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Title:

Mapping ecosystem service capacity, flow and demand for landscape and urban planning: A case study in the Barcelona metropolitan region

REGULAR RESEARCH PAPER

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Abstract

Ecosystem services (ES) mapping is attracting growing interest from landscape and urban planning but its operationalization in actual decision-making is still limited. A clear distinction between ES capacity, flow and demand can improve the usefulness of ES mapping as a decision-support tool by informing planners and policy-makers where ES are used unsustainably and where ES flow is failing to meet societal demand. This paper advances a framework for mapping and assessing the relationships between ES capacity, flow and demand with a focus on the identification of unsatisfied demand. The framework was tested in the Barcelona metropolitan region, Spain, considering two ES of critical relevance for the urban population: air purification and outdoor recreation. For both ES, spatial indicators of capacity, flow, demand and unsatisfied demand were developed using proxy- and process-based models. The results show a consistent spatial pattern of all these components along the urban-rural gradient for the two ES assessed. The flow of both ES mainly takes place in the periurban green areas whereas the highest capacity values are mostly found in the protected areas located on the outskirts of the metropolitan region. As expected, ES demand and particularly unsatisfied demand are mostly situated in the main urban core (i.e., Barcelona and adjacent cities). Our assessment also reveals that the current landscape planning instrument for the metropolitan region mostly protects areas with high capacity to provide ES, but might lead to declining ES flows in periurban areas due to future urban developments. We contend that the mapping of ES capacity, flow and demand can contribute to the successful integration of the ES approach in landscape and urban planning because it provides a comprehensive picture of the ES delivery process, considering both ecological and social underlying factors. However, we identify three main issues that should be better addressed in future research: (1) improvement of ES demand indicators using participatory methods; (2) integration of ecological thresholds into the analysis; and (3) use of a multi-scale approach that covers both the local and regional planning levels and cross-scale interactions between them.

Keywords: air purification; ecosystem service mismatch; outdoor recreation; urban-rural gradient; spatial modeling.

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1. Introduction

Ecosystem services (ES) mapping is gaining prominence in the environmental science and policy agendas (Egoh et al., 2012; Crossman et al., 2013; Malinga et al., 2015). For example, the European Union (EU) Biodiversity Strategy to 2020 called Member States to assess and map ES in their national territory as a supporting action to maintain and enhance ecosystems (EC, 2011). More generally, ES mapping can inform a variety of decision-making contexts (Gómez-Baggethun and Barton, 2013). These include: awareness raising and communication (e.g., Hauck et al., 2013); ecosystem accounting (e.g., Schröter et al., 2014); landscape and conservation planning (e.g., Palomo et al., 2014); and instrument design (e.g., Locatelli et al., 2014), among others.

In order to make ES maps operational for landscape and urban planning, recent ES literature calls for a clearer distinction between the three main components of the ES delivery process, namely ES capacity, flow and demand (Bastian et al., 2013; Villamagna et al., 2013; Burkhard et al., 2014; Schröter et al., 2014). Most spatially explicit ES assessments have focused on studying the ES capacity, i.e., the ecosystems' potential to deliver ES (see Martínez-Harms and Balvanera, 2012 for a review). In contrast, despite increased interests and efforts to assess and map ES flow and demand (e.g., García-Nieto et al., 2013; Palomo et al., 2013; Schröter et al., 2014), the conceptualization of both components is still subject to different approaches (Villamagna et al., 2013; Wolff et al., 2015). According to Wolff et al. (2015), ES demand is framed either as the direct use or consumption of the ES or as the desired or required level of the ES by society. However, the conceptual framework developed by Villamagna et al. (2013) argues that only the latter approach should be considered ES demand, whereas the actual use of the ES constitutes its flow.

At the operational level, the spatially explicit distinction and assessment of ES capacity, flow and demand can enhance the integration of ES in planning, management and decision-making because it can inform planners and policy-makers about the localization of potential ES mismatches, either in terms of *unsustainable uptake* of ES or in terms of *unsatisfied demand* for ES (Geijzendorffer et al., 2015). This information can be used to design plans or policy regulations oriented to: (1) redirect ES flows from overused areas (Schröter et al., 2014), and

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(2) improve access to ES benefits by identifying areas where ES flows fail to meet societal demand (Kabisch and Haase, 2014).

The aim of this paper is to advance an operational framework for assessing and mapping ES capacity, flow and demand to inform landscape and urban planning. First, we build on previous conceptual frameworks to distinguish between ES capacity, flow and demand, as well as their relationships in terms of (un)sustainable uptake of ES and (un)satisfied demand for ES. Second, we use proxy-based and process-based models within the ESTIMAP tool (Zulian et al., 2014) to develop, test and discuss suitable spatial indicators for the three components with a focus on the identification and mapping of unsatisfied demand. Third, we assess the spatial patterns observed from the application of these indicators in a case study and discuss their implications for planning and policy.

The framework is applied in the Barcelona metropolitan region, Spain. Assessing and mapping ES capacity, flow and demand can be particularly relevant in urban landscapes, where urban development impinges upon ecosystem's capacity to deliver sustained ES flows and where the high concentration of human population and assets usually entails high demands for ES (Kroll et al., 2012; Burkhard et al., 2012; Haase et al., 2014). We focused on air purification and outdoor recreation, two ES of key importance for improving health and well-being in urban areas since they contribute to air pollution abatement and the provision of opportunities for relaxation and physical activity (Bolund and Hunhammar, 1999; Gómez-Baggethun et al., 2013).

2. Methods and materials

2.1. Conceptual distinction between ecosystem service capacity, flow, and demand

The distinction between ES capacity, flow and demand ultimately builds on the conceptual framework for ES assessment known as the "ES cascade model", which illustrates the links between ecosystems and human preferences along a chain of ecosystem properties, functions, services, benefits and values (Haines-Young and Potschin, 2010; **Fig. 1**). Despite the varying understanding, terminology and application of the capacity, flow and demand concepts in the ES literature (see Villamagna et al., 2013; Wolff et al., 2015), in this paper we mostly follow

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the framework developed by Villamagna et al. (2013) because it provides a flexible, yet consistent approach for decision-making. Therefore, we define ES capacity as "the ecosystem's potential to deliver services based on biophysical properties, social conditions, and ecological functions", ES flow as "the actual production of the service" used or experienced by people, and ES demand as "the amount of a service required or desired by society" (Villamagna et al., 2013:116). We further developed this approach into an operational framework (**Fig. 1**) to inform decision-making on the basis of the relationships between capacity, flow and demand which can express two different ES mismatches (Geijzendorffer et al., 2015). On the one hand, the relationship between ES capacity and flow can indicate ES overuse or unsustainable uptake when capacity is smaller than flow, if the ES is rival or congestible (Schröter et al., 2014). On the other hand, the relationship between ES flow and demand can indicate unsatisfied demand when flow is not meeting the amount of ES demanded by society (Geijzendorffer et al., 2015). The relationship between ES capacity and demand is not explicitly considered in this framework because if demand is higher than capacity, the mismatch usually expresses an unsatisfied demand, unless flow is meeting the demand. In the latter case, the mismatch would express an unsustainable ES uptake.

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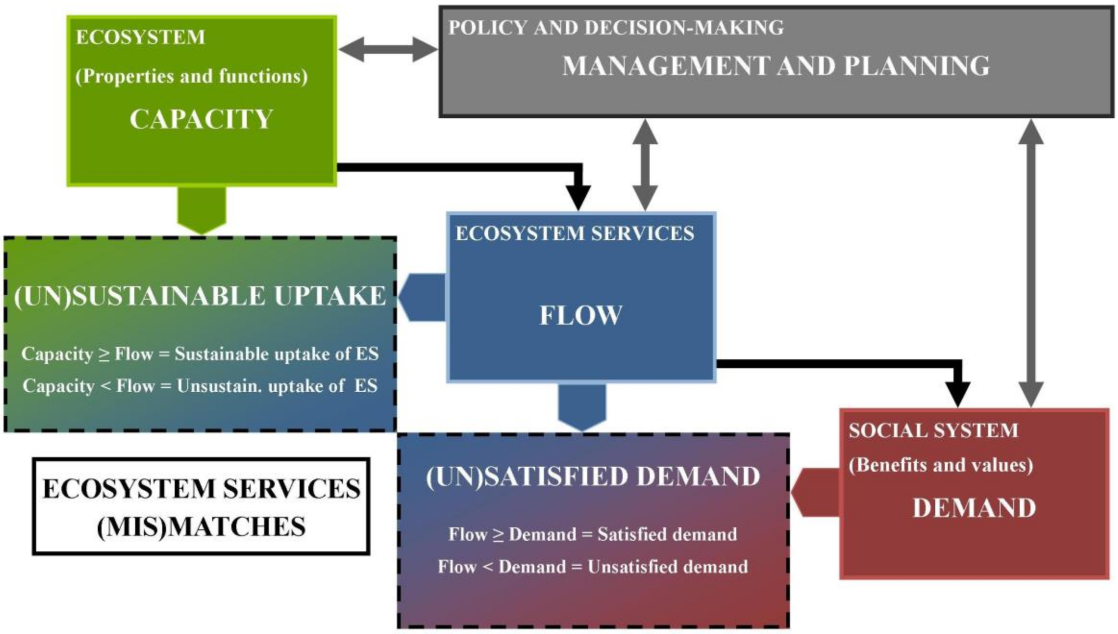

Fig.1. Framework for assessing the relationships between ES capacity, flow and demand, i.e., if the uptake of ES is sustainable (capacity & flow) and if demand is being satisfied (flow & demand). Management and planning affect and are affected by ES capacity, flow and demand. Building on Haines-Young and Potschin (2010), Villamagna et al. (2013) and Geijzendorffer et al. (2015).

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The conceptualization of ES demand (and unsatisfied demand) used here is inherently challenging at the operational level because it requires information about desired or required end conditions which can vary among different stakeholder groups, especially for cultural ES. For the sake of our analysis, in this paper we used environmental quality standards and recommendations as prescribed in policy as a proxy threshold to determine expected desired or required end conditions related to ES demand from a societal perspective (see Paetzold et al., 2010; Baró et al., 2015). A risk perspective is commonly used to quantify demand for regulating ES (Wolff et al., 2015). Under this approach, demand for air purification can be indirectly indicated considering the magnitude of pressures needing regulation (i.e., air pollution levels) and population exposed to these pressures (Burkhard et al., 2014). Besides, air quality standards can be used to provide a minimum threshold to identify a possible mismatch between flow and demand for air purification (i.e., exceedance of air quality limit values in inhabited areas indicate an unsatisfied demand). Yet, this situation does not necessarily imply that air quality improvement is to be achieved solely by more ES flow because the demand driver is human-induced (Baró et al., 2015). In the case of outdoor recreation, recommended standards are related to the proximity to recreational sites (e.g., Stanners and Bourdeau, 1995), as distance has been observed to be a critical variable explaining recreational use of green space in urban areas (Schipperijn et al., 2010; Paracchini et al., 2014). Following this rationale, outdoor recreation demand can be indicated based on the availability of recreational sites close to people's home and population density assuming that all inhabitants in the case study area have similar desires in terms of (everyday life) outdoor recreational opportunities (Paracchini et al., 2014; Ala-Hulkko et al., 2016).

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2.2. Description of the case study area

We tested the framework in the Barcelona metropolitan region (BMR), located North-East of Spain, by the Mediterranean Sea (**Fig. 2**). The BMR (5.03 million inhabitants and 3,244 km^2, Statistical Institute of Catalonia, year 2015) embeds 164 municipalities and seven counties, but its urban core, known as Barcelona metropolitan area, is constituted by the municipality of Barcelona (1.61 million inhabitants) and several adjacent middle-size cities (**Fig. 3**).

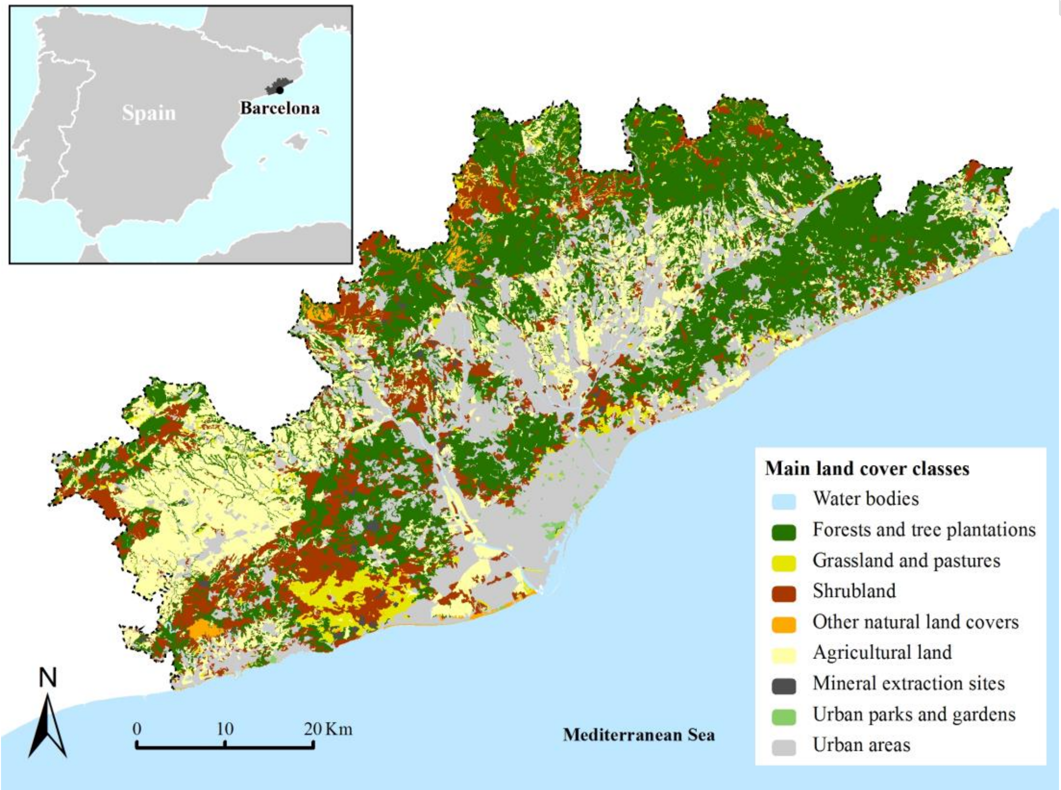

Fig. 2. Main land covers in the Barcelona Metropolitan Region (BMR). Own elaboration based on the spatial dataset of habitats of Catalonia (year 2013).

The BMR is one of the seven regional planning areas of the 'General Territorial Plan of Catalonia' (PTGC, 1995), the uppermost landscape planning instrument in the region of Catalonia. The 'Territorial Metropolitan Plan of Barcelona' was developed following PTGC's strategic guidelines and approved in 2010 by the Government of Catalonia (PTMB, 2010). The PTMB establishes three main planning categories, so-called "systems", for land use regulation: (1) open areas; (2) urban land; and (3) transport infrastructure. Because the latter system is highly dependent on transport planning and it has a limited impact in terms of land use change, yet an important one in landscape connectivity, the focus of this paper is on the

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'open areas' and 'urban' planning systems. However, given the relationship between transportation and certain components of the selected ES (e.g., demand for air purification), some implications for transport policy are discussed. The open areas planning system regulates the land protected from urbanization, including, fully or partially, fourteen Natura 2000 sites. The urban planning system regulates built-up land and defines strategies for urban expansion by the tentative delimitation of development areas that can be subsequently refined by municipalities through urban master plans. For example, most municipalities (including Barcelona) of the urban core share a common urban master plan (General Metropolitan Plan) which is currently under major revision. See **Table 1** for more details and **Fig. 3** for the spatial representation of the two PTMB planning systems.

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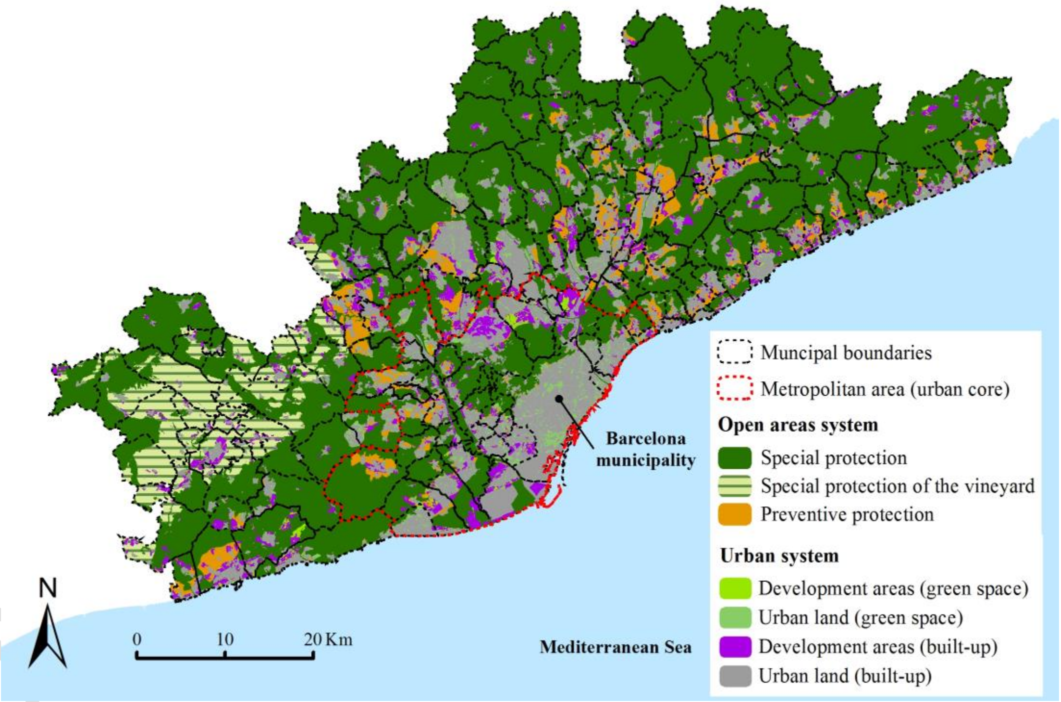

Fig. 3. Administrative boundaries in the BMR and planning systems of the Territorial Metropolitan Plan of Barcelona (PTMB, 2010). See also **Table 1.**

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Table 1. Description of the planning systems of the Territorial Metropolitan Plan of Barcelona (PTMB, 2010).

Planning systems	Main zoning categories	Short description	Total area (km^2 and % of BMR)
Open areas system	Special protection	Highly protected land for its ecological and agricultural values. Includes Natura 2000 sites and other areas under different protection categories.	2031.70 (62.6%)
	Special protection of vineyard	Highly protected land for its landscape and agricultural values for the wine sector.	230.33 (7.1%)
	Preventive protection	Areas where urban development is, a priori, restricted. Normally transitional between urban and protected land. Urbanization may be possible under certain circumstances.	142.84 (4.4%)
Urban system	Urban land (consolidated)	Consolidated urban build-up land (residential, industrial, commercial, etc.), including urban green areas.	Total: 634.92 (19.6%) Green space only: 84.41 (2.6%)
	Development areas	Areas designated for future urban development, including the creation of new urban green areas.	Total: 205.38 (6.3%) Green space only: 36.05 (1.1%)

We contend that the BMR is an exceptional testing ground for the purpose of this research for at least three reasons: (1) the BMR is one of the most densely populated urban regions in Europe (1550 inhabitants per km^2), which poses great challenges for sustainable landscape and urban planning; (2) it contains a rich variety of natural habitats of high ecological value, including Mediterranean forests (1184.56 km^2; 36.5%) and shrub land (448.62 km^2; 13.8%), agro-systems of strategic economic importance (e.g. vineyards) (654.51 km^2; 20.2%), and inland water bodies (24.08 km^2; 0.7%) (see **Fig. 2**); and (3) both local and regional authorities have shown interest in implementing the ES approach in landscape and urban planning (e.g., Barcelona Green Infrastructure and Biodiversity Plan 2020, Barcelona City Council, 2013).

2.3. Selection of ecosystem services

The ES outdoor recreation and air purification were chosen as exemplars for the assessment because of their relevance to urban areas (Bolund and Hunhammar, 1999; Gómez-Baggethun and Barton, 2013; Haase et al., 2014) and particularly the BMR. Moreover, unlike other ES such as global climate regulation (see Schröter et al., 2014), a meaningful distinction between capacity, flow and demand can be drawn for these two ES.

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The cultural ES outdoor recreation is probably one of the most valued ES in cities, decisively contributing to enhance physical and mental health of the urban population (Chiesura 2004; Gómez-Baggethun et al., 2013; Triguero-Mas et al., 2015). The city of Barcelona and many of its surrounding middle-size cities are characterized by a high degree of compactness and high population density, involving a scarcity of inner green areas (Baró et al., 2014). Periurban parks and other natural suburban areas represent thus an important option for outdoor recreational opportunities in the BMR. For example, the periurban park of Collserola, located in a central position of the BMR and virtually surrounded by urban fabric, receives about two million visitors according to a recent study (IERMB, 2008).

The regulating ES air purification is also the subject of growing attention in the policy agenda. Abatement of air pollution is still a pressing challenge in most major urban areas worldwide, especially in regard to dioxide nitrogen (NO_2) and particulate matter (WHO, 2014). For example, the 2015 annual report on air quality in Europe (EEA, 2015) estimated that, during the period 2011–2013, 8–12% of the urban population within the EU was exposed to NO_2 concentrations above the limit value set both by the EU (EU, 2008) and the World Health Organization (WHO, 2005) in 40 $\mu g\ m^{-3}$ (annual average). The harmful impacts of air pollution on human health are consistently supported by scientific evidence (e.g., Brunekreef and Holgate, 2002; WHO, 2013). Vegetation in urban landscapes can improve air quality by removing pollutants from the atmosphere, mainly through leaf stomata uptake and interception of airborne particles (Nowak et al., 2006). In the last decade, the city of Barcelona has repeatedly exceeded the EU limit values for average annual concentrations of NO_2 and particles with diameter of ten micrometers or less (PM_{10}). Urban trees and shrubs within the municipality of Barcelona removed 166.0 t of PM_{10} and 54.6 t of NO_2 during the year 2008 according to Baró et al. (2014) estimates.

2.4. Description of spatial ecosystem service models and indicators

We used the methodological framework provided by the Ecosystem Services Mapping tool (ESTIMAP) for the spatial assessment of the two selected ES (Paracchini et al., 2014; Zulian et al., 2013; 2014). ESTIMAP is a collection of spatial models for ES assessment originally

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developed to support environmental policies at European scale such as the EU Biodiversity strategy (Maes et al., 2014). Because ESTIMAP is based on the conceptual model of the ES cascade (Haines-Young & Potschin, 2010), its spatial outputs are consistent with the ES capacity, flow, and demand framework used in this study. ESTIMAP was designed for a continental scale, therefore it was adapted to the regional scope of this paper to make it usable for urban and landscape planning.

In the following subsections we describe this adaptation and downscaling process. **Table 2** provides an overview of the ES indicators developed and used in the assessment and a brief description of the spatial input data. More details on the methods applied and data used to compute these indicators are provided in **Appendix A**. All geoprocessing operations were carried out using ArcGIS v.10.1 (ESRI) or GRASS GIS v. 7.0 (GRASS Development Team).

2.4.1. Outdoor recreation

The model used here for assessing outdoor recreation focuses on nature-based recreational activities in the everyday life (Paracchini et al., 2014). Those activities include practices such as walking, jogging, bike riding, picnicking, observing flora and fauna, or simply enjoying nature, among other possibilities, but it excludes nature-related tourism activities involving long trips, which some classifications consider a distinct ES (e.g., TEEB, 2010).

Like other approaches to cultural ES mapping (e.g., Casado-Arzuaga et al., 2014), ESTIMAP-recreation assumes that all ecosystems, including natural, semi-natural and intensively managed ecosystems, are potential providers of recreational opportunities, although the capacity level depends on ecosystem features related to people's recreational preferences. The rationale for assessing recreation capacity in our model can be summarized as follows: (1) the lesser human influence on landscapes, the higher value in terms of nature-based recreational potential; (2) protected natural areas and features (e.g., remarkable trees) are considered indicators of high recreational capacity; and (3) water bodies exert a specific attraction on the surrounding areas (see Paracchini et al., 2014). Recreation capacity was hence mapped on the basis of the assessment of three components: degree of naturalness, nature protection, and presence of water. Each component was composed of one to four internal factors considered

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relevant in the case study of the BMR and for which spatial input data was available (see **Appendix A** for a detailed description of factors and data sources). A score or weight (in the 0-1 range) was assigned to every factor standing for their relative importance or impact in terms of recreation potential. The final selection of factors and definition of scores was based on a consultation process (via focus group) with four experts working in environmental planning and territorial analysis for the Barcelona Regional Council. The experts were asked to: (1) revise a preliminary proposal of factors suggested by the research team (introducing changes if necessary); and (2) assign a score to every factor based on their thorough knowledge of the socio-ecological context in the case study area. In case of no consensus for a specific score, a compromise value was agreed (e.g., average value of suggested scores). Five factors were subject to a distance decay modeling, assuming that the recreation potential decreases as the distance from the specific feature (e.g., a beach or remarkable tree) increases (see **Appendix A** for details). The final dimensionless value of recreation capacity was normalized in the 0-1 range.

Mapping outdoor recreation flow is challenging because data on the actual recreational use or experience of ecosystems by people is often inexistent or limited to certain areas (but see some attempts in Palomo et al., 2013, Schröter et al., 2014 and Wood et al., 2009). The ESTIMAP approach is based on a population analysis in which the expected service flow is mapped by modeling the number of visitors, or trips, that reach a given recreational area considering a defined distance threshold (Paracchini et al., 2014). The adjustment applied in the case study area involved several considerations: (1) the road and track network reaches nearly every point in the BMR, hence it was not considered in the proximity analysis; (2) a distance threshold of 1 km representing close-to-home daily trips was set based on recommended standards by regulatory agencies (Stanners and Bourdeau, 1995; Barbosa et al., 2007); (3) a population density grid was created based on an intersect between census tract dataset (INE, 2011) and residential use classes extracted from a high resolution land cover map (LCMC, 2009) assuming equal population distribution within residential land for each census tract; (4) an impedance function was applied in the modeling following Paracchini et al. (2014) (see **Appendix A** for details); (5) the expected flow was only represented in medium to very high capacity recreation areas (i.e., recreation capacity equal or higher than

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0.4) assuming that inhabitants want to reach these areas and not low capacity areas (recreation capacity lower than 0.4 mostly corresponds to artificial land covers, see also **Fig. 4A**).

Following the rationale described above (**subsection 2.1**), outdoor recreation demand was mapped based on the availability of recreational sites (i.e., recreation capacity equal or higher than 0.4) close to people's homes and population density. A spatial cross-tabulation was carried out between a reclassified raster of Euclidian distances to recreation sites and the population density grid, assuming that all inhabitants in the case study area have similar desires in terms of (everyday life) outdoor recreational opportunities, but their level of fulfillment depends on proximity to recreation sites (see cross-tabulation matrix in **Appendix A**). The resulting raster indicates ES demand in residential land following a 0 (i.e., no relevant demand) to 5 (i.e., very high demand) value range. The assessment and mapping of unsatisfied demand for outdoor recreation was accomplished by selecting the number of people from the population density grid living further than 1 km (i.e., the assumed threshold distance) from any recreational site. Therefore, the spatial indicator represents the population with unfulfilled recreational expectations according to our approach.

2.4.2. Air purification

The ES air purification focuses on the air pollutant NO_2 for the reasons mentioned above and was modeled and mapped using the following indicators: (1) NO_2 dry deposition velocity on vegetation, considered here as a proxy to assess the ecosystems capacity to remove pollutants from the atmosphere; (2) modeled NO_2 removal flux by vegetation, considered here as measure for the ES flow; and (3) an ES demand index based on population density and exposure to NO_2 concentrations (see also Baró et al., 2015).

In many studies (e.g., Nowak et al., 2006; Escobedo et al., 2009) dry deposition velocities of the gaseous pollutants for the in-leaf season are estimated using a series of resistance formulae (Baldocchi et al., 1987) that require specific information regarding the structure and species composition of urban vegetation. Since this information was not available for the entire case study area, the capacity indicator for air purification was estimated following the

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approach proposed by Pistocchi et al. (2010), which estimates deposition velocity (V_d) as a linear function of wind speed at 10 m height (w) and land cover type:

$$V_d = \alpha_j + \beta_j \cdot w \tag{1}$$

Where α and β are, respectively, the intercept and slope coefficients corresponding to each broad land cover type j, namely forest, bare soil, water or any combination thereof.

The NO_2 removal indicator (flow) was mapped based on the spatial distribution of NO_2 annual average concentrations and the capacity map. Concentrations of NO_2 were estimated using Land Use Regression (LUR) models, a computation approach widely used for assessing air pollution at different scales (e.g., Briggs et al., 1997; Hoek et al.; 2008; Beelen et al. 2013). The LUR model was built using NO_2 concentration measurements (year 2013) from the operational monitoring stations located in the BMR (n = 40) as dependent variable, and a set of spatial predictor parameters (i.e., independent variables) related to land cover type, geomorphology, climate, population density, and road network (see **Appendix A** for input data details), that were considered to be the most relevant for distribution of NO_2 concentrations. Because several of the independent variables influence air pollution concentration at different spatial scales, we evaluated the correlation between each of the parameters at different scales and the measured NO_2 concentrations. We developed spatial buffers around each monitoring station from 50 to 1500 m every 50 m, and calculated for each buffer statistical values (mainly mean and sum) of the parameters. We selected the most relevant spatial buffer as the one reporting the highest R^2 between the statistical value and the measured concentration given that the correlation had the expected sign (i.e. higher concentrations with higher values of urban areas but lower concentrations with higher values of forest areas). Within this optimal buffer, values of the original parameter were aggregated and the resulting values were used as parameters for the LUR model. Annual NO_2 removal was estimated as the total pollution removal flux in the areas covered by vegetation, calculated as the product of NO_2 concentration and deposition velocity maps (Nowak et al., 2006).

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Considering the risk perspective described above (**subsection 2.1**), air purification demand was mapped based on NO_2 concentration levels and population density. A spatial cross-tabulation was carried out between both variables following the same approach as for recreation, i.e., the higher NO_2 concentration and population density the higher demand values (see cross-tabulation matrix in **Appendix A**). The resulting index spatially represents ES demand for air purification in the 0 (i.e., no relevant demand) to 5 (i.e., very high demand) value range. The map of unsatisfied demand for this ES was generated by selecting the population living in areas where annual mean NO_2 concentrations exceed the EU limit value (40 µg m^{-3}).

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Table 2. Overview of ES indicators and main input data used in the assessment (building on the blueprint by Crossman et al., 2013). All indicators were mapped at a regional scale (pixel size 100x100m) using data corresponding to years 2011-2013. For further details see **Appendix A.**

Mapped ES	ES component indicator	Unit	Main input data	Mapping method	Comments and main methodological references
Outdoor recreation (everyday life)	Recreational potential index (Capacity)	Dimensionless value (0-1)	Naturalness of habitats Protected natural areas and features Water features	Composite mapping	Paracchini et al. (2014) Zulian et al. (2014) Threshold distance considered: 1km (Stanners and Bourdeau, 1995)
	Expected trips to recreational sites (Flow)	Nº trips ha^{-1}	Population density grid Recreation potential map	Distance analysis (including impedance function)	
	Demand index (considering population density and distance to recreation sites)	Dimensionless value (0-5)	Population density grid Recreation potential map	Spatial cross-tabulation	
	Population with low recreation opportunities (Unsatisfied demand)	Inhabitants ha^{-1}	Population density grid Recreation potential map	Spatial extraction	
Air purification (NO_2)	NO_2 dry Deposition velocity (Capacity)	mm s^{-1}	Land cover dataset Wind speed at 10 m height	Composite mapping	Nowak et al. (2006) Beelen et al. (2009) Pistocchi et al. (2010). Zulian et al. (2014). NO_2 concentration limit value (annual average): 40 µg m^{-3} (EU, 2008)
	NO_2 removal flux (Flow)	kg ha^{-1} $year^{-1}$	Air quality monitoring stations data Spatial predictors Vegetation maps Climatic and physiographical maps	Land use regression modeling (LUR)	
	Demand index (considering population density and NO_2 concentration)	Dimensionless value (0-5)	Spatial distribution of NO_2 annual average concentrations Population density grid	Spatial cross-tabulation	
	Population exposed to NO_2 concentration beyond limit (Unsatisfied demand)	Inhabitants ha^{-1}	Spatial distribution of NO_2 annual average concentrations Population density grid	Spatial extraction	

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2.5. Assessing urban-rural and landscape planning gradients

Urban-rural gradients have been used to analyze ecological patterns and processes in urban landscapes, including the consideration of ES indicators (Kroll et al., 2012; Larondelle and Haase, 2013). Following these approaches, we computed urban-rural gradients of the capacity, flow, demand and unsatisfied demand of outdoor recreation and air purification using the resulting ES maps as described above. A 50-km concentric buffer with 1-km intervals was created around the city center of Barcelona (Catalunya square), covering almost all the BMR area. For each concentric ring, the average reclassified ES value (0-5 range) was calculated omitting null values. As pointed out by Kroll et al. (2012), urban-rural gradients imply a generalization of the spatial patterns existing in an urban region, but it is suitable approach to analyze major trends, relationships and variability between urban, suburban and rural areas in relation to ES provision and demand.

Assessing ES capacity, flow and demand maps in relation to current landscape planning instruments can provide relevant insights for land use policies. For example, it is possible to assess the level of protection of relevant ES providing areas in terms of capacity and flow and predict possible impacts to ES hotspots from future urbanization processes. Additionally, expected new areas of ES demand, and potentially unsatisfied demand, can be predicted from urban development areas. The intersect tool of ArcGIS v.10.1 (ESRI) was applied to extract the areas of ES capacity, flow, demand (only medium to very high values were considered, see **Fig. 4** and **Fig. 6** legends for the corresponding value ranges), and unsatisfied demand (all values were considered) allocated to the various landscape planning classes of the PTMB (see **Fig. 3** and **Table 1**).

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3. Results

3.1. Spatial patterns of ecosystem service capacity, flow, and demand

Capacity, flow, demand and unsatisfied demand distribution maps for the ES outdoor recreation and air purification are shown in **Fig. 4** and **Fig. 6** respectively. Following Burkhard et al. (2014), maps show data classified into six categories, from no relevant to very high values. Classification is based on equal intervals in order to make the different classes and their values comparable with each other; except for population related indicators which required a manual classification (see break values in the corresponding map legends of **Fig. 4** and **Fig. 6**) in order to meaningfully represent the strong unevenness of urban densities (from urban sprawl to compact city).

Outdoor recreation capacity shows the highest values mainly in the forest areas located on the outskirts of the BMR (**Fig. 4a**). For example, the massif of Montseny, a natural park since 1977, located north-east of the study area, contains the most part of land classified as having high or very high recreational capacity (57.0%). Generally, these areas correspond to forest habitats, but a closer look also show high recreation capacity areas in aquatic habitats, such as the wetlands located in the delta of the Llobregat River, nearby the city of Barcelona. Air purification capacity values show a similar spatial pattern, yet the highest values are clearly circumscribed to the forest areas located north of the BMR (**Fig. 6a**). Medium capacity values in both ES are mainly distributed across the forest areas covering the coastal mountain range. For example, the periurban natural area of Collserola, a natural park since 2010, located at the core of the BMR, mostly presents medium values for both ES. Low to no relevant capacity areas generally correspond to urban and agricultural land covers. However, while lowest values in the case of outdoor recreation are clearly restricted to urban areas, the areas where air purification capacity is very low or no relevant include a broader range of land cover types, such as grassland or scrubland.

Unlike recreation capacity, the largest amount of high recreation flow values is to be found in the forest areas located in the surroundings of urban settlements (**Fig. 4b**). In general, riverine and coastal (e.g., beaches) ecosystems also show very high recreation flow values. Obviously, these results were expected as the flow assessment was restricted to close-to-home outdoor

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recreation trips for which distance to residential land is the explanatory variable. The case of air purification also shows higher flow values in periurban forest areas than other natural sites located in the hinterland, although the spatial transition is smoother as compared to recreation (**Fig. 6b**). Again, the natural parks of Collserola and Montseny illustrate these patterns clearly: the latter mainly contains very low to low flow values whereas the former shows mostly medium to very high values. The impact of traffic emissions over the spatial configuration of air purification flow is also noticeable on the maps, as forest areas located along the main roads have higher values in general terms. The lowest flow values for air purification are again located in urban and agricultural land, showing a similar pattern as for capacity.

As expected, the municipality of Barcelona and adjacent middle-size cities show the highest demand values in the BMR for both analyzed ES (**Fig. 4c** and **Fig. 6c**). This urban agglomeration is characterized by a compact urban form, very high population density and a relatively small share of inner green areas. The other middle-size cities, located both along the coastline and hinterland, show mostly middle to low demand values for air purification and low to high demand values for outdoor recreation. Smaller towns and sprawling urban areas mostly show very low to no relevant demand values. The impact of relevant ES providing areas, both in terms of capacity and flow, over demand distribution is also evident from the obtained maps, as residential land located close to these areas has generally lower values than more distant settlements.

Finally, results show that unsatisfied demand is circumscribed to the urban core of Barcelona and several middle-size cities (**Fig. 4d** and **Fig. 6d**). Unsatisfied demand for recreation includes a substantial portion of the city of Barcelona and other compact urban areas (163.54 km^2 in total) whereas unsatisfied demand for air purification is principally limited to the urban areas surrounding the main roads and streets of Barcelona and adjacent cities (only 46.63 km^2 in total) where NO_2 concentration is highest.

The urban-rural gradients of recreation and air purification for the BMR illustrate graphically the spatial patterns shown on the maps and described in the above paragraphs (see **Fig. 5** and **Fig. 7**). The gradient for ES capacity is similar for both ES. The lowest values are in the first

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5 km, in the Barcelona core city, and they present a gradual rise as we move away from the city centre. In both cases, capacity shows a substantial increase after km 5 followed by a slight decrease after km 10-11. The periurban natural areas surrounding Barcelona (e.g., Collserola) followed by the urban and agricultural land located in the inland plains explain this pattern.

Flow gradient of air purification shows a pattern similar to the one observed for capacity, but after the first decrease (km 11 – 17) values follow a steady flat trend without any substantial increase. On the other hand, recreation flow shows a sharp increase in km 3 followed by a similar decline after km 5, illustrating the high flow values of periurban forests and other land covers located close to urban areas such as beaches. From km 8 until 20 a series of small picks and troughs precede a slow downward trend which corresponds to the gradual increase in the amount of recreational sites located far away from urban areas.

Demand gradients are also quite similar for both ES, showing highest values in the urban core area (1-5 km) followed by a decreasing trend as the distance to the city increases. Outdoor recreation values show a rapid decline after km 4 whereas air purification demand decreases more gradually. This result highlights that the impact of the urban core area upon ES demand is higher for recreation than for air purification in the BMR. Finally, unsatisfied demand gradients show a decreasing trend similar to the one observed for demand. The various peaks observable in mid to high distances for both ES can be attributed to the relative low amount of unsatisfied demand values, causing mean values to be more variable across the concentric rings than in the other three cases.

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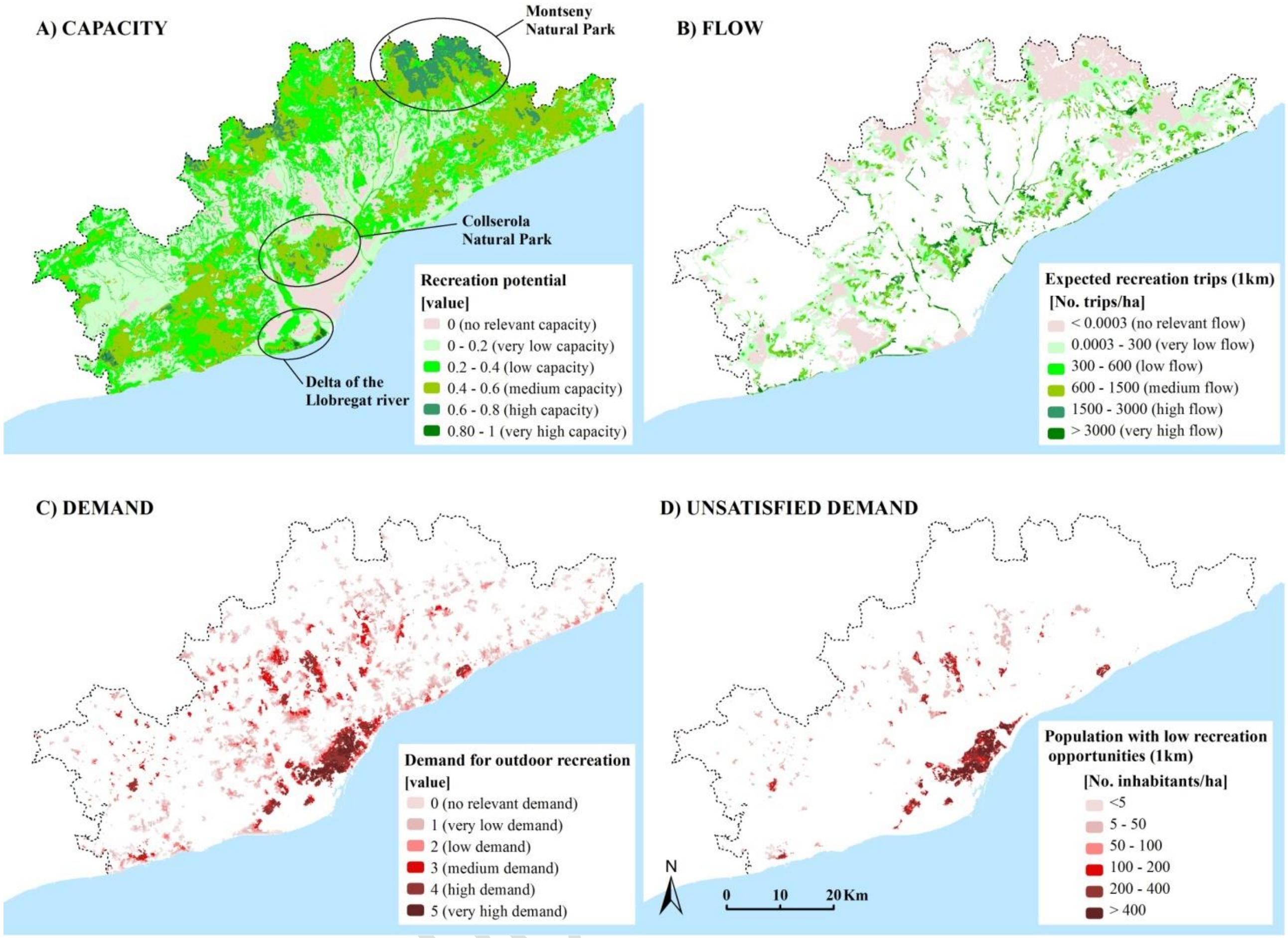

Fig. 4. Capacity, flow, demand and unsatisfied demand maps for the ES outdoor recreation in the BMR. See **Table 2** and **Appendix A** for data sources.

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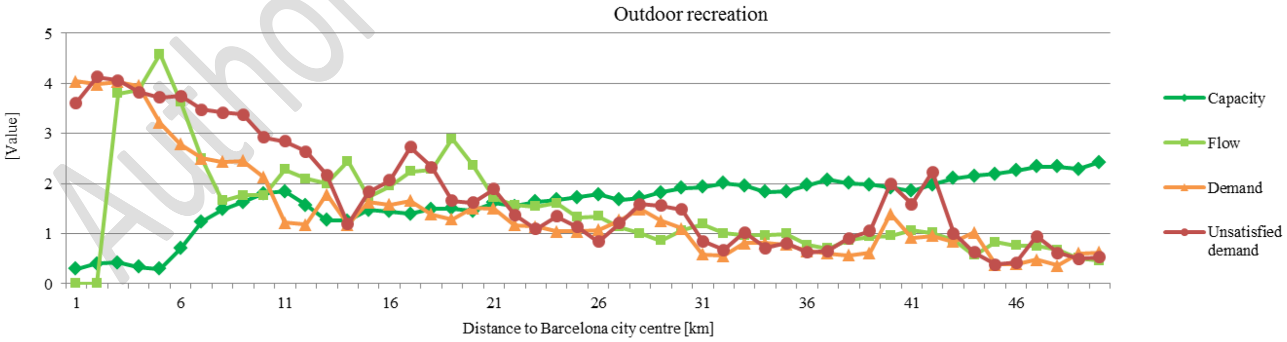

Fig. 5. Urban rural gradient (50km) of the ES outdoor recreation for the BMR. Each point represents the average reclassified value (0-5 range) in the concentric ring at the respective distance from the Barcelona city centre. Null values are not considered.

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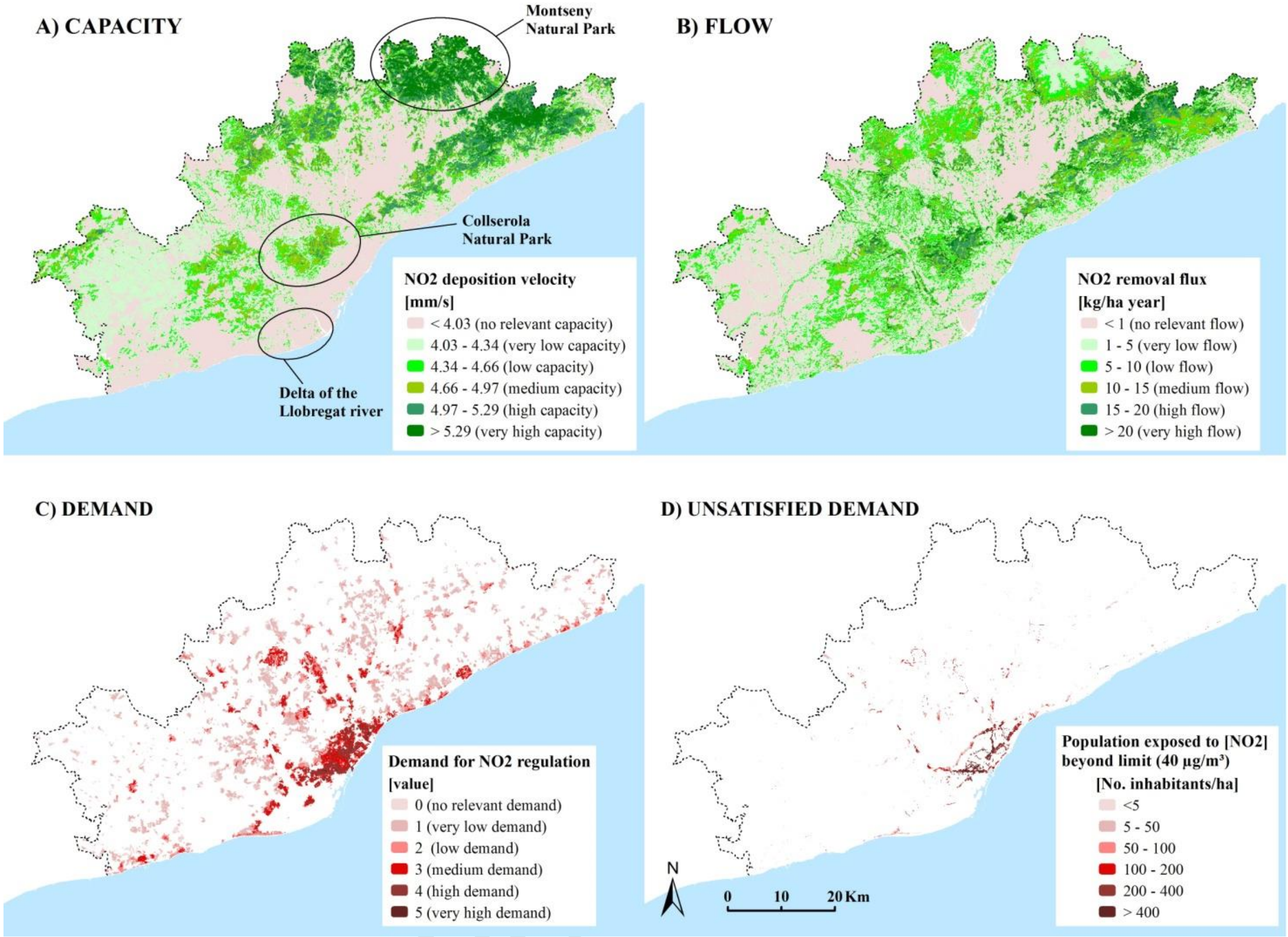

Fig. 6. Capacity, flow, demand and unsatisfied demand maps for the ES air purification in the BMR. See **Table 2** and **Appendix A** for data sources.

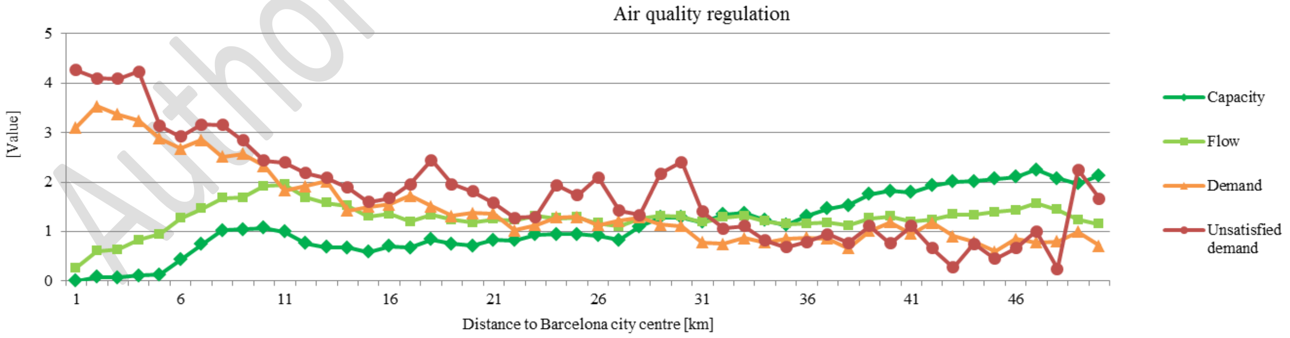

Fig. 7. Urban rural gradient (50km) of the ES air purification for the BMR. Each point represents the average reclassified value (0-5 range) in the concentric ring at the respective distance from the Barcelona city centre. Null values are not considered.

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3.2. Landscape planning assessment

The total area of ES capacity, flow, demand and unsatisfied demand overlapping each of the landscape planning classes of the PTMB is shown in **Table 3**. Relevant areas for their capacity to provide ES are almost entirely classified as special protection (i.e., open areas planning system) since nearly 96% of the total area fall into this planning category for both ES. This result indicates that relevant ES capacity areas largely correspond to land covers that have already been protected by the PTMB due to their ecological and landscape values. Relevant ES flow areas mostly correspond to special protection land as well, yet a substantial share also corresponds to preventive protection, also open areas planning system, or the urban planning system. For example, in the case of air purification, 83.22 km^2 of flow areas (12.6%) fall into urban system categories or preventive protection whereas for ES capacity the total area is only 31.18 km^2 (4.0%). As observed on the maps, the highest flow values are generally located nearby or within suburban and urban land; hence possible impacts in terms of urbanization processes can be anticipated in these areas. As expected, demand and unsatisfied demand areas are mostly classified in the urban planning system.

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Table 3. Total area of ES capacity, flow, demand (only medium to very high values, see **Fig. 4** and **Fig. 6** legends for the corresponding value ranges), and unsatisfied demand in relation to landscape planning classes (PTMB) (in km^2). Notes: special protection class includes special protection of the vineyard and urban classes includes both urban consolidated land and development areas.

Mapped ES	**ES Component**	**Open Areas Planning System**		**Urban Planning System**	
		Special protection	Preventive protection	Urban (green space)	Urban (built-up)
Outdoor recreation (everyday life)	Capacity	857.01 (96.0%)	7.76 (0.9%)	9.27 (1.0%)	19.00 (2.1%)
	Flow	142.04 (72.8%)	9.37 (4.8%)	10.63 (5.5%)	33.08 (17.0%)
	Demand	3.19 (2.4%)	1.23 (0.9%)	12.91 (9.6%)	117.31 (87.1%)
	Unsatisfied Demand	9.89 (6.1%)	5.67 (3.5%)	16.56 (10.1%)	131.41 (80.4%)
Air purification (NO_2)	Capacity	747.09 (96.0%)	10.18 (1.3%)	7.66 (1.0%)	13.35 (1.7%)
	Flow	579.14 (87.4%)	20.36 (3.1%)	19.53 (3.0%)	43.34 (6.5%)
	Demand	0.80 (0.7%)	0.62 (0.5%)	10.08 (8.7%)	103.98 (90.0%)
	Unsatisfied Demand	1.82 (3.9%)	1.77 (3.8%)	5.10 (10.9%)	37.94 (81.4%)

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4. Discussion

4.1. Operationalization of the framework in the case study and policy implications

Our results indicate that the spatial patterns of ES capacity, flow and demand along the urban-rural gradient are similar for the two ES considered in the assessment. As expected, demand for both outdoor recreation and air purification is especially relevant in the urban core of the BMR. The actual use (i.e., flow) of both ES mainly takes place in the periurban and suburban green areas whereas the highest capacity values are mostly to be found in the protected natural areas located on the outskirts of the BMR. These findings suggest that there is a potential to increase ES capacity, and hence ES flow, in the periurban green areas of the BMR such as in the Collserola Natural Park through conservation planning and management. The current landscape planning instrument for the BMR (PTMB, 2010) classifies a substantial share of periurban areas as special protection land, thus the implementation of conservation practices intended to maintain and eventually enhance the current flow of ES could be supported. However, a considerable share of relevant ES flow areas is also located within the urban planning system or the preventive protection zoning category, indicating a potential risk of degradation due to future urbanization processes. Therefore, the revision of urban master plans such as the General Metropolitan Plan affecting the urban core of the BMR should ensure that relevant ES flows are maintained in these sensitive areas.

The assessment of ES mismatches between flow and demand shows that unsatisfied demand is mostly located in the urban core of the BMR and in several middle-size cities. We consider that planning and policy strategies intended to reconcile flow and demand at the local level should focus on different components of the framework depending on each ES.

For air purification, urban policies should focus on drivers of demand (i.e., air pollution concentrations). Previous studies (Baró et al., 2014; 2015) show that average air quality improvements due to air pollution removal by vegetation is relatively low at the urban core, suggesting a limited effectiveness to address ES mismatches by increasing ES flow through strategies such as implementing tree-planting programs or selecting trees with high air pollution removal capacity. Moreover, factors such as vegetation configuration and climate conditions can limit the ability of vegetation to remove air pollutants, especially at the patch

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scale such as in street canyons (Vos et al., 2013). Therefore, policy interventions should focus on reducing and limiting traffic in certain areas, increasing public transport, incentivizing the use of non or low-emitting vehicles (e.g., bicycles and electric vehicles), and enhancing planning towards shorter commuting needs. The Air Quality Action Plan in the agglomeration of Barcelona (horizon 2020)[1] approved in 2014 by the Catalan Government is an important move towards the implementation of these policies in the case study area.

For outdoor recreation, different strategies could be put in place to reduce flow-demand spatial mismatches, which mainly focus on the capacity and flow aspects. For example, new protected areas and other conservation interventions such as green belts could be designed in the PTMB open areas system and urban master plans, reducing the risk of degradation due to urban sprawl processes as it occurred over recent decades (Catalán et al., 2008). An optimized fulfillment of outdoor recreation demand could also be fostered in core urban areas through strong planning and policy instruments intended to preserve existing green spaces and innovative ways to restore or create new ones. For example, the expansion of rooftop gardens in cities represents a promising solution in order to increase the delivery of a wide range of ES, including recreation opportunities (Orsini et al., 2014). The implementation of the Barcelona Green Infrastructure and Biodiversity Plan 2020 (Barcelona City Council, 2013) offers an important strategic policy framework with potential to substantially increase outdoor recreation opportunities in the municipality of Barcelona as it encourages the expansion of green infrastructure in all sorts of available land, including rooftops, inner courtyards, vacant plots, etc.

4.2. Methodological limitations and challenges for future research

As all data used in this study is likely available in other urban regions, it should be possible to extend this mapping approach elsewhere. Moreover, the framework can be potentially applied to other ES since capacity, flow and demand indicators have been suggested for all ES classes and groups (Burkhard et al., 2014; Mononen et al., 2016). Based on previous applications of the models (e.g., Maes et al., 2014; Paracchini et al., 2014), we consider that the maps developed here for the two selected ES are sufficiently credible and salient for landscape and

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[1] The plan is available in English from www.airemes.net

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urban planning purposes in the case study area. However, several limitations and challenges for future research can be highlighted from our assessment.

One of the main limitations of this approach is that the mapping of ES demand and flow mostly relies on proxies (e.g., population density, air quality and distance) to indicate expected demand and use. Therefore, there is potential for error if the assumed causal variables are not actually good spatial predictors (Eigenbrod et al. 2010). However, there is a lack of empirical data which could be used for model validation. For example, visitor data in recreational sites is only partially available for some protected areas (e.g., see IERMB, 2008 for Collserola Natural Park). Air purification flow is based on a regression model using primary data on air pollution concentrations, but available NO_2 monitoring stations in the BMR are relatively few ($n = 40$), hence real heterogeneity in air pollution distribution is likely masked by the modeling process. The recreation capacity model depends strongly on expert knowledge (experts choose input data and scores), so validation or improvement could be realized through additional or complementary participatory methods as suggested below.

Improvement of results could be achieved by using other approaches and methods for mapping ES demand (see Wolff et al., 2015 for a review). For example, outdoor recreation demand indicators could be further refined by incorporating preferences, desires and expectations via household questionnaires, surveys or participatory mapping techniques (see also Vollmer and Grêt-Regamey, 2013; Burkhard et al., 2014; Brown and Fagerholm, 2015; García-Nieto et al., 2015). These approaches can capture the diversity of demands for cultural ES and improve the spatial location of ES flows, but are usually resource intensive or site-specific (Wolff et al., 2015). Some European countries have collected data on people's recreational preferences through national visitor surveys (see Paracchini et al., 2014), but unfortunately we are not aware of any recreation survey at the regional or national level which covers the case study area. The demand approach for air purification, considering the exposure of population to air pollution levels, is consistent with most assessments of demand for regulating ES based on risk reduction (Wolff et al., 2015). However, a further refinement could be achieved by identifying and mapping specific risk groups such as children and

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elders, or by considering the areas where inhabitants practice outdoor activities and, therefore, where they can be exposed to air pollution (Sunyer et al., 2015).

Another issue not considered in the spatial models used here relates to ecological thresholds or tipping points (Andersen et al., 2009). An ecological threshold can be defined as a "point at which an (ecological) system experiences a qualitative change, mostly in an abrupt and discontinuous way" (Jax, 2014:1). It is often very difficult to determine when and under what conditions or pressures, ecosystems experience thresholds which can affect their ability to provide ES (Gómez-Baggethun et al., 2011). In the case of air purification, high pollutant concentrations can severely damage vegetation or lead to stomatal closure, reducing air pollution removal capacity and consequently flow (Robinson et al., 1998; Escobedo and Nowak, 2009). In the case of outdoor recreation, the threshold is probably related to congestion. A very high number of visitors in a given recreational area, at the same time or progressively during a persistent period of time, might lead to a deterioration of the recreational experience and to the degradation of the ecosystem itself, hence jeopardizing its ability to provide this ES (Lynn and Brown 2003). The visitor carrying capacity of a given area could be defined based on expert knowledge and or participatory approaches (Schröter et al., 2014). **Figure 8** provides an illustrative outline of hypothetic patterns of ES capacity, flow and demand under increasing pressures considering ecological thresholds. In the case of air purification, capacity and flow would likely experience an abrupt decrease after the ecological threshold while for outdoor recreation the change would probably be more gradual. Moreover, air purification flow cannot exceed capacity because of biophysical constraints, but recreation flow can indeed surpass capacity and ultimately trigger its decline due to congestion (Schröter et al., 2014).

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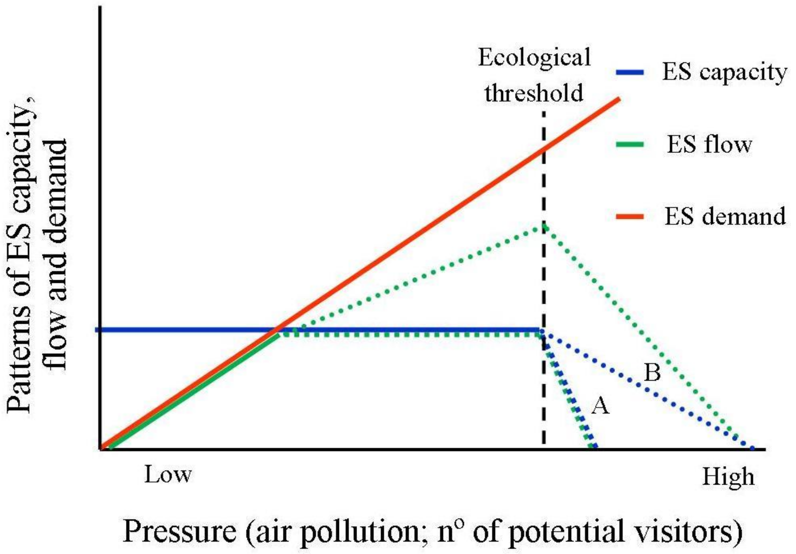

Fig. 8. Outline of hypothetic patterns of ES capacity, flow and demand under increasing pressures considering ecological thresholds. In the case of air purification, capacity and flow would likely experience an abrupt decrease after the ecological threshold (case A) while for outdoor recreation the change would probably be more gradual (case B). Further, air purification flow cannot exceed capacity because of biophysical constraints, but recreation flow can indeed surpass capacity and ultimately trigger its decline due to congestion.

The issue of the spatial scale of ES capacity, flow and demand maps (Geijzendorffer and Roche, 2014) also arises from this research. Our spatial results reflect that the actual use or experience of the two ES analyzed highly depends on the proximity between ES providing areas and benefiting areas (Syrbe and Walz, 2012), leading to relevant unsatisfied demands which are mainly located at the urban core of the BMR. Therefore, we argue that both the regional and local scales should be considered in these assessments in order to comprehensively support planning and policy (Scholes et al., 2013). For instance, a more detailed resolution could take into account small ES providing areas which are often overlooked in regional assessments. These areas might have a relevant impact in terms of ES flow and unsatisfied demand in the urban core. Moreover, the proposed interventions for both ES could be much more accurately designed in local scale studies. However, the lack of fine resolution spatial data for the appropriate quantification of ES capacity, flow and demand indicators is probably a major challenge for this type of analyses (Derkzen et al., 2015). This issue also calls for a strong institutional coordination between local and regional authorities dealing with urban and environmental policy and for the harmonization of planning instruments at different scales.

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5. Conclusions

We advanced a spatial application of the ES capacity, flow and demand framework and tested its usefulness for landscape and urban planning in a case study. Our results suggest that the current landscape planning instrument for the BMR (PTMB, 2010) could foster the enhancement of relevant ES providing areas (i.e., ES capacity), but at the same time it might lead to degradation of some important ES flows due to possible future urban developments.

We argue that planning and policy strategies intended to reconcile flow and demand at the local level should focus on different components of the framework depending on each ES. For air purification, urban policies should focus on decreasing demand drivers (i.e., air pollution concentrations), whereas an optimized fulfillment of outdoor recreation demand could be fostered in core urban areas mainly through strong planning instruments intended to maintain and foster ES capacity and flow, for example by preserving and enhancing existing green spaces and restoring or creating new ones. A promising strategy could consist of a policy mix combining prescriptive policy regulations (e.g., enforcement of caps and stricter green infrastructure ratios) and economic incentives (e.g., environmental taxes, subsidies and payments), accompanied by awareness rising campaigns on the links between ecosystems and human well-being.

From our study, we contend that the mapping of ES capacity, flow and demand can contribute to the successful integration of the ES approach in landscape and urban planning because it provides a comprehensive picture of the ES delivery process, considering both ecological and social underlying factors. However, we identified three main issues that should be better addressed in this type of assessments: (1) improvement of ES demand indicators using participatory methods (i.e., incorporating different preferences or expectations); (2) integration of ecological thresholds into the analysis and models; and (3) use of a multi-scale approach that covers both the local and regional planning levels and cross-scale interactions between them.

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Appendix A. Supplementary data

Mapping of outdoor recreation

As shown in **Figure A1**, the model follows a composite mapping procedure based on the aggregation of the three components (i.e., degree of naturalness, nature protection and water). Each component was developed through one or several factors considered relevant in the case study of the BMR and for which spatial input data was available (**Table A1**). All the scores assigned to the water component factors and to the 'remarkable trees' factor of the nature protection component were subject to a distance decay modelling, assuming that the recreation potential decreases as the distance from the specific feature (e.g., a beach) increases. The following inverse logistic function (1) was applied to these factors:

$$f\,(d) = \frac{1+K}{K+e^{\alpha \cdot d}} \cdot w \qquad (1)$$

Where: *d* is the distance from the specific feature, α and *K* are the size and shape parameters of the function adjusted according to a distance threshold assessment, and *w* is the assigned score. The parameters α and *K* were respectively set at 0.0035 and 30 for the factor 'beaches', corresponding to a distance thresholds of 1000 m at which the score is decreased by 50% and 2000 m at which the score is zero, and 0.008 and 30 for the rest of factors, corresponding to distance thresholds of 500 m and 1000 m (see also **Table A1**). The distance thresholds were defined based on the expert consultation process.

Factors within each component were aggregated by a simple linear summation method and normalized between 0 and 1 following equation (2). The three components were aggregated in the same way in order to obtain the final recreation potential index (RPI). Unlike the factors, all the components were given equal weights under the assumption that they cover complementary aspects of the recreational potential (Paracchini et al., 2014).

$$v' = \frac{v - min}{\max - min} \qquad (2)$$

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Table A1

Recreation potential components and data sources. Factors, scores and distance function thresholds defined in the expert consultation process.

Component	Factors (spatial dataset)	Data source	Assigned score	Distance function thresholds (m)		Comments
				50%	0%	
Degree of naturalness	Closeness to potential native vegetation	SITxell database – Habitats dataset (Barcelona Regional Council)	0-1	N/A	N/A	Based on an ecosystem assessment of its ecological succession stage. Originally scores ranged from 0 (artificial land covers) to 4 (climax ecosystem).
Nature protection	Areas designated as natural parks	Environment geodatabase (Catalan Government)	1	N/A	N/A	
	Areas designated as regional protected areas or Natura 2000 sites	Environment geodatabase (Catalan Government)	0.8	N/A	N/A	It excludes areas which are also designated as natural parks.
	Remarkable protected trees	Environment geodatabase (Catalan Government)	0.8	500	1000	
	Areas designated as geological heritage	Environment geodatabase (Catalan Government)	0.5	N/A	N/A	
Water	Lakes, ponds, reservoirs and wetlands	SITxell database – Habitats dataset (Barcelona Regional Council)	1	500	1000	
	Beaches	SITxell database – Habitats dataset (Barcelona Regional Council)	1	1000	2000	
	Main river network	Environment geodatabase (Catalan Government)	0.5	500	1000	Rivers usually having permanent water flow all the year.
	Angling river areas	Environment geodatabase (Catalan Government)	0.3	500	1000	

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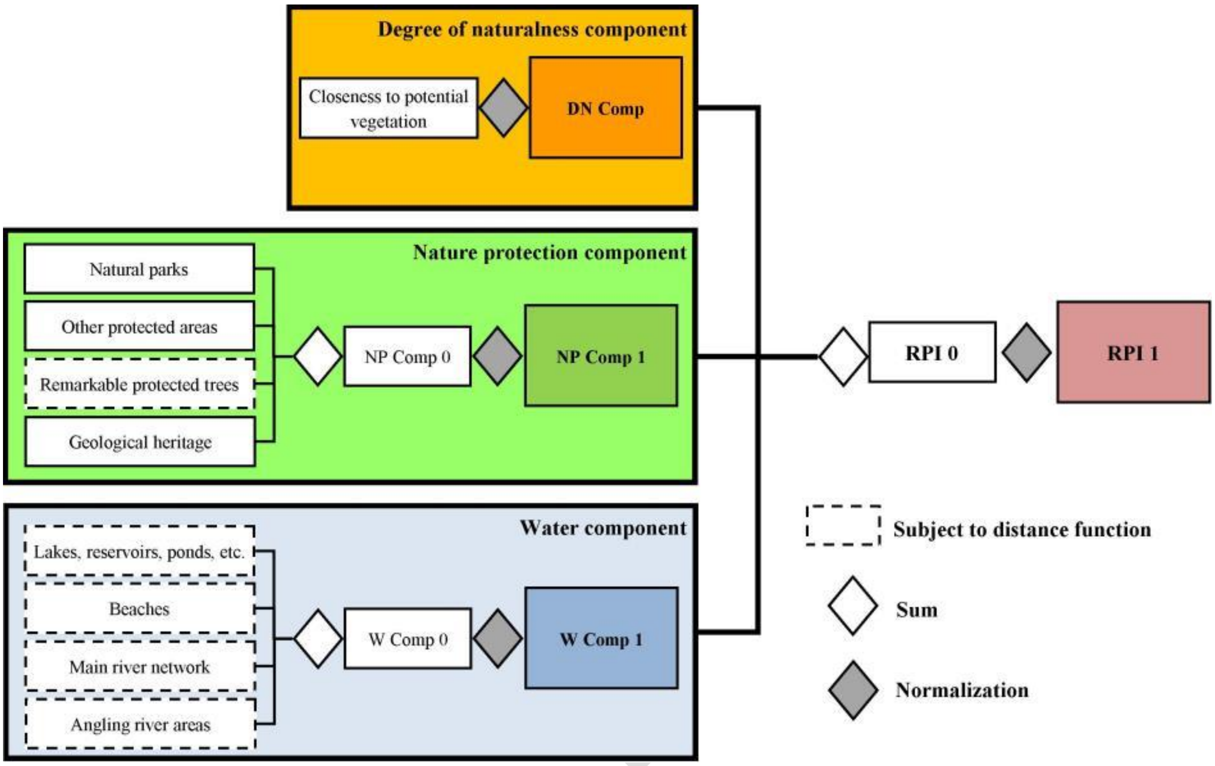

Fig. A1. Flowchart of the procedure to obtain the recreational potential map (adapted from Paracchini et al., 2014).

Potential trips for mapping the expected outdoor recreation flow were estimated using a neighbor operator with a custom matrix. The custom matrix was based on the distance decay function (1) considering α = 0.008 and K = 30 (see also **Fig. A2**).

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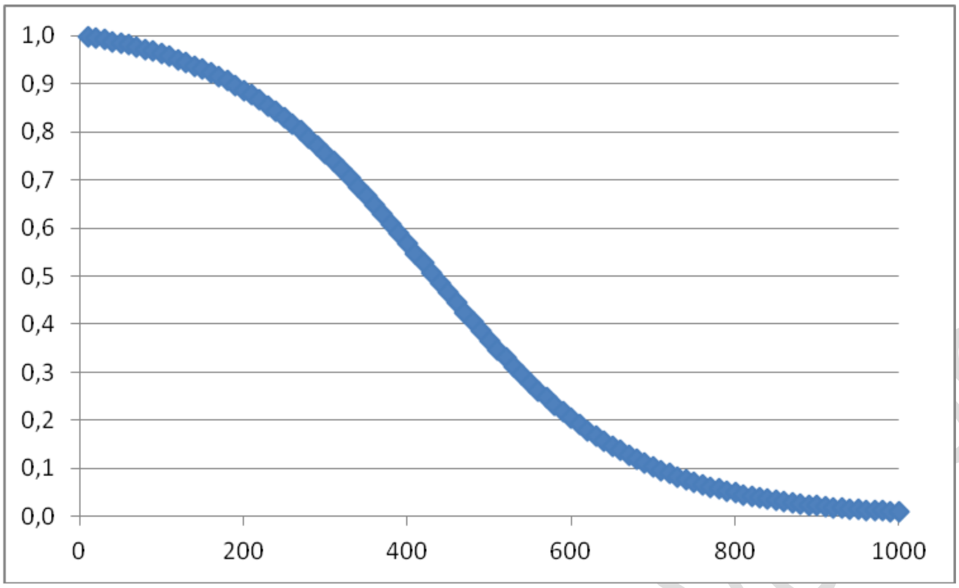

Fig. A2. Distance function (in m) applied for mapping the expected outdoor recreation flow. The function shape shows that the probability of travelling beyond 500m decreases below 0.5 (Paracchini et al., 2014).

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Table A2.

Cross-tabulation matrix between a reclassified raster of Euclidian distances to recreation sites and the population density grid used to obtain the outdoor recreation demand values (legend on the right). It assumes that all inhabitants in the case study area have similar desires in terms of (everyday life) outdoor recreational opportunities, but their level of fulfillment depends on proximity to recreation sites. Distance breaks consider the recommended standards by regulatory agencies (Stanners and Bourdeau, 1995; Barbosa et al., 2007).

Population density (inhab. ha^{-1})	**Distance to recreation sites (m)**					
	< 300	300 - 600	600 - 900	900 - 1200	1200 – 1500	> 1500
< 5	**0**	**0**	**0**	**0**	**0**	**0**
5 - 50	**0**	**1**	**1**	**2**	**2**	**3**
50 – 100	**0**	**1**	**2**	**2**	**3**	**4**
100 - 200	**0**	**2**	**2**	**3**	**3**	**4**
200 – 400	**0**	**2**	**3**	**3**	**4**	**4**
> 400	**0**	**3**	**4**	**4**	**4**	**5**

0	Lowest demand
1	
2	
3	
4	
5	Highest demand

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Mapping of air purification

Table A3 includes the complete list of the parameters considered for the modeling. Some of the predictor variables reflect sources or sinks of air pollution such as the road network, different types of land use and population density. The latter was considered also a proxy for traffic flow levels since no complete information is currently available. Furthermore, factors such as elevation, topographical exposure, distance to the sea, annual mean temperature, and annual mean wind speed also influence the spatial concentration of pollutants and were included in the modeling.

Annual air pollution removal was estimated as the total pollution removal flux in the areas covered by vegetation, where the removal flux (F; in t ha^{-1} $year^{-1}$) is estimated as:

$$F = V_d \cdot C \cdot 0.365 \qquad (3)$$

where V_d is the deposition velocity of the pollutant to the leaf surface (in m s^{-1}) and C is the pollutant concentration (in µg m^{-3}), and 0.365 a coefficient used for units adjustment. Areas covered by vegetation were calculated by a combination of detailed land cover maps of urban green areas and forest, aggregated to 100 m resolution. For urban vegetation, the green layers of the Global Human Settlement Layer (GHSL) (JRC, IPSC, Ferri et al., 2014) were used. For forests, the High Resolution Global Forest map developed by Hansen (2013) was used. Both GHSL and Hansen map are by now the most detailed information available on vegetation cover in the case study area. In overlapping areas, the maximum value of both maps was applied. Final map of vegetation had values between zero (i.e., no vegetation) and one (i.e., totally covered by vegetation).

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Table A3

Input data for the processing of the air purification model. All the input variables were computed at 100 m of resolution (pixel size).

Component	Data description	Data source	Comments
Air pollution measurements	Average annual pollutant concentrations in BMR monitoring stations (NO_2) - year 2013	Air quality database (Catalan Government - http://qualitatdelaire.cat)	Exported to vector data (points)
Spatial predictors	Land cover dataset	SITxell database (www.sitxell.eu) (Barcelona Regional Council)	Converted from vector data (polygons)
	Digital Elevation Model (DEM)	SITxell database (www.sitxell.eu) (Barcelona Regional Council)	Resampled from 15x15m raster (bilinear resampling)
	Average mean temperature (annual)	Climatic Digital Atlas of Catalonia (www.uab.es/atles-climatic)	Resample from 180x180 m raster (bilinear resampling)
	Average mean precipitation (annual)	Climatic Digital Atlas of Catalonia (www.uab.es/atles-climatic)	Resample from 180x180 m raster (bilinear resampling)
	Average wind speed at 60m altitude from land surface (annual)	Environment geodatabase (Catalan Government)	Resample from 200x200 m raster (bilinear resampling)
	Population density grid	Census tract dataset (INE, 2011) Residential use classes extracted from land cover map (LCMC, 2009)	Intersect assuming equal population distribution within residential land for each census tract
	Road network	TeleAtlas® MultiNet™ dataset (update 2014)	
Vegetation map	Urban vegetation	Global Human Settlement Layer (GHSL JRC, IPSC, Ferri et al., 2014)	
	Forest vegetation	High Resolution Global Forest map (Hansen, 2013)	
	Permanent crops	SITxell database (www.sitxell.eu) (Barcelona Regional Council)	Extracted from land cover dataset

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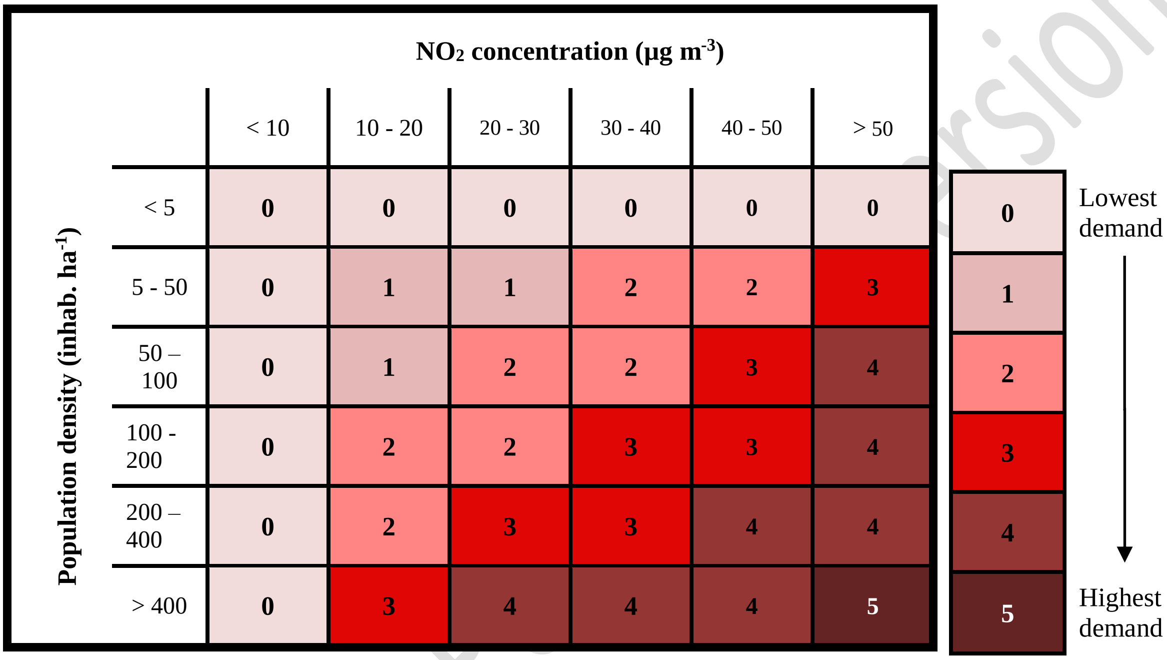
Table A4

Cross-tabulation matrix between NO_2 concentration levels and population density used to obtain the air purification demand values (legend on the right). It assumes that the higher NO_2 concentration and population density the higher demand values. NO_2 concentration break consider the current NO_2 concentration limit in Europe (EU, 2008).



	NO_2 concentration (μg m^{-3})					
Population density (inhab. ha^{-1})	< 10	10 - 20	20 - 30	30 - 40	40 - 50	> 50
< 5	0	0	0	0	0	0
5 - 50	0	1	1	2	2	3
50 – 100	0	1	2	2	3	4
100 - 200	0	2	2	3	3	4
200 – 400	0	2	3	3	4	4
> 400	0	3	4	4	4	5

0 Lowest demand
1
2
3
4
5 Highest demand

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