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REVIEW

Quantifying urban ecosystem services based on high-resolution data of urban green space: an assessment for Rotterdam, the Netherlands

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Summary

1. The urban dimension of ecosystem services (ES) is underexposed, while the importance of ES for human well-being is nowhere as evident as in cities. Urban challenges such as air pollution, noise and heat can be moderated by urban green space (UGS), simultaneously providing multiple other services. However, available methods to quantify ES cannot typically deal with the high spatial and thematic resolution land cover data that are needed to better understand ES supply in the urban context.

2. This study derives methods to quantify and map a bundle of six ES as supplied by UGS, using land cover data with high spatial and thematic resolution, and applies these to the city of Rotterdam, the Netherlands. Land cover data comprise eight classes of UGS. Methods are derived from an evidence base on the importance of UGS types for the supply of each of the six ES that was built using literature review.

3. The evidence base reveals that UGS types differ in their contribution to various ES, although the strength of the evidence varies. However, existing indicators for urban ES often do not discriminate between UGS types. To derive UGS-specific indicators, we combined methods and evidence from different research contexts (ES, non-ES, urban, non-urban).

4. Rotterdam shows high spatial variation in the amount of UGS present, and accounting for this in ES supply reveals that ES bundles depend on UGS composition and configuration. While the contribution of UGS types to ES supply differed markedly with UGS type and ES considered, we demonstrate that synergies rather than trade-offs exist among the ES analysed.

5. *Synthesis and applications*. Our findings underline the importance of a careful design of urban green space (UGS) in city planning for ecosystem services (ES) provision. Based on the latest insights on how different UGS provide ES, the methods presented in this study enable a more detailed quantification and mapping of the supply of ES in cities, allowing assessments of current supply of key urban ES and alternative urban designs. Such knowledge is indispensable in the quest for designing healthier and climate-resilient cities.

Key-words: climate adaptation, ecosystem services bundles, green infrastructure, mapping, spatial planning, trade-off analysis, urban ecology, urban greening

Introduction

In recent years, many studies have developed methods for the quantification (e.g. Willemen *et al.* 2008; Gómez-Baggethun & Barton 2013) and valuation (e.g. Boyd & Banzhaf 2007; Johnston & Russell 2011) of ecosystem services (ES). Most publications aim at quantifying ES at regional or national scales with a focus on natural and rural landscapes. Less than 10% of all ES publications deal with urban ES (Gómez-Baggethun & Barton 2013; Hubacek & Kronenberg 2013). This is surprising, as the importance of studying ES for human well-being seems most evident in cities. An important part of changes in land use and ecosystems is driven by urbanization (Larondelle & Haase 2013) causing typical city problems such as air pollution,

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noise and heat stress that may be moderated by urban ES.

The limited attention received by urban ES may be explained by the small size of urban ecosystems and the relatively low ecological value (Davies *et al.* 2011). Many of the available studies on urban ES relate to the benefits provided by urban green space (UGS) (e.g. Bolund & Hunhammar 1999; Priego, Breuste & Rojas 2008). Vegetated and water-rich areas are the most appreciated natural elements in cities (Swanwick 2009). These UGS are known to improve people's physical and mental health, moderate the urban heat island effect, heighten the quality of life, facilitate social inclusion and boost real estate prices (e.g. Bowler *et al.* 2010; Chang & Chou 2010; Tzoulas *et al.* 2007). UGS provides essential ES to counter challenges that need to be addressed *in situ* at the time that the nuisance occurs, such as noise, heat stress and excessive storm water run-off, and is therefore a good starting point for urban ES assessments (Andersson *et al.* 2014a; Niemelä 2014).

Among those studies undertaken in cities, very few consider a broad bundle of ES required for human well-being, go beyond the use of arbitrary classifications and coarse land cover data, or apply methods that allow to spatially link ES supply with demand (Haase *et al.* 2014; Seppelt *et al.* 2011; but see for an exception McPhearson, Kremer & Hamstead 2013). For policymakers, land managers and environmental educators to work with the ES concept, knowledge must be provided in a form that suits their specific needs (Burkhard, Petrosillo & Costanza 2010). Mapping exercises that depict which ES bundles are supplied, on which location, in what quantity and by which UGS type can support decision-making by guiding the way to a more optimal allocation and design of UGS. Although requests from policymakers for such tools are considerable, ES maps still suffer from a lack of spatial and thematic detail to account for the fine-scale green features that supply ES in cities close to people's demand (Burkhard *et al.* 2012; Gaston, Ávila-Jiménez & Edmondson 2013).

This study aims to address the research gaps identified above by (i) developing methods to quantify a bundle of six urban ES, as supplied by different UGS types; (ii) determining the spatial distribution of ES supply by mapping them on the city scale using high-resolution data and (iii) identifying synergies and trade-offs between the type and quantity of UGS and ES supply. We first review the literature on the relevance of UGS for the supply of six ES and derive from insights on the underlying processes the evidence base to quantify and map the provision of these ES by various UGS types for the city of Rotterdam, the Netherlands. Subsequently, we apply these insights to identify possible synergies and trade-offs in urban ES supply for different neighbourhoods in Rotterdam. As such, this study translates empirical evidence of ES supply into practical methods that enable the assessment and enhancement of ES supply in cities.

Materials and methods

STUDY AREA AND DATA SOURCES

Rotterdam (Fig. 1) is the second largest city of the Netherlands and Europe's major port. The city covers 326 km^2 and has a population of over 600 000 (1·3 million in metropolitan area).

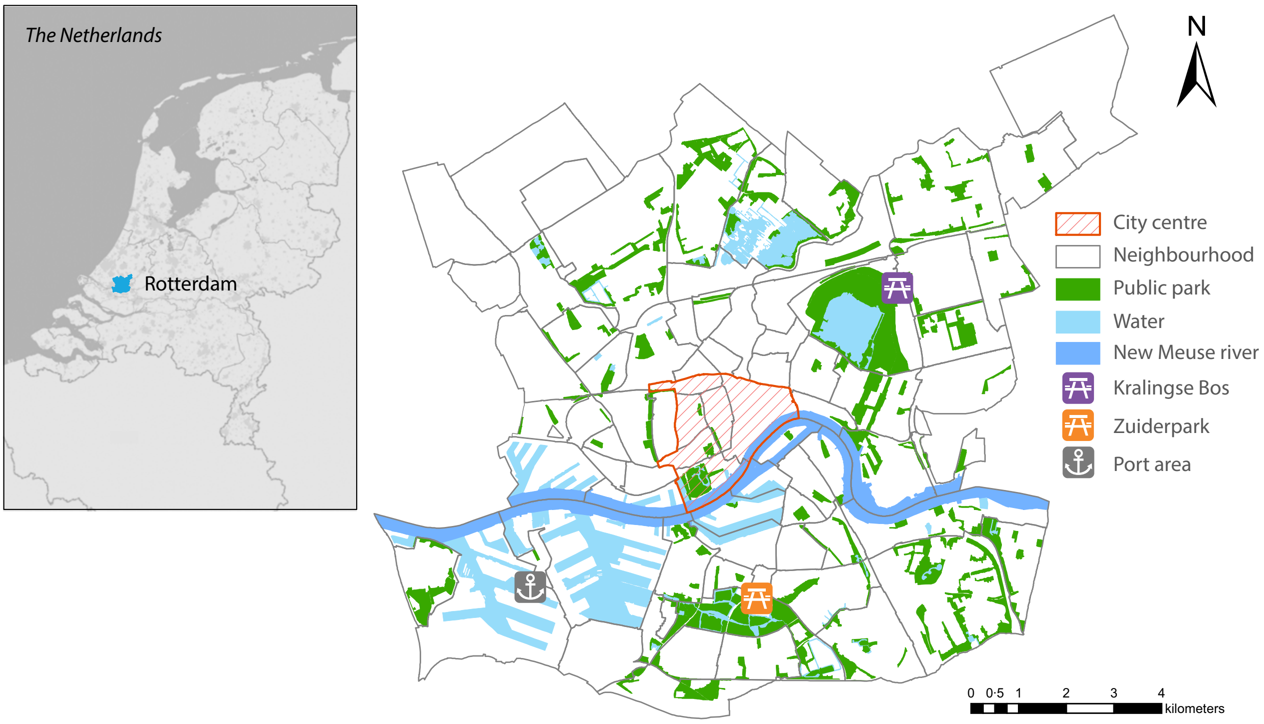

Fig. 1. Map of Rotterdam, the Netherlands, highlighting key characteristics.

Rotterdam is a commercial and industrial hub at the New Meuse River, a modern city famous for its architecture rather than greenness. With the 'Rotterdam Climate Change Adaptation Strategy', the city invests in climate-proofing against its major challenges: heat stress, flooding and air and noise pollution. To characterize UGS and map ES, we used data that represent the spatial occurrence of different UGS types. Data of eight UGS categories, that is high thematic detail, were compiled from urban green maintenance maps, cadastral maps and land use maps (Table 1, Fig. 2, Appendix S1, Supporting Information). All urban green elements were available as polygon or point data delimiting each UGS element (i.e. high spatial resolution).

QUANTIFICATION OF URBAN ECOSYSTEM SERVICES

We selected six ES given their relevance for human health and well-being in cities: air purification, carbon storage, noise reduction, run-off retention, cooling and recreation. For each of these ES, we reviewed the literature to devise methods to quantify and map the services (See Table 2 for a summary of quantification methods; and Appendix S2 for details on the literature used, assumptions made and methods applied).

Air purification

Waste treatment, industry, transport and residential heating installations pollute the urban air and lead to increased occurrences of cardiovascular and respiratory disease (Leiva G *et al.* 2013). Vegetated areas improve air quality by filtering atmospheric particulates such as nitrogen dioxide (NO_2), particulate matter (PM_{10}) and sulphur dioxide (SO_2). Vegetation takes up more pollutants when pollution concentrations are high (Tallis *et al.* 2011), which supports having trees near an emission source to benefit citywide average air quality. However, at the very local scale, trees may hamper emissions mixing with the surrounding atmosphere, leading to high localized pollution concentrations (Vos *et al.* 2013). We define air purification as the lowering of background air pollution concentrations.

We focus on PM_{10} because it is most harmful to citizens' health and most effectively captured by UGS. Pollutant uptake increases with greater leaf area so that tall plants and trees are most efficient. Most studies use mathematical derivations and the Urban Forest Effects (UFORE) or i-Tree model (see Nowak & Crane 2000) to calculate air pollutant capture by UGS. A drawback of these methods is that the heterogeneous UGS pattern throughout the city is not taken into account. Therefore, we distinguished between different UGS types and their air pollution capture capacities, expressed as g PM_{10} captured per m^2 UGS per year (Table 2 and Appendix S2). To account for the influence of pollution concentration, we used a 50-m buffer around main roads (see Appendix S1) within which the air purification rates of UGS were considered twice as high as reported in Table 2.

Carbon storage

Although the contribution of UGS in overall carbon storage is relatively small and undervalued in national assessments, its potential as a carbon reservoir is significant (Hostetler & Escobedo 2010). In quantifying carbon storage, two factors are important, the first being biomass volume, which is proportional to the carbon storage capacity of trees. The second factor is vegetation type. Almost all above-ground carbon storage takes place in trees and only a small percentage is stored in shrubs and herbaceous vegetation. Especially in cities, it is important to realize that typical UGS such as pruned trees, lawns, and flower beds generally do not sequester much CO_2 and its maintenance can even emit sizeable amounts of CO_2 and N_2O through fertilization practices (Jo & Mcpherson 1995; Escobedo, Seitz & Zipperer 2012). Yet, soils do contain a large carbon stock, particularly the soil beneath lawns (Pouyat, Yesilonis & Nowak 2006). However, quantifying soil carbon in urban contexts is complex, as urban soils are often mixed and disturbed. We, therefore, define this ES as gross above-ground carbon storage and consider the amount of carbon stored rather than its dynamics in time.

We applied UGS-specific carbon storage estimates to all UGS categories except water. Rates are expressed as kg carbon per m^2 and derived from studies presenting estimates for cities comparable to Rotterdam (Table 2).

Table 1. Description of urban green space (UGS) data*

UGS type	Description	Data base†	Type	Year
Tree	Individual tree, mostly street trees	Public works	Line	2008–2012
		Tree maintenance	Point	2012
Woodland	Clustered trees, urban forest	Green maintenance	Polygon	2012
Tall shrub	Shrub or hedge sized 2–5 m	Green maintenance	Polygon	2012
Short shrub	Shrub or hedge sized <2 m	Green maintenance	Polygon	2012
Herbaceous	Low vegetation consisting of non-woody plants, mostly grasses and herbs	Green maintenance	Polygon	2012
Garden	Domestic garden consisting of a mix of vegetation, water and sealed surface	Plot boundaries	Polygon	2010–2012
		Building boundaries	Polygon	2012
Water	Pond, lake, canal, river	Land use Rijnmond‡	Polygon	2008
		Land use Rijnmond‡	Polygon	2009
		Land use Rotterdam	Polygon	2012
Other	Allotment garden, sports field, zoo, golf course, cemetery	Land use Rotterdam	Polygon	2012

*See Appendix S1 for background information on data sets.
†Made available by Rotterdam municipality.
‡Available online from *Geoplaza*: http://geoplaza.vu.nl/cdm/search/collection/gpz/collection/gpz.

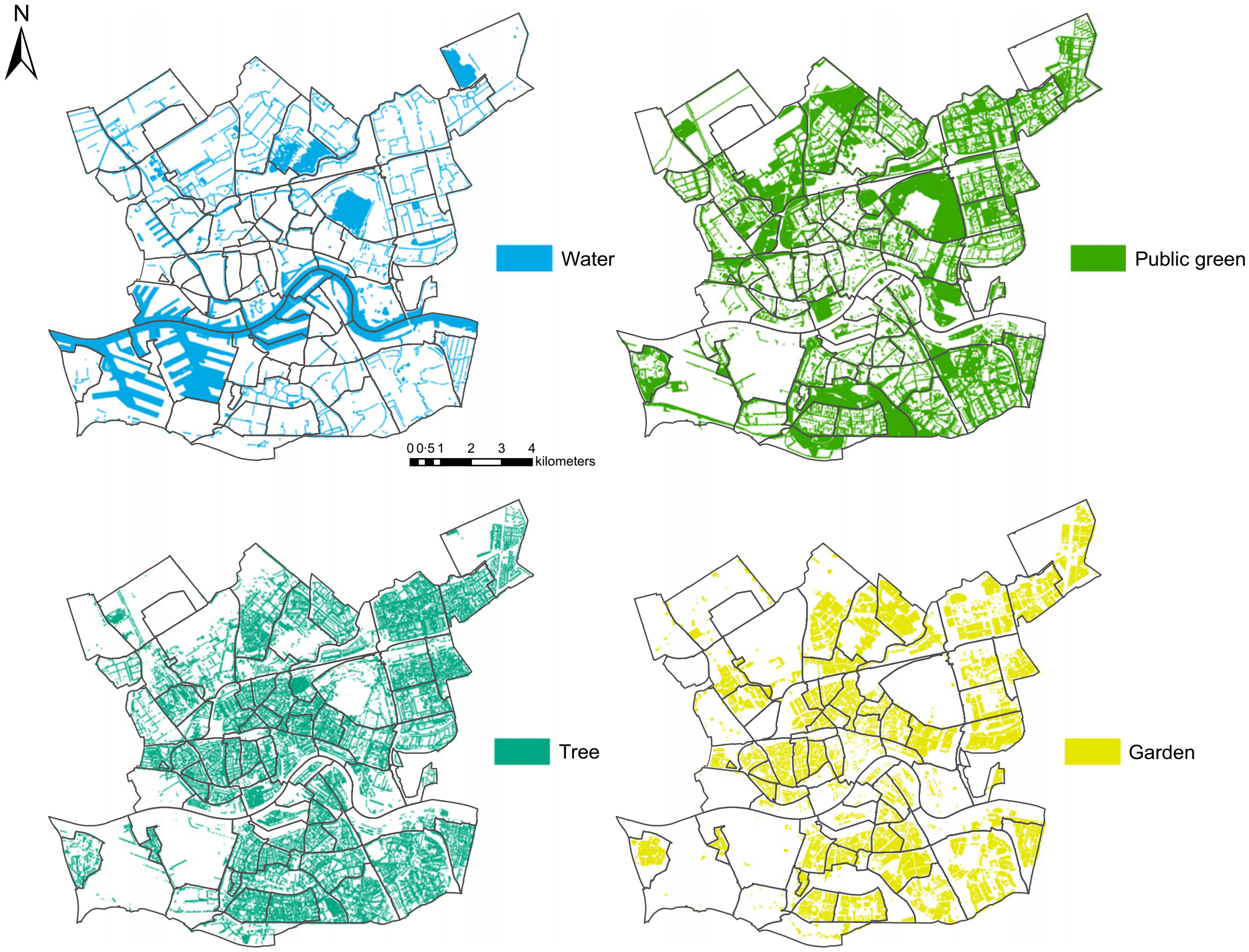

Fig. 2. Maps of Rotterdam neighbourhoods with water, public green, tree and garden cover. Public green comprises the urban green space categories 'woodland', 'tall shrub', 'short shrub', 'herbaceous' and 'other'.

Noise reduction

Nuisance from noise is detrimental to neighbourhood liveability, living comfort and work environments and can increase risk of serious health problems such as hearing loss and cardiovascular disease (Bolund & Hunhammar 1999). Urban ecosystems provide noise reduction services by serving as natural sound buffers (Van Renterghem, Botteldooren & Verheyen 2012). Vegetation provides both a direct and an indirect barrier to environmental noise. Starting with its direct functions, green belts attenuate noise by absorption, dispersal and destructive interference of sound waves, though sound levels can intensify locally if measured right below tree crowns. Indirect noise reduction effects are generated by lessened wind speeds and the absorptive capacity of pervious soils (Aertsens *et al*. 2012).

Several factors influence the acoustic effect of UGS (Chaparro & Terradas 2009; Aertsens *et al*. 2012): (i) distance: the closer vegetation is placed to a noise source, the more noise it mutes; (ii) the frequency (Hz) of noise emissions and (iii) vegetation characteristics. Other factors that affect noise reduction are sound duration, climate (temperature, humidity, wind direction, wind speed) and soil type (Van Renterghem, Botteldooren & Verheyen 2012). We define the ES noise reduction as the physical capacity of vegetation to attenuate environmental noise.

We accounted for two factors that influence noise reduction services: vegetation characteristics and distance to the noise source. Our analysis focuses on road traffic noise as this is a constant source and most disturbing to people (Van Wijk 2012). A 50-m buffer around main roads (Appendix S1) ensured that only UGS within a short distance from the noise source contributed to our estimate. Most noise attenuation effects are measured up to a distance of 50 m from the road, and in a dense urban environment, most sound waves are blocked by buildings beyond that distance (Fang & Ling 2003). Single rows of trees are not effective in reducing noise levels; therefore, we set noise reduction by individual trees to zero. The same applies to gardens, as traffic noise generally does not reach gardens. This leaves five UGS categories for which we used mean values derived from a range of noise attenuation rates in the literature and expressed as attenuated dB(A) per 100 m^2 (Table 2).

Run-off retention

In cities, natural drainage is severely hindered by large-scale sealing – with sewer overflow, street pollutant wash-off, obstruction of groundwater recharge and damage to homes and businesses as possible consequences (Chaparro & Terradas 2009). UGS mitigates these undesirable effects and supports

Table 2. Overview of ecosystem service (ES) indicators and supply rates, specified per urban green space (UGS) type

UGS type	Air purification* (g m^{-2} year^{-1})	Carbon storage (kg m^{-2})	Noise reduction* (dB(A) 100 m^{-2})† (range)	Run-off retention[p] (L m^{-2})	Cooling (UGS fraction: weight)	Recreation*[q] (Index value m^{-2})
Tree	3·97[a,b]	10·64[f,g,h,i,j,k]	–	8·4‡	1·0	2·15
Woodland	2·69[b]	15·62[g,i,j]	1·125 (0·75–1·50)[m]	8·7	1·0	2·90
Tall shrub	2·05[c,d]	7·79[g]	2·000 (1·50–2·50)[m,n]	7·3	1·0	2·55
Short shrub	2·05[c,d]	5·61[g]	1·125 (0·75–1·50)[m]	7·3	1·0	2·55
Herbaceous	0·90[a,e]	0·17[g,l]	0·375 (0·00–0·75)[m,o]	8·0	0·5	2·55
Garden	0·82§	1·07[g,j]	–	6·0	0·5	–
Water	–	–	–	10·0	–	2·20
Other	0·82§	1·07 [g,j]	0·375 (0·00–0·75)[m]	6·0	0·5	2·35

*Rate is dependent on UGS location (air purification rate doubles for UGS within 50-m road buffer; noise reduction rate only applies to UGS within 50-m road buffer; recreation rate doubles for UGS within municipal parks).
†dB(A) stands for A-weighted decibels and is used to express sound as perceived by the human ear, by reducing the decibel values of low-frequency sounds.
‡Expressed per tree instead of per m^2 crown area because most individual trees stand in small pits within paved surfaces and are therefore less effective in mitigating surface run-off; however, the rate should be seen as a minimum as it is based on a small canopy tree and therefore likely underestimates the service.
§Rate is based on garden composition (Appendix S2).
[a]McDonald *et al.* (2007); [b]Tallis *et al.* (2011); [c]Escobedo & Nowak (2009); [d]Baumgardner *et al.* (2012); [e]Stewart *et al.* (2002); [f]Chaparro & Terradas (2009); [g]Davies *et al.* (2011); [h]Nowak *et al.* (2013); [i]Raciti *et al.* (2012); [j]Strohbach & Haase (2012); [k]Zhao *et al.* (2010); [l]Jo & Mcpherson (1995); [m]Fang & Ling (2003); [n]Aertsens *et al.* (2012); [o]Bolund & Hunhammar (1999); [p]Tratalos *et al.* (2007); [q]Recreation index is based on: Burgess, Harrison & Limb (1988); Richards & Curson (1992); Gobster (1995); Coles & Bussey (2000); Roovers, Hermy & Gulinck (2002); Akbar, Hale & Headley (2003); Van Herzele & Wiedemann (2003); Todorova, Asakawa & Aikoh (2004); Jim & Chen (2006); Tyrväinen, Mäkinen & Schipperijn (2007); Kong, Yin & Nakagoshi (2007); Priego, Breuste & Rojas (2008); Swanwick (2009); Qureshi, Hasan Kazmi & Breuste (2010); Jacobs *et al.* (2010); Grahn & Stigsdotter (2010); Korpela *et al.* (2010); Aertsens *et al.* (2012); Kienast *et al.* (2012); De Vries *et al.* (2013).

cities in adapting to climate change through natural storm water management (Bolund & Hunhammar 1999). Vegetation intercepts rainfall and gradually releases it to the ground as stem flow or by falling and stores rainwater in its branches and leaves to later evaporate (Xiao & McPherson 2003). Rainfall also directly infiltrates the permeable soil underneath vegetation. Factors influencing the run-off regulation function are intensity and duration of precipitation events, climate, slope and vegetation characteristics. Trees contribute largely through interception, while grass absorbs most of the rainwater through infiltration (Armson, Stringer & Ennos 2013). Water bodies support retention through their storage capacity (Everard & Moggridge 2012). The topography of Rotterdam includes hardly any sloping; hence, we define the ES run-off retention as the combined effect of rainfall interception, infiltration and storage by water bodies.

We estimated the combined effect of interception and infiltration services based on the approach of Tratalos *et al.* (2007). Run-off calculations were made for a 10-mm rainfall event which indicates a typical 'wet day' in the Netherlands. For extreme rainfall events, the ES is more critical, but also in case of moderate rainfall, the service is important in limiting water treatment and drainage costs. We adopted run-off coefficients used by Tratalos *et al.* (2007) and calculated run-off retention rates for the UGS types, expressed as litres of retention per m^2 (Table 2 and Appendix S2). Water bodies were included and appointed the highest rate as they capture all rainfall for such an event (Pauleit & Duhme 2000).

Cooling

Climate change is expected to lead to an increase in the frequency and intensity of heatwaves (IPCC 2012), leading to increased energy costs and enhanced morbidity and mortality. The urban heat island (UHI) effect is caused by paved surfaces that impede evapotranspiration, dense structures that reduce wind speed and dark building materials that absorb solar energy in the daytime and release the heat gradually at night, slowing down the air cooling process. For example, an UHI of 7 °C has been measured in London (Wilby 2003) and Rotterdam (Klok *et al.* 2012). UGS provides a cooling effect at local to regional scales that moderates the UHI, enhances human comfort and reduces energy demand (Armson, Stringer & Ennos 2012).

Vegetation regulates the urban microclimate in three ways: (i) by intercepting incoming solar radiation (shading); (ii) through the process of evapotranspiration and (iii) by altering air movement and heat exchange. Shading and evapotranspiration contribute most to the cooling effect (Skelhorn, Lindley & Levermore 2014). Vegetated patches have a cooling effect of 1–4 °C that lessens with increasing distance and depends on surface area, vegetation type and spatial conjunction (Xie *et al.* 2013). The cooling effect of herbaceous plants occurs mostly in smaller patches and not so much in park lawns because short grasses tend to heat up easily. Water can contribute to a cooler microclimate through evaporation, movement and heat absorption, but its effectiveness is contested (Steeneveld *et al.* 2014). We define the ES 'cooling' as temperature reduction by vegetation through shading and evapotranspiration and consider the cooling effect of water bodies to be zero.

We estimated Rotterdam's cooling service by calculating total UGS cover (Table 2). This included the surface area of trees, shrubs and woodland. Herbaceous vegetation, gardens and other green areas were given a weight of 0·5 because these are primarily composed of lawns which have a low cooling potential (Skelhorn, Lindley & Levermore 2014).

Recreation

Recreation opportunity may be the greatest perceived benefit of UGS (Andersson *et al.* 2014b). Research points out that spending time in green areas results in improved physical and mental health, and cities become more attractive when offering ample recreation opportunities. Recreation opportunity is a cultural ES closely related to aesthetics; scenic beauty generally increases a site's recreation potential. Although area size is important, informal UGS such as allotments and neighbourhood green is found to be equally as attractive for recreational purposes as formal UGS such as parks (Van Herzele & Wiedemann 2003).

Here, we consider the potential of UGS for everyday outdoor recreation of short duration, such as (dog) walking, physical exercise and relaxation. Most quantification methods in the literature are fairly coarse, using proxies such as UGS area per capita (e.g. Haase *et al.* 2012; Dobbs, Kendal & Nitschke 2014), number of people within a given distance from UGS (e.g. Maes *et al.* 2013) or number of UGS within a given distance from census tracts (e.g. La Rosa 2014). Such methods do not distinguish between specific UGS types. Alternatively, recreation supply is quantified using relations between landscape structure and perception. Whereas most preference studies refrain from differentiating between vegetation types, they do provide a more detailed insight into which landscape features influence a site's attractiveness and we could deduct the following generalizations: (i) people slightly prefer a vegetation landscape over a water landscape; (ii) people prefer a high degree of naturalness; (iii) people prefer variation and an open structure. In the absence of appropriate quantitative data on how much particular UGS types are valued over others, we transferred the above-mentioned findings into an indicator that can be applied to the UGS categories (Table 2). Because parks are more likely to feature a combination of vegetation, water, naturalness, variation and an open structure than for example street vegetation, we doubled the index value of UGS elements located within Rotterdam's parks.

MAPPING AND ANALYSIS METHODS

The ES indicators devised from the literature and described in the previous section were applied to high-resolution UGS data within a GIS environment (ESRI ArcMap 10·1). In the first step, the ES supply per UGS element was calculated by multiplying the area of each element by the ES supply per m^2 of the respective UGS type, as listed in Table 2 (see Appendices S1 and S2 for details on data handling and quantification methods). Subsequently, ES supply by individual UGS elements was aggregated to neighbourhood (n = 81) and district (n = 17) level and normalized by area to enable comparison. Results are interpreted at individual ES level as well as at ES bundle level, in terms of spatial patterns. To identify ES bundles, we performed a cluster analysis on neighbourhood level that differentiates between ES bundle types using a K-means cluster analysis. To facilitate the cluster analysis, we normalized ES values on a scale 0–1 using minimum and maximum scores.

Results

ECOSYSTEM SERVICE QUANTIFICATION

The capacity to deliver ES differs per UGS type (Table 2). While some UGS types are able to provide several services in high quantities, particularly individual trees and woodland, there is no single best UGS type that outperforms all others for each ES. Individual trees do not contribute to noise reduction, while per unit area woodland is less effective in air purification than individual trees and reduces noise less effectively than tall shrubs. Tall shrubs supply ES in equal or larger quantities than short shrubs, herbaceous vegetation and gardens. The only exception is that herbaceous vegetation contributes more to run-off retention. Water bodies contribute to run-off retention and recreation only and are the most effective UGS type for run-off retention.

At the city scale, UGS types rank differently in the quantity of ES supplied, which is due to large differences in coverage (see Table 3 for UGS area and relative ES contribution). While shrub land has much potential (Table 2), tall and short shrubs together comprise only 3·9% of UGS in Rotterdam, thus having relatively little effect at the city scale (Table 3). Individual trees are very effective ES suppliers: while comprising only 13% of all UGS, they contribute mostly to air purification, carbon storage and cooling. Water bodies are the most abundant UGS type (29·2%) and responsible for the largest shares in run-off retention and recreation. While herbaceous vegetation does not provide ES in high quantities per unit area (Table 2), due to its abundance (18·3%), it contributes most to noise reduction (35%) and second most to recreation and air purification (Table 3).

Table 3. Ecosystem service (ES) supply capacity in Rotterdam per urban green space (UGS) type

			Relative contribution of UGS types to ES					
UGS type	Area (in ha)	Area (in % of total UGS)	Air purification	Carbon storage	Noise reduction	Run-off retention	Cooling	Recreation
Tree	891	13·0	45·4	49·5	–	0·3	28·0	14·4
Woodland	359	5·2	12·5	29·3	26·9	6·5	11·3	11·1
Tall shrub	56	0·8	1·5	2·3	7·8	0·8	1·7	1·2
Short shrub	210	3·1	5·5	6·1	14·8	3·2	6·6	3·9
Herbaceous	1270	18·5	15·2	1·1	35·0	21·3	19·9	27·1
Garden	1257	18·3	11·9	7·0	–	15·8	19·7	–
Water	1999	29·2	–	–	–	41·8	–	30·4
Other	815	11·9	8·0	4·6	15·4	10·2	12·8	12·0

SPATIAL PATTERNS IN ECOSYSTEM SERVICE SUPPLY

For certain ES, the spatial arrangement of UGS is a key determinant in service supply (Andersson *et al.* 2014a). For air purification, for example, UGS filters more pollutants from the air when located in the vicinity of a pollution source, in this case the main road (Fig. 3). Supply of several other ES is also affected by UGS type, size and location but in different ways. For example, for carbon storage, it does not matter whether a city boasts a few large or many small green areas, whereas noise reduction is best supplied by long, continuous vegetation strips.

Differences in the availability of UGS between neighbourhoods (Fig. 2) and the differences in ES supplied by UGS types create considerable spatial variation in ES supply across the city (Fig. 4). The ES supply score generally

Fig. 3. Detailed map illustrating the distribution of urban green space (UGS) elements and air purification supply in relation to UGS. Upper: distribution of UGS, residential buildings, major roads. Lower: air purification supply per individual UGS element normalized for element area and proximity to air pollution source.

Fig. 4. Supply of six ecosystem services, aggregated to neighbourhood level.

increases with increasing distance from the city centre because central neighbourhoods are the most densely built-up and hence least green. The north-west region, which is characterized by agriculture, business areas and the airport, scores lowest for each ES whereas the natural area of *Kralingse Bos* east of the centre scores highest. Also the *Zuiderpark* neighbourhood in the south supplies relatively many ES, whereas the area next to it in the south-west supplies relatively few. ES specific patterns can be detected for air purification, which is in high supply when a dense road network coincides with a high fraction of tall vegetation, which is the case just outside the city centre and less in areas along the river. Run-off retention shows a contrasting pattern with high supply in neighbourhoods with a large water fraction along the central east–west (river) axis. Presence of large water surfaces also boosts recreation potential, especially when combined with forested areas.

ECOSYSTEM SERVICE BUNDLES

Rotterdam has distinct spatial discrepancies in terms of ES supply (Fig 5). Certain districts are being completely deprived of UGS and thus of ES, while others have high values for many or even all services. Central districts have average scores. Several districts in the west supply low values of ES, either for all services, or for all except run-off retention and recreation. The latter pattern is explained by the districts' proximity to the river, while UGS abundance is low otherwise.

A cluster analysis at neighbourhood level reveals five types of neighbourhoods with a comparable ES bundle (Table 4; Fig. 6). Cluster 1 is characterized by a large supply of all ES and consists of neighbourhoods that feature major city parks. Cluster 2 is concentrated in the west and has high values for air purification, cooling and noise reduction (due to a higher road density), but relatively low ES otherwise. Cluster 3 comprises many neighbourhoods across Rotterdam and is characterized by a mixed ES bundle with moderate ES supply rates. Cluster 4 is characterized by a high value for run-off retention, a moderate recreation value and low values for other ES, which is due to the high water fraction in these neighbourhoods. Cluster 5 is also large and consists of neighbourhoods with low values for all ES, found across Rotterdam.

Between these six ES, synergies rather than trade-offs occur at the neighbourhood and district scale (Figs 5 and 6). Cooling, carbon storage and air purification demonstrate synergies as these are primarily being supplied by the same UGS types. To a lesser degree, the same applies to noise reduction. Another synergy occurs between recreation and run-off retention, which are most strongly provided by water bodies. At the local scale, the choice for

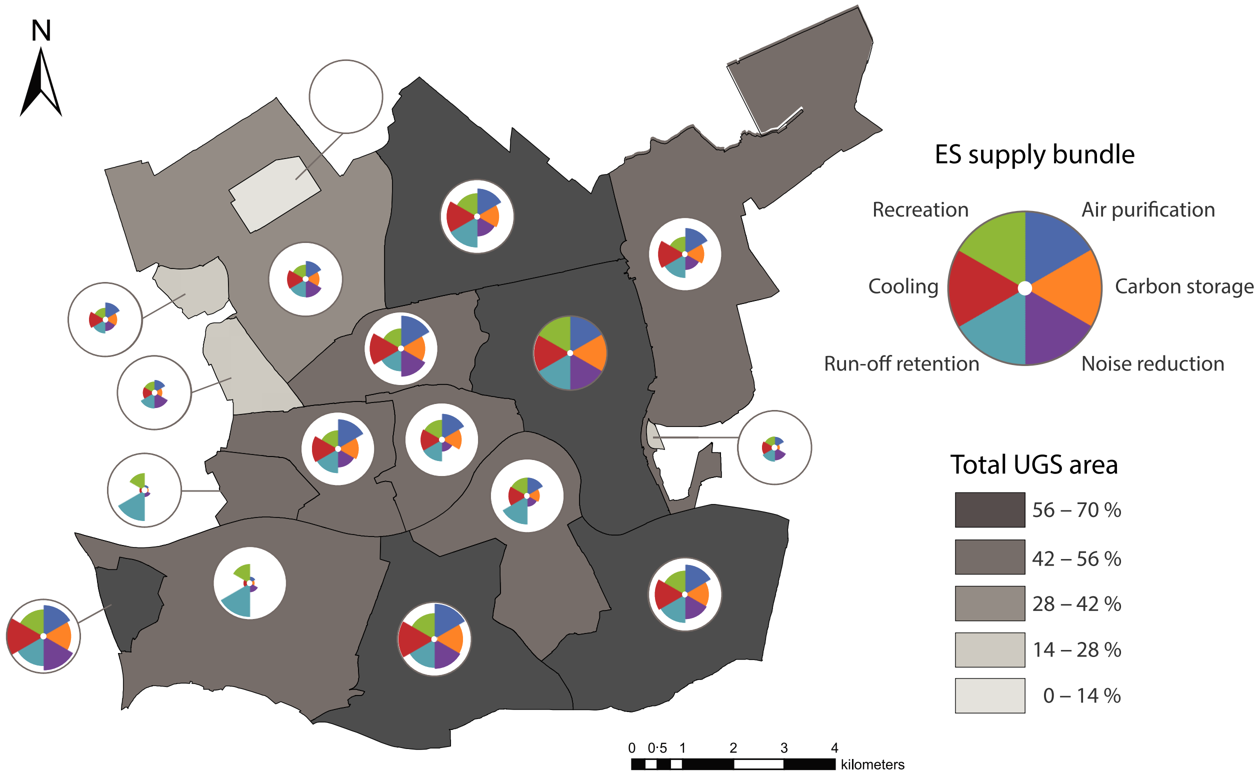

Fig. 5. Supply of ecosystem services bundles, aggregated to district level, with background colours depicting total urban green space area (normalized for district area).

particular UGS types may incur trade-offs between services, as not all UGS types are able to provide all ES (Tables 2 and 3).

Discussion

Our work demonstrates that it is important to differentiate between UGS types and their spatial configuration in the quantification of ES in cities. From the literature, we devised methods to quantify and map the supply of multiple urban ES using high-resolution data (both spatially and thematically) on UGS types. For cities, high-resolution data on green elements are often readily available from public space management plans and cadastral maps (e.g. Kremer, Hamstead & McPhearson 2013; Liu & Yang 2013). While understanding ES supply is nowhere as evident as in cities (Bolund & Hunhammar 1999), there are only a few studies that provide empirical evidence on how specific UGS types provide ES (Demuzere *et al.* 2014). For the six ES studied, no indicators were available in the literature that could quantify these ES based on the UGS data presented here. This necessitated the adaptation and combination of quantification methods from different research contexts and regions to make the best possible use of the data. The quantification methods were based on available empirical evidence in the literature that allowed the quantification of ES based on the most important determinants of ecosystem function of the different green elements.

For the six ES presented, the evidence base to be able to construct the quantification methods differed substantially. Most information is available for carbon sequestration, but primarily for trees and less for other UGS (Table 2). For run-off retention, evidence comes primarily from non-urban contexts (Armson, Stringer & Ennos 2013). For noise reduction and cooling, contradicting evidence for UGS contribution exists, hampering the development of reliable indicators. Recreation indicators often do not distinguish between different UGS types. Often the data available were too detailed for the existing coarse

Table 4. Mean values for each ecosystem service (ES) within each of the clusters. The number of neighbourhoods per cluster is indicated with *n*

ES	Cluster 1 (n = 3)	2 (n = 5)	3 (n = 30)	4 (n = 12)	5 (n = 31)
Air purification	0·82	0·80	0·54	0·18	0·28
Carbon storage	0·75	0·44	0·36	0·11	0·16
Noise reduction	0·52	0·73	0·22	0·11	0·11
Run-off retention	0·86	0·52	0·40	0·80	0·27
Cooling	0·82	0·81	0·58	0·20	0·28
Recreation	0·77	0·29	0·19	0·36	0·10

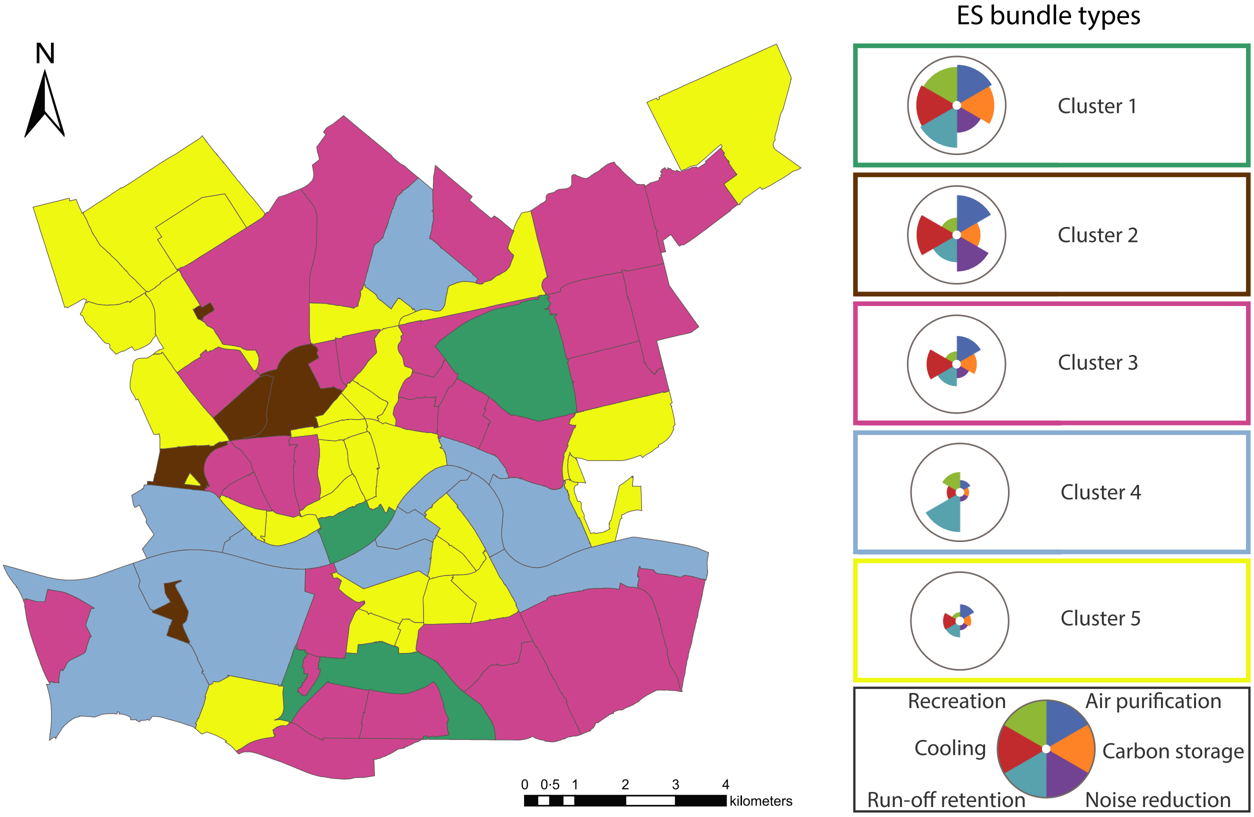

Fig. 6. Spatial distribution of ecosystem services (ES) bundle types and average ES bundle for each cluster (in rose plots).

quantification methods, when ES rates were unavailable for the eight UGS categories or specific tree species that are expected to have differences in ES provisioning. Data limitations were the incomplete canopy size and missing Leaf Area Index data which would have been beneficial in calculating air purification services. Also, more specific soil data would have been helpful for estimating below-ground carbon storage and infiltration capacities for water retention services.

The review of the evidence base in this paper therefore also provides insight into the needs and focus of future empirical studies on the ES capacity of UGS categories to reduce the uncertainties in quantification. The imbalance in availability of data between different ES and for different UGS types follows partly from the bias in frequency with which different ES are studied, and the lack of multi-service studies in the urban context (Haase *et al.* 2014).

While in most ES assessments uncertainties are due to both data quality and assessment methods, the major uncertainties in the urban environment relate to the quantification methods and the available empirical evidence to implement these methods. Available data on the location and characteristics of green elements are very detailed as compared to data available in rural ES assessments and are not considered a limiting factor as long as the different types of data bases are correctly integrated to avoid double counting (e.g. individual tree registries and park area data are overlapping). The uncertainties in the assessment are assumed to be large and difficult to quantify. A major source of uncertainty is the absence of specific values for the city of Rotterdam so that estimates from other studies and cities have been combined to generate an average value for Rotterdam. Only in case of independent measurements of the actual supply of the ES, the validity of the assessment can be indicated. For most ES, such data are not available. Only for cooling, a comparison could be made with measured temperatures as described in Appendix S3. Ecological studies measuring ecosystem functions that can be used as indicators for urban ES are desperately needed in multiple urban contexts, both for improving current indicators, as well for cross-city comparison.

Our results showed mostly synergies rather than trade-offs for the bundle of ES considered. Partly, this is explained by the fact that UGS types provide multiple ES. Additionally, some services are provided by UGS only within a certain radius from the source of nuisance, such as air pollution and noise reduction, which are both related to road traffic. While the processes were devised independently for each ES from relevant literature, these processes happen to operate at similar scales, which explains another part of the synergies found.

Because we studied ES supply within cities we did not take into account green areas in the urban–rural fringe while carbon storage, pollution removal, recreation, etc. are not bound to administrative borders (see Mcdonnell *et al.* 1997; Larondelle & Haase 2013). Hence, our assessment may underestimate the ES supply in some neighbourhoods of the city because non-typical urban green infrastructure such as agricultural land was not considered. Only two outer districts contained agricultural lands (see S3), and given that we otherwise included all UGS types, including private gardens, we expect the underestimation to be limited. Our approach is justified by the primary focus on quantifying the role of typical UGS in the city rather than estimating total ES supply of the city.

Quantifying ES based on detailed UGS data for Rotterdam demonstrates that not just the amount, but also the composition and configuration of UGS play a major role determining the bundle of ES provided to neighbourhoods, as similar studies also found (e.g. McPhearson, Kremer & Hamstead 2013; Andersson *et al.* 2014a). Our analysis disentangled the expected contribution of each UGS type to each of the six ES. The assessment of multiple ES reveals major differences between neighbourhoods in amount and type of ES supplied. To some extent, these differences may reflect differences in citizens' demand for ES in different city neighbourhoods (residential districts require different ES as compared to districts dominated by business and industrial activities). However, the demand side of ES is incorporated in very few studies (Grêt-Regamey, Brunner & Kienast 2012; McPhearson, Kremer & Hamstead 2013; Haase *et al.* 2014) while information about spatial matches and mismatches between supply and demand is of great use to planners (McDonald 2009). But even in the absence of detailed data on the demand for services, the different ES bundles in different neighbourhoods of Rotterdam reflect the different characteristics of these neighbourhoods and the possible ES shortages. The characterization of the neighbourhoods in terms of their ES bundle provides valuable information to urban planners and policymakers by providing insight into both the overall abundance of ES provision and the diversity of ES supply. In planning, this information may be used by accounting for the capacity of different UGS types in ES provisioning to ensure an adequate response to the needs for ES by planning and selecting UGS.

Where most earlier studies on urban ES are often restricted to one or two ES, a coarser resolution of analysis and a single vegetation type (Haase *et al.* 2014), we have shown the usefulness of considering a bundle of six urban ES, analysing different urban scales (street, neighbourhood, district, city) and making use of data at high spatial resolution and a lot of thematic detail in terms of UGS types. By doing so, we demonstrate an approach that can enhance the planning of green and sustainable cities by operationalizing the ES concept in a spatially explicit manner. The results indicate the multi-functionality of UGS, but also the strong variation in ES provided across the city. When related to residents' demands and needs for ES, our results can help to prioritize locations and UGS types to better match the ES demand and supply by UGS.

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Data accessibility

The following data are presented in Appendix S1 in the Supporting Information:

- Urban green space descriptions and data accessibility
- Administrative divisions description and data accessibility
- Main roads description and data accessibility

The following data are deposited in Dryad Digital Repository, doi:10·5061/dryad.kk504 (Derkzen, Van Teeffelen & Verburg 2015):

- GIS map of ecosystem service air purification at neighbourhood level
- GIS map of ecosystem service carbon storage at neighbourhood level
- GIS map of ecosystem service noise reduction at neighbourhood level
- GIS map of ecosystem service water retention at neighbourhood level
- GIS map of ecosystem service cooling at neighbourhood level
- GIS map of ecosystem service recreation at neighbourhood level
- GIS map of ecosystem services totals at district level
- GIS map of main roads in Rotterdam

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Data sets and data handling

Appendix S2. Detailed literature review underlying quantification methods

Appendix S3. Validation of ecosystem service cooling