages.

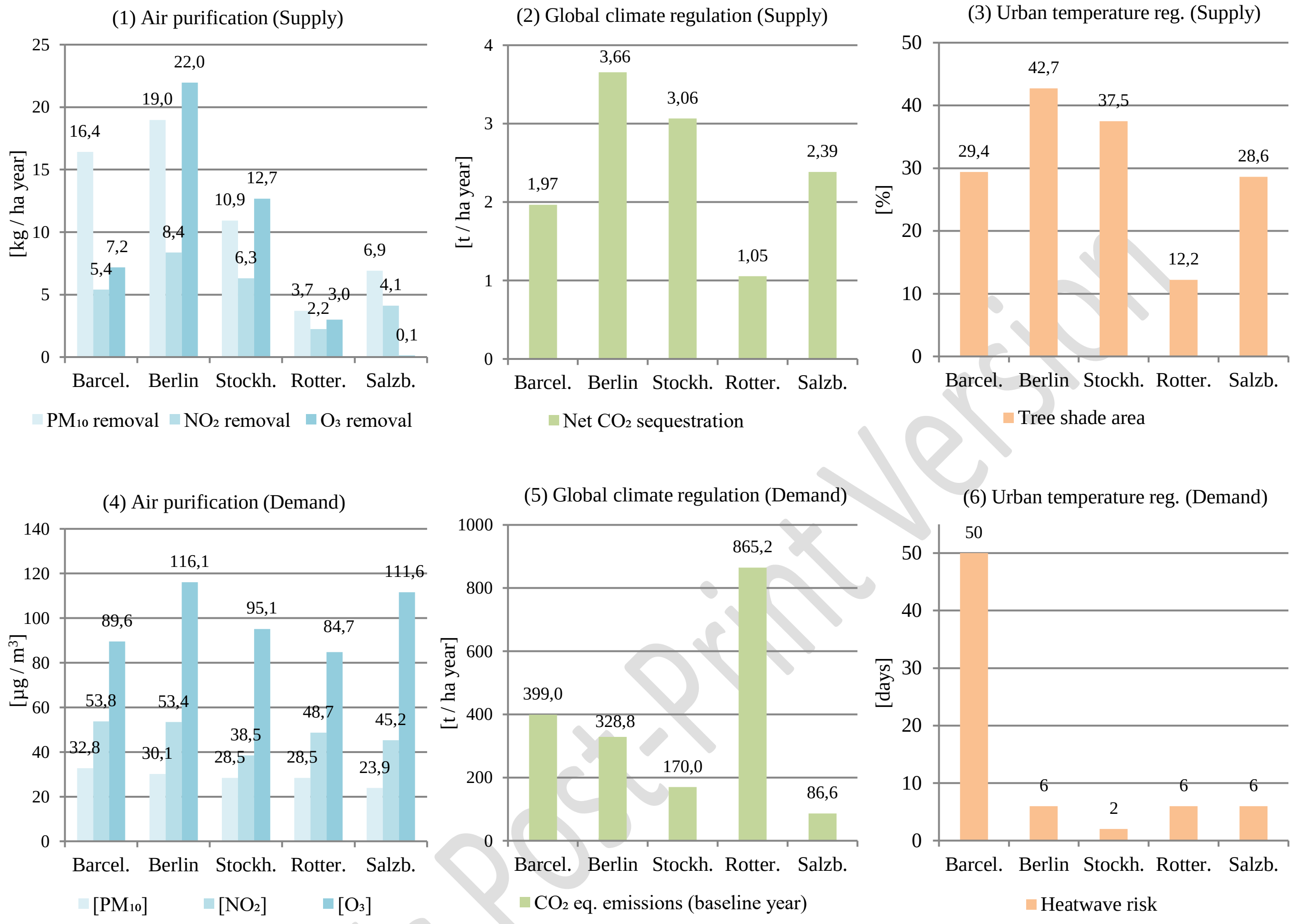

Fig. 2. Quantification results of ES supply and demand indicators for the five case study cities. Notes: Air purification demand values are in annual mean concentration for PM_{10} and NO_2 and in daily max 8-hour averages for O_3 (26th highest value). Urban temperature regulation demand values are the maximum number of days of heatwave risk, except for the case of Barcelona which is the minimum (Fischer and Schär, 2010). Supply and demand values are not directly comparable except for global climate regulation.

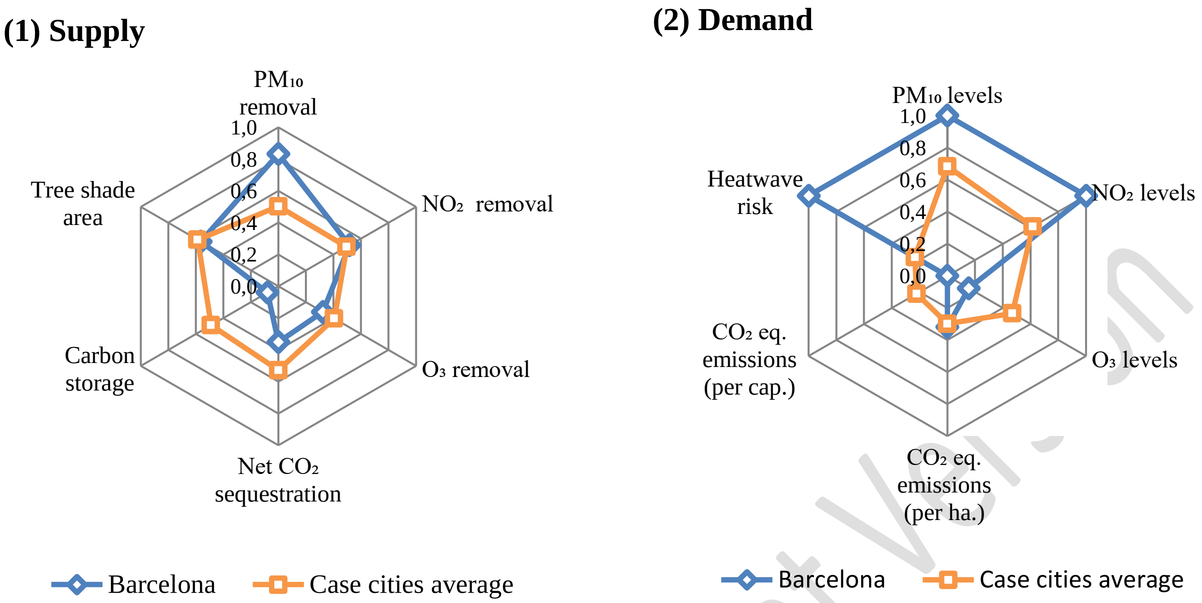

Fig.3. Spidergrams comparing the standardized values of ES supply and demand indicators for Barcelona with the average values of the five case study cities. Supply and demand values are not directly comparable. Standardization is based on a linear rescaling of values in the 0-1 range on the basis of their minimum and maximum value.

3.2. Mismatches in ES supply and demand

Following the criteria described above, matches and mismatches between ES supply and demand were identified, showing a number of cases (12) where demand was clearly not totally met by supply considering the different case study cities (marked as red cells in **Table 5**). In only two cases ES demand was not totally met by supply, but the mismatch was considered minor, suggesting that the corresponding EQS could be met after the implementation of measures intended to increase ES supply (marked as yellow cells). Finally, ES supply matched with demand based on the corresponding EQS in almost half of the cases (14, marked as green cells).

The mismatch assessment of the ES air purification service indicated heterogeneous results across air pollutants and EQS. All cities met the EU limit value for PM_{10} annual average concentration (40 µg m^{-3}), but none of them complied with the WHO standard (20 µg m^{-3}). Only Stockholm met the limit value for NO_2 levels (set at 40 µg m^{-3} for both standards). Tropospheric O_3 levels were below EU regulation in all case cities, but above WHO's air quality limit in Berlin and Salzburg (assuming 25 allowed exceedances per year as well), although the determination of the magnitude of the mismatch was not possible due to data limitations. The relative contribution of the ES service supply to meet air quality standards across the different case study cities is shown in **Table 6**. Air quality improvements due to ES supply showed the lowest values in Rotterdam and the highest values in Stockholm for all the analyzed pollutants, varying between 0.20% and 2.42% for PM_{10} levels, between 0.07% and 0.81% for NO_2 levels and between 0.10% and 1.16% for O_3 levels. According to i-Tree model results, expected air quality improvements are considerably more relevant in areas with 100% tree cover (e.g., urban forests or tree-covered urban parks). However, city-scale average annual air pollution levels in a hypothetic scenario without green space would not differ substantially from the current levels. Therefore, the ES mismatch should be minor if realistic increases in ES supply are intended to meet the standards. The results suggest that this situation only occurs for Salzburg's PM_{10} levels in relation to WHO limit value.

CO_2 offsets by urban GI (ES supply) compared to city-based CO_2 eq. emissions (corresponding to the baseline year for the reduction target) were modest in all case studies, ranging from 0.12% for Rotterdam to 2.75% for Salzburg. Similarly, the contribution of the ES supply in relation to CO_2eq reduction targets for 2020 was low in all case study cities. Salzburg was the only case where the annual sequestration rate was higher than the 10% threshold contribution (13.8%), although it must be noted that the city has the lowest reduction target among the case studies.

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Table 5

Identification and assessment of mismatches in ES supply and demand across the case study cities. Red cells indicate a substantial mismatch between ES supply and demand (ES contribution is lower than 10% in relation to the EQS exceedance or reduction target), suggesting that the corresponding EQS can be unlikely met by increase in ES. Yellow cells indicate a moderate mismatch between ES supply and demand (ES contribution is higher than 10% in relation to the EQS exceedance or reduction target) suggesting that the corresponding EQS could be met after the implementation of measures intended to increase ES supply. Green cells indicate that ES supply matches with demand based on the corresponding EQS. Blank cells indicate that the mismatch assessment could not be consistently done due to data limitations. See also subsection 2.5.

ES	Assessment	EQS	Barcel.	Berlin	Stockh.	Rotter.	Salzb.
Air purification	PM_{10} levels	EU	🟩	🟩	🟩	🟩	🟩
	PM_{10} levels	WHO	🟥	🟥	🟥	🟥	🟨
	NO_2 levels	EU/WHO	🟥	🟥	🟩	🟥	🟥
	O_3 levels	EU	🟩	🟩	🟩	🟩	🟩
	O_3 levels	WHO	🟩		🟩	🟩	
Global climate regulation	Contribution to city CO_2eq reduction target	City CO_2eq reduction target	🟥	🟥	🟥	🟥	🟨
Urban temp. regulation	N/A	Heatwave thresholds					

Table 6

Estimated air quality improvement due to air pollution removal by urban trees in case study cities (year 2011)

	Average percent air quality improvement at the city scale			Average percent air quality improvement only in areas with 100% tree cover			Expected average annual air pollution levels without urban trees at the city scale (µg m^{-3})		
	PM_{10}	NO_2	O_3	PM_{10}	NO_2	O_3	PM_{10}	NO_2	O_3
Barcelona	0.50	0.19	0.29	1.64	0.63	0.96	32.92	53.88	39.81
Berlin	0.73	0.21	0.30	1.67	0.49	0.70	30.33	53.49	47.41
Stockholm	2.42	0.81	1.16	6.14	2.12	2.96	29.16	38.81	55.62
Rotterdam	0.20	0.07	0.10	1.57	0.57	0.81	28.51	48.69	35.93
Salzburg	1.89	0.60	0.85	6.24	2.04	2.83	24.32	45.48	41.75

4. Discussion

4.1. The contribution of ES supply to human well-being in cities

The impact of urban green space on air quality in cities is a subject of scientific debate. Several empirical and modelling studies support that urban vegetation provides substantial air quality improvements followed by associated health benefits (Nowak et al., 2006; Yin et al., 2011; Islam et al., 2012; Nowak et al., 2013). However, factors such as vegetation configuration or climate conditions can strongly limit the ability of vegetation to remove air pollutants, especially at the patch scale (Setälä et al., 2013; Vos et al., 2013). The modelling results presented here indicate that average air quality improvements due to air purification supply is relatively low at the city scale for the three analyzed air pollutants in all case study cities (e.g., from 0.07% in Rotterdam to 0.81% in Stockholm for NO_2), although positive effects are likely to be more relevant in highly tree-covered areas such as urban forests (e.g., expected air improvements are higher than 6% for PM_{10} in Stockholm's and Salzburg's areas with an hypothetical 100% tree cover, see **Table 6**). Therefore, the average contribution of ES supply in regard to the compliance with air quality standards is considered modest at the local level in all case studies, suggesting a limited effectiveness to address ES mismatches by increasing ES supply (e.g., implementing tree-planting programs) unless air pollution concentration exceedance is minor (e.g., PM_{10} levels compared to WHO standard in the case of Salzburg).

A number of studies have assessed the role of urban green space as a climate change mitigation strategy by offsetting city CO_2 emissions (Pataki et al., 2009; Escobedo et al., 2010; Zhao et al., 2010; Liu and Li, 2012). Impacts of net CO_2 sequestration rates on offsetting annual city CO_2 emissions vary from 3.4% in Gainesville, US (Escobedo et al., 2010) to 0.26% in Shenyang, China (Liu and Li, 2012). As expected, similar results have been obtained for the case study cities (ranging from 0.12% in Rotterdam to 2.75% in Salzburg). This paper has gone one step further by considering city-specific GHG reduction targets as a desired condition at the city level. Again, results show a modest contribution of ES supply (less than 15%) in all case study cities, suggesting that increases in direct carbon sequestration delivered by GI (e.g., by doubling tree density) is not likely to be an effective means for reaching local CO_2-eq. reduction targets (in line with Pataki et al., 2011).

Previous empirical evidence on the supply of urban temperature regulation (Bowler et al., 2010) revealed that the cooling effect of urban GI can be relatively relevant at the patch scale. For example, a maximum of 2ºC difference relative to built-up area was observed in an urban park in Stockholm (Jansson et al., 2007). However, the extension of the cooling effect of green space beyond its boundaries is uncertain, especially at the wider city scale (Bowler et al., 2010). Therefore, heatwave

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thresholds cannot be consistently balanced against the cooling effect provided by GI elements at the city scale. Additional empirical research is required to assess these mismatches, especially by establishing specific temperature thresholds according to each climate zone and measuring the cooling impact of GI interventions at the city scale.

The findings of this research suggest that GI can only play a minor or complementary role, at least at the core city level, to urban mitigation measures intended to abate air pollutant and GHG emissions at the source (e.g., road traffic management or energy efficiency measures) or to adaptation policies intended to cope with heat extremes (e.g., heat warning plans). Yet, there are important reasons for which the current and potential supply of these ES should not be neglected in local policy decision-making. First, GI can provide other important benefits to urban population due to its multifunctional capacity (e.g., stormwater runoff mitigation or recreational opportunities), while technological substitutes are normally designed as single-purpose. Second, although GI expansion in compact cities such as those analyzed in this paper might be challenging due to lack of available land and densification processes, measures for preserving existing green spaces and innovative ways to allocate new ones could considerably enhance ES supply at the city level (Jim, 2004). For instance, the potential of green roofs and walls to deliver a wide range of ES has been assessed in various empirical studies (Oberndorfer et al., 2007; Rowe 2011).

4.2. Strengths and weaknesses of using EQS to assess ES mismatches

The demand side is frequently omitted or underrepresented in ES assessments which usually focus on ES supply (Burkhard et al., 2014). Yet, an increasing number of studies have developed assessment methods considering both the ES supply and demand in order to provide a complete picture of the ES delivery process where mismatches between both sides can be identified (e.g., Van Jaarsveld et al., 2005; Burkhard et al., 2012; Kroll et al., 2012; García-Nieto et al., 2013; Boithias et al., 2014; Schulp et al., 2014; Geijzendorffer et al., 2015). This paper contributes to the ES research agenda (de Groot et al., 2010) suggesting a novel methodological approach based on the use of EQS to assess mismatches between ES supply and demand with a focus on regulating ES in core city areas. Based on the assessment of ES mismatches in five European cities, strengths and weaknesses of this approach could be recognized.

This approach can be especially advantageous for regulating ES assessments because of several reasons: (1) demand for regulating ES usually cannot be indicated by direct market prices, unlike many provisioning ES for example (De Groot et al., 2012); (2) the interactions between regulating ES and human benefits are often very complex, thus ES demand is challenging to indicate (Burkhard et al., 2014). EQS are generally meaningful to society and can reasonably express a common threshold to assess regulating ES mismatches across different societal contexts as they provide a benchmark representing the minimum desirable environmental quality conditions under which some components of human well-being such as health can be secured, hence allowing comparative analyses; (3) this approach allows relatively quick assessments of ES demand if data on environmental quality is available at the city level. In contrast, other demand-side assessments like socio-cultural elicitation are usually more time consuming and resource intensive (Martín-López et al., 2014).

However, the use of EQS in ES assessments has also drawbacks. The existence of different EQS regulating the same environmental condition (or ecological pressure) can create uncertainty about which thresholds are more adequate in terms of expressing a societal demand related to human needs for well-being. In this paper, both WHO and EU standards for air quality have been used giving different ES mismatch results for some air pollutants. Although only EU standards are legally binding for case study cities, WHO standards are probably more reliable expressing a desirable or required end condition of air quality (Brunekreef and Holgate, 2002). The main shortcoming of local GHG emission reduction targets is that often they are not based on scientific evidence about possible climate change impacts, but on political reasons. Regarding urban temperature regulation, the multiple factors involved in the relationship between temperature extremes and human health vulnerability call for specific temperature thresholds to properly account for varying environmental conditions and societal demands at the local level.

More generally, the use of specific or local-based thresholds is possibly the most appropriate option when assessing ES for which demand is strongly context/user/stakeholder dependent (Paetzold et al., 2010), despite it would make cross-city comparisons less meaningful. This is clearly the case of cultural ES. For example, several standards have been suggested as thresholds for assessing the desirable amount of recreational opportunities delivered by green space in urban areas, normally based on criteria of accessibility to green space (i.e., distance) and space size (Van Herzele and Wiedemann, 2003; Söderman et al., 2012; Kabisch and Haase, 2014). The former is commonly seen as the most important factor related to the recreational use of urban green space and a maximum 300-400 meter distance from home has been observed as a threshold after which the use decreases substantially (Schipperijn et al., 2010). Some regulatory agencies have consequently recommended standards based on these criteria. For example, the European Environment Agency (EEA) recommends that people should have access to green space within 15 min walking distance (Stanners and Bourdeau, 1995) and the English standard ANGSt (Accessible Natural Greenspace Standard, Natural England, 2010) recommends that urban population should have an accessible green space no more than 300 m from home (Barbosa et al., 2007). However, these standards have been criticized because they fail to address issues such as green space quality or local context and needs (Pauleit et al., 2003). Still, some authors claim that green space recreational standards are needed but they should be locally developed according to specific social and quality criteria (Baycan-Levent and Nijkamp, 2009). Therefore, a possible extension of the approach presented in this paper beyond regulating ES should be carefully designed.

4.3. Spatially explicit ES mismatches

The spatial distribution of ES supply and demand at the city level has not been addressed in this paper. Yet, for some ES such as air purification or urban temperature regulation both their supply and demand can substantially vary across the urban fabric. The use of spatially explicitly indicators could show the specific location of ES mismatches at the inner-urban level (or higher scales), hence informing about ES deficit areas (demand is higher than supply) to urban planners and managers. Several attempts of mapping ES mismatches have already been developed at different spatial scales (e.g., Kroll et al., 2012; García-Nieto et al., 2013; Boithias et al., 2014; Schulp et al., 2014). However, assessments at the core city scale are scarce, probably due to the lack of fine-resolution data for the appropriate quantification of ES supply and demand indicators.

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5. Conclusion

This paper provides an innovative approach for assessing mismatches in regulating ES supply and demand using EQS as a common minimum threshold for determining whether the difference between supply and demand is problematic in terms of human well-being. The approach has revealed to be appropriate for the ES air purification, for which there is a large body of evidence on the health impacts of air pollution and EQS are well-established at the international level. Similarly, local GHG reduction targets can reasonably express a demand for mitigating the impacts of climate change in urban areas (global climate regulation), thus the assessment of ES mismatches was also possible. The application of the approach for the ES urban temperature regulation has proved more problematic. The demand for urban temperature regulation is strongly context and user dependent, thus common thresholds (such as heatwave thresholds) are less appropriate. Furthermore, the spatial scale to which the ES is delivered is still not totally clear in terms of scientific evidence, creating uncertainties in the ES mismatch assessment. In general, more empirical studies are needed to improve GI design and monitor its effectiveness in meeting local or international environmental standards and goals in different urban areas.

The case study of five European cities reveals mismatches between ES supply and demand in half of the 28 ES/EQS/City combinations analyzed, suggesting that further protection and restoration of urban GI will be required if ES are to play a more relevant role in meeting EQS to enhance human well-being in cities. However, the assessment indicates that ES supply contributes very moderately in relation to the compliance with the EQS in most part (12 out of 14) of the identified mismatches. Results suggest that EQS could be met after the implementation of feasible measures intended to increase ES supply only in two analyzed cases. Therefore, this research suggests that regulating ES supplied by urban GI are expected to play only a minor or complementary role (currently and potentially) to other urban policies intended to abate air pollution and GHG emissions at the city scale. Urban managers and policy-makers should take into account these considerations when designing and implementing GI programs, but recognizing at the same time the multiple benefits associated to GI in urban contexts not addressed in this assessment (e.g., runoff mitigation, noise reduction and recreational opportunities).

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Appendix. Quantification of ES supply and demand indicators

Table A1

ES supply indicators for the five case study cities

ES	Indicator	Barcel.	Berlin	Stockh.	Rotter.	Salzb.	Mean
Air purification	**PM_{10} removal** kg ha^{-1} $year^{-1}$ (Mg $year^{-1}$)	16.42 (166.01)	18.97 (1690)	10.93 (235.77)	3.71 (101.74)	6.92 (45.46)	11.39 (447.80)
	NO_2 removal kg ha^{-1} $year^{-1}$ (Mg $year^{-1}$)	5.40 (54.59)	8.36 (745)	6.29 (135.78)	2.24 (61.37)	4.12 (27.05)	5.28 (204.76)
	O_3 removal kg ha^{-1} $year^{-1}$ (Mg $year^{-1}$)	7.18 (72.62)	21.96 (1,957)	12.67 (273.44)	2.99 (81.94)	0.12 (0.78)	8.98 (477.16)
Global climate regulation	**Net CO_2 sequestration** t ha^{-1} $year^{-1}$ (t $year^{-1}$)	1.97 (19,986)	3.66 (325,726)	3.06 (66,131)	1.05 (29,218)	2.39 (15,673)	2.43 (91,347)
	Carbon storage t ha^{-1} (Mg)	11.22 (113,437)	32.84 (2,925,924)	28.84 (622,326)	9.38 (257,071)	21.99 (144,421)	20.85 (812,636)
Urban temperature regulation	**Tree shade area** % (ha)	29.40 (2,973)	42.70 (38,048)	37.50 (8,093)	12.20 (3,343)	28.60 (1,878)	30.08 (10,867)

Note: see references and corresponding time-ranges in **Table 2**.

Table A2

ES demand indicators for the five case study cities

ES	Indicator	Barcel.	Berlin	Stockh.	Rotter.	Salzb.	Mean
Air purification	**PM_{10} annual mean concentration** $\mu g\ m^{-3}$	32.76	30.11	28.45	28.45	23.86	28.72
	NO_2 annual mean concentration $\mu g\ m^{-3}$	53.78	53.38	38.50	48.66	45.21	47.90
	26th highest O_3 value based on daily max 8-hour averages $\mu g\ m^{-3}$	89.60	116.14	95.14	84.74	111.63	99.45
Global climate regulation	**CO_2-eq. emissions per ha.** t ha^{-1} $year^{-1}$	398.99	214.70	128.59	1,067.35	86.59	379.25
	CO_2-eq. emissions per capita t $capita^{-1}$ $year^{-1}$	2.51	5.40	3.40	48.51	3.82	12.73
Urban temperature regulation	**Heat wave risk** days	>50	2-6	0-2	2-6	2-6	N/A

Note: see references and corresponding time-ranges in **Table 3**.