Chapter 9
Assessing the Potential of Regulating Ecosystem Services as Nature-Based Solutions in Urban Areas

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Abstract Mounting research assesses the provision of regulating ecosystem services by green infrastructure in urban areas, but the extent to which these services can offer effective nature-based solutions for addressing urban climate change-related challenges is rarely considered. In this chapter, we synthesize knowledge from assessments of urban green infrastructure carried out in Europe and beyond to evaluate the potential contribution of regulating ecosystem services to offset carbon emissions, reduce heat stress and abate air pollution at the metropolitan, city and site scales. Results from this review indicate that the potential of regulating ecosystem services provided by urban green infrastructure to counteract these three climate change-related pressures is often limited and/or uncertain, especially at the city and metropolitan levels. However, their contribution can have a substantially higher impact at site scales such as in street canyons and around green spaces. We note that if regulating ecosystem services are to offer effective nature-based solutions in urban areas, it is critically important that green infrastructure policies target the relevant implementation scale. This calls for a coordination between authorities dealing with urban and environmental policy and for the harmonization of planning and management instruments in a multilevel governance approach.

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9.1 Introduction

In an increasingly urban planet, cities and metropolitan areas are facing multiple climate change-related challenges, including heat stress, inland and coastal flooding, drought, increased aridity, and air pollution (Revi et al. 2014; UN 2015). Making cities and human settlements resilient, sustainable and safe should be thus a major priority on any government's agenda, as reflected in one of the seventeen United Nations (UN) Sustainable Development Goals (SDGs[1]). In this context, policy-makers, practitioners and scientists are paying growing attention to the sustainable planning and management of urban and periurban green spaces as a way to cope with threats affecting urban areas (McDonnell and MacGregor-Fors 2016). In the European Union (EU), strategies relying on ecosystems and their processes are mostly built on the concepts of 'green infrastructure' (GI, see EC 2013) and, more recently, 'nature-based solutions' (NBS, see EC 2015). Both terms are very much related as reflected in the EU GI strategy, which defines GI as "a successfully tested tool for providing ecological, economic and social benefits through natural solutions" and states that GI is based on the principle that "the many benefits human society gets from nature, are consciously integrated into spatial planning and territorial development" (EC 2013:2).

GI and NBS are useful notions for the operationalisation of the ecosystem services (ESS) framework, a powerful way of examining the interaction between ecosystems and human well-being (see also Pauleit et al., this volume). Since the seminal paper by Bolund and Hunhammar (1999), a growing body of literature has advanced our understanding of urban ESS in their spatial, temporal, value or practical dimensions (Gómez-Baggethun et al. 2013; Haase et al. 2014). Gómez-Baggethun and Barton (2013) synthesized knowledge and methods to classify and value urban ESS for planning, management and decision-making. Regulating ESS such as air purification, noise reduction, urban temperature regulation or runoff mitigation, not explicitly considered in MEA (2005) and TEEB (2010) classifications, were highlighted in that work due to their expected relevance for the quality-of-life of the urban population. Further, NBS examples in cities are often referred to air quality improvements, local temperature regulation, or increased energy savings provided by green roofs, urban parks or street trees (see Kabisch et al. 2016 and Enzi et al., this volume).

Although regulating ESS are the most frequently assessed ESS group in urban areas (Haase et al. 2014; Luederitz et al. 2015), the actual and potential contribution of regulating ESS to climate change mitigation and adaptation policies is often

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[1] See http://www.un.org/sustainabledevelopment/sustainable-development-goals/

overlooked in these evaluations, and therefore unknown to local authorities (see Baró et al. 2014). Considering both the potential magnitude of regulating ESS and the scope of the associated pressures to be addressed (e.g., greenhouse gas emissions, heat stress, air pollution) is essential to understand the extent to which regulating ESS can offer effective NBS at different spatial scales (Pataki et al. 2011). According to the framework developed by Villamagna et al. (2013), the flow of regulating ESS contributes to maintain or improve environmental quality within socially acceptable ranges (defined by standards or policy targets) up to a certain level of pressure. Once this threshold of pressure is exceeded, regulating ESS flow will no longer sustain a good environmental quality and therefore its impact as NBS will cease (see Fig. 9.1 and Baró et al. 2015).

In this chapter, we synthesize knowledge and findings of urban GI assessments carried out in Europe and beyond to evaluate the potential contribution of regulating ESS to cope with climate change-related challenges across metropolitan, city and site scales. Improving our understanding on the scale at which regulating ESS can offer most effective NBS is essential to link greening strategies to appropriate levels of planning and decision-making (Scholes et al. 2013; Demuzere et al. 2014). Here we focus on the role of regulating ESS in climate change mitigation (carbon sequestration and avoided emissions), climate change adaptation (urban temperature regulation) and air quality regulation (indirectly related to climate change adaptation). Following a sample of studies assessing the potential of regulating ESS as NBS in urban areas (Sect. 9.2), the case study of Barcelona, Spain, is described in more

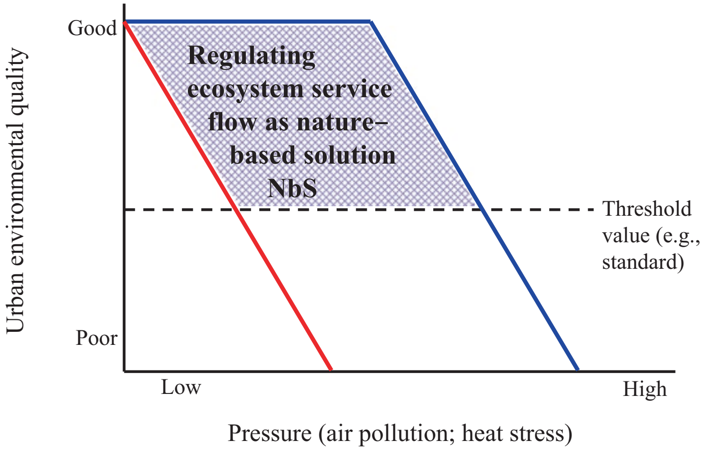

Fig. 9.1 Effects of climate change-related pressures (e.g., air pollution, GHG emissions, heat stress) on urban environmental quality within a system with low to no regulating capacity (*red line*) and a system with high regulating capacity (*blue line*). In the latter system, the flow of regulating ecosystem service contributes to maintain environmental quality within socially acceptable ranges (defined by standards or policy targets) up to a certain level of pressure. Once this threshold of pressure is exceeded, regulating ecosystem service flow will no longer sustain a good environmental quality and therefore its impact as nature-based solution will cease (Source: own elaboration building on Villamagna et al. (2013))

detail (Sect. 9.3). Section 9.4 synthesizes our main findings and points out the main policy implications as well as the priorities for the research agenda on the role of regulating ESS as NBS in urban areas.

9.2 Regulating Ecosystem Services as Nature-Based Solutions in Urban Areas

9.2.1 Global Climate Regulation (Carbon Sequestration and Avoided Emissions)

According to Satterthwaite (2008), 60–70% of total anthropogenic greenhouse gas (GHG) emissions could be assigned to urban activities. Urban climate change-related risks, such as droughts, flash floods and heatwaves, have increasing impacts on urban population (Revi et al. 2014). In response to this trend, a mounting number of cities worldwide are committing themselves to reduce their local GHG emissions by implementing climate change mitigation policies within their territories (see Bulkeley 2010).

Urban vegetation, in particular trees, can directly offset GHG emissions by sequestering carbon dioxide (CO_2) through photosynthesis and biomass storage (Nowak et al. 2013b). Further, urban trees can avoid GHG emissions associated to energy use in buildings due to their micro-climate regulation effects related to shading and evapotranspiration (McPherson et al. 2013, see also next subsection). Some studies suggest that urban green spaces can play an important role as carbon sinks (e.g., Nowak et al. 2013b) and that carbon sequestration rates are comparable to other local mitigation strategies based on energy savings (Escobedo et al. 2010). However, some authors argue that global climate regulation does not stand amongst the most relevant regulating ESS in urban areas because cities can benefit from carbon offsets performed by ecosystems located elsewhere (Bolund and Hunhammar 1999).

Most studies quantifying carbon storage and sequestration by urban vegetation use methods based on tree biomass and growth equations (e.g., i-Tree Eco model; Nowak et al. 2008). Main data inputs include field survey data on urban vegetation structure and remote sensing imagery (e.g., Liu and Li 2012). Recent meta-analyses in USA and China showed that urban GI can sequester and store substantial amounts of carbon. Nowak et al. (2013b) estimated total tree carbon storage and annual gross sequestration in USA urban areas at 643 and 25.6 million tonnes respectively (year 2005). Chen (2015) estimated carbon storage and yearly sequestration by the urban vegetation in 35 major Chinese cities at 18.7 and 1.9 million tonnes respectively (year 2010). However, the latter study also revealed that the offsetting impact by this regulating ESS represented only 0.33% of the carbon emissions from fossil fuel consumption in the case study cities. Generally, studies estimating carbon budgets in urban areas show very modest or marginal impacts in terms of carbon offsetting by urban vegetation (e.g., Escobedo et al. 2010; Liu and Li 2012; Vaccari et al. 2013; Zhao and Sander 2015; see also Table 9.1). Besides, Baró et al. (2015) showed

Table 9.1 Selected sample of modelling and empirical studies on carbon offsetting by vegetation in urban areas at different spatial scales

Study sites	Scale and green infrastructure considered	Methods and data	Indirect energy effects considered?	Annual % offset of total CO_2 emissions	References
35 Chinese cities	City (green space in general)	Meta-analysis of various empirical studies	No	From 0.01 (Hohhot) to 22.45 (Haikou). 0.33 (overall)	Chen (2015)
Shenyang (China)	Metropolitan (urban trees)	Biomass equations, field survey data and satellite images	No	0.26	Liu and Li (2012)
Beijing (China)	City (street trees)	Field surveys, tree growth measurements and statistical data	No	0.2	Tang et al. (2016)
Urbanized portion of Miami-Dade County and city of Gainesville (USA)	Metropolitan and city (Urban trees and palms)	UFORE model (allometric equations), field data	Yes	3.4 (Gainesville) 1.8 (Miami-Dade)	Escobedo et al. (2010)
Municipality of Florence (Italy)	City (urban green space in general)	Eddy covariance technique, GIS data	No	6.2 (total) 1,1 (urban green) 5.1 (periurban green)	Vaccari et al. (2013)
Urbanized areas of Dakota and Ramsey County (USA)	Metropolitan (urban trees)	Allometric models and LiDAR data	No	1.08	Zhao and Sander (2015)
5 EU cities (Barcelona, Berlin, Rotterdam, Stockholm, Salzburg)	City (urban trees)	i-Tree Eco model, tree cover data	No	From 0.12 (Rotterdam) to 2.75 (Salzburg)	Baró et al. (2015)
Residential neighbour-hoods in Singapore and Mexico City	District (Trees and other vegetation, soils)	Eddy covariance technique, biomass and growth equations, tree survey	No	1.4 (Mexico City)-4.4 (Singapore)	Velasco et al. (2016)
Salt Lake Valley (USA)	Metropolitan (urban trees)	Forest growth model and satellite imagery	No	0.2 (relative to a scenario of doubling the tree-planting density after 50 years)	Pataki et al. (2009)

Note: Annual % offset of total CO_2 emissions are based on different baseline years and considering different carbon inventories (see corresponding references) that contribution is also minor in relation to local GHG reduction targets, suggesting that greening strategies are not likely to be an effective carbon mitigation strategy in cities. For example, Pataki et al. (2009) found that doubling the tree-planting density in the urban region of Salt Lake Valley (USA) would offset only 0.2% of total annual CO_2 emissions over the period 1980–2030. Most of these studies, however, only consider direct carbon sequestration, omitting the indirect effects of urban vegetation that can lead to reduced energy use in cities (see Table 9.1). Yet, the assessments considering emissions avoided due to micro-climate regulation by urban GI show that the related offsets are lower than those related to direct sequestration (Escobedo et al. 2010; McPherson et al. 2013).

Generally, estimates of direct carbon sequestration and indirect energy effects provided by urban GI face multiple uncertainties and limitations. Urban vegetation is usually exposed to unique environmental conditions (e.g., restricted rooting volumes, higher temperature and CO_2 concentration than in rural areas) and maintenance characteristics (e.g., intensity of pruning and irrigation) which can positively or negatively impact their total carbon offsetting capacity (Pataki et al. 2011; Tang et al. 2016). Allometric and growth equations used to quantify carbon storage and sequestration are mostly based on non-urban conditions, yet adjustment factors are often considered in the modelling to minimize error (Nowak et al. 2008). In addition, fossil fuel emissions associated to urban green space maintenance (e.g., pruning) and decomposition rates of removed trees can eventually compensate sequestration gains or even generate negative carbon balances (Nowak et al. 2002). Using a life cycle approach, Strohbach et al. (2012) predicted positive carbon balances of an urban green space project in Leipzig (Germany) over a lifetime of 50 years considering different design and maintenance scenarios. However, the study revealed that small increases in tree mortality can lead to substantial sequestration reductions, thus adequate tree species selection and management can play a key role in carbon offsetting potential.

Most part of the above-mentioned studies only consider the CO_2 flux associated to urban trees and other vegetation, omitting the contribution related to soils. Urban soils can act as relevant carbon sinks (Pouyat et al. 2006), especially those primarily composed by organic materials (e.g., histosols or peat soils). However, soil respiration can constitute an important emission source too (Velasco et al. 2016), thereby adding a new layer of complexity in urban carbon budget estimates.

9.2.2 Local Climate Regulation (Urban Temperature Regulation)

The negative impacts of heat stress on human health, particularly during heatwaves, are singularly strong in cities due to the exacerbating effect of the urban heat island (UHI) (EEA 2012). Human health vulnerability to temperature extremes depends on a complex interaction between different factors such as age, health status and socio-economic variables such as housing (Kovats and Hajat 2008; Fischer and Schär 2010). However, general critical temperature thresholds for health impacts in Europe have been estimated based on the spatial and temporal variance in excess mortality during recent heatwaves episodes (Fischer and Schär 2010). For example, more than 70,000 excess deaths were attributed to the European heatwave occurred during the summer of 2003 (Robine et al. 2008). Consequently, there is a pressing need to develop effective adaptation strategies against mounting heat stress associated to more frequent and intense extreme heat events in cities expected from human-induced climate change (Revi et al. 2014).

Urban greening has been proposed as an effective strategy to mitigate the human health impacts from increased temperatures in urban areas (e.g., EEA 2012). Basically, urban vegetation can reduce local temperatures through evapotranspiration and shading. Obviously, urban trees have a major role in both processes compared to other types of vegetation such as shrubs or grass (Bowler et al. 2010).

The extensive review by Bowler et al. (2010) of the empirical evidence for the cooling effect of urban GI revealed that this impact can be especially relevant at the site scale. The main findings of this meta-analysis were: (1) urban parks are, on average, around 1 °C cooler than non-green sites in the day, with maximum difference values around 2 °C or even higher (e.g., Jansson et al. 2007); (2) street trees have a cooling effect at the urban canyon level, but its magnitude depends on a number of factors such as tree species, canyon orientation or canyon width (see also Norton et al. 2015); (3) studies show that other types of urban GI elements such as green roofs and green walls can also regulate urban temperature at the site scale (see Alexandri and Jones 2008 and Enzi et al., this volume); and (4) the extension of the cooling effect of green space beyond its boundaries is likely, but uncertain, especially at the wider city and metropolitan scales. By using a modelling approach, Chen et al. (2014) predicted substantial reductions in heat stress-related mortality in the city of Melbourne (Australia) associated to the urban cooling effects generated by city-scale greening strategies.

9.2.3 Air Quality Regulation (Air Pollution Removal)

Abatement of air pollution is a pressing challenge in most major urban areas worldwide, either in low-, middle or high-income countries (World Health Organization – WHO – Global Urban Ambient Air Pollution Database, update 2016[2]). For example, the 2015 annual report on air quality in Europe (EEA 2015) estimated that, during the period 2011–2013, 17–30% of the European urban population was exposed to

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[2] See http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/

PM_{10} (particulate matter with a diameter of 10 μm or less) concentrations above the limit value set by the EU Air Quality Directive (50 μg m^{-3}, 24-h mean value; EU 2008). This percentage of people exposed to problematic pollution levels increases to 61–83% if the more stringent WHO standard (WHO 2005) is applied (20 μg m^{-3}, annual mean value). The harmful impacts of ambient air pollution on human health are consistently and increasingly supported by scientific evidence (Brunekreef and Holgate 2002; EEA 2015) and its global burden of disease was estimated to be 3.7 million deaths during 2012 (WHO 2014). Urban air quality in most cities is compromised by local air pollution emissions from transport, industry and other sources, but it is also sensitive to climate change (Revi et al. 2014). Recent literature shows evidence that climate change will generally increase ground-level ozone in the USA and Europe, but the impacts on air quality in particular urban areas are highly uncertain, as are the effects on other pollutants' concentrations such as particulate matter (Jacob and Winner 2009).

Vegetation in urban landscapes, in particular trees, can remove pollutants from the atmosphere, mainly through leaf stomata uptake and interception of airborne particles (Irga et al. 2015). Further, urban vegetation can act as physical barrier that prevents the penetration of pollutants into specific areas (Salmond et al. 2013). Thus, urban greening strategies have been proposed as a means to reduce air pollution levels (e.g., Nowak et al. 2006). However, the potential for vegetation to improve urban air quality (and consequently population health) in meaningful ways is contested due to uncertainties associated to the modelled estimations and the scarcity of empirical studies (Pataki et al. 2011). Further, urban vegetation can emit biogenic volatile compounds (BVOCs) which eventually contribute to the formation of ground-level ozone and CO (carbon monoxide) air pollutants (Kesselmeier and Staudt 1999).

Most studies estimating air pollution removal by urban vegetation are based on dry deposition models such as i-Tree Eco[3] (e.g., Yang et al. 2005; Nowak et al. 2006; Escobedo and Nowak 2009; Nowak et al. 2013a; Selmi et al. 2016). Generally, these models are applied at a city or metropolitan scale considering green space attributes (such as leaf area index, LAI), pollution concentration data (from available monitoring stations) and meteorological data (Nowak et al. 2008). Results from these modelling studies show that urban vegetation can remove substantial amounts of air pollution. For example, Nowak et al. (2006) estimated that total annual air pollution removal (considering five different pollutants) by urban trees and shrubs in conterminous US amounted to 711.300 t during 1994. Nevertheless, estimated average percent air quality improvements in the 55 selected USA cities attributable to air pollution removal by vegetation were very low (from 0.1 to 0.6% for nitrogen dioxide, NO_2, and 0.2 to 1.0% for PM_{10}). Modelling studies in urban areas of South America (Escobedo and Nowak 2009), Asia (Yang et al. 2005) or Europe (Selmi et al. 2016) showed similar marginal impacts on air quality

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[3] Formerly known as UFORE (Urban Forest Effects), see http://www.itreetools.org/

at the city or metropolitan scale (see also Table 9.2). These results suggest that greening strategies (e.g., implementing tree-planting programs) might have a limited effectiveness to address air pollution problems (e.g., if pollutant concentrations are surpassing air quality standards) at the city scale (Baró et al. 2015). Still, modelling studies also show that air quality improvements by vegetation are likely to be more relevant at the site scale. For example, Escobedo and Nowak (2009) and Baró et al. (2015) estimated average percent air quality improvements higher than 6% for PM_{10} in urban areas with an hypothetical 100% tree cover (e.g., contiguous forest stands). In street canyons, however, some modelling studies (e.g., Wania et al. 2012; Vos et al. 2013; Jin et al. 2014) reveal that most part of green street designs (such as double tree row) have a negative effect on local air quality because they reduce ventilation and hence dispersion of traffic emitted pollutants such as particulate matter (PM) and NO_2. Jin et al. (2014) suggested intense pruning of street tree canopies (optimal canopy density was estimated at 50–60%) in order to minimize their negative trapping effect on particles. In contrast, Pugh et al. (2012) argued that GI elements such as green roofs and especially green walls can substantially reduce street-level concentrations (as much as 43% for NO_2 and 62% for PM_{10}) because they increase pollutant deposition without the negative aerodynamic effects on ventilation.

As for other models attempting to simulate complex biophysical processes, there are many uncertainties and limitations in dry deposition models which prevent a more accurate determination of air pollution uptake by urban vegetation. For instance, some sources of uncertainty include non-homogeneity in spatial distribution of air pollutants, particle re-suspension rates, soil moisture status, transpiration rates or leaf boundary resistance (Manning 2008). Local fine-scale input data for these variables are not usually available and empirical data on the actual uptake of pollutants by urban vegetation is still limited (Pataki et al. 2011; Setälä et al. 2013). In general, available experimental studies show that green space is quantifiably associated with reduced air pollution levels at the site scale, especially in regard to particulate matter (Irga et al. 2015; see also Table 9.2). For example, urban parks in Shanghai, China, could remove pollution at ground-level by a maximum of 35% for TSP (total suspended particles) and 21% for NO_2 (Yin et al. 2011); an approximate average removal of 50% for TSP was attributed to greenbelts in Khulna City, Bangladesh (Islam et al. 2012); and the average reduction of air pollutants under tree canopy in two Finnish cities was as much as 40.1% for airborne particles and 7.1% for NO_2 relative to pollutant concentrations in open areas (Setälä et al. 2013). However, this last study found no significant associations between the variation in pollution concentrations and vegetation structure attributes such as canopy closure or number and size of trees. Janhäll's review (2015) concluded that design and selection of urban vegetation is critical for air quality improvements at the site level. Low, dense and porous vegetation close to pollution sources was suggested as the most effective design because it increases pollutants deposition and at the same time does not hinder dilution of emissions with the higher clean atmospheric layer.

Table 9.2 Selected sample of modelling and empirical studies assessing the role of air purification by vegetation in urban areas at different spatial scales

Study site(s)	Scale and green infrastructure considered	Air pollutants assessed	Method	Estimated % air quality improvement	References
55 USA cities	City (urban trees and shrubs)	CO, NO_2, O_3, PM_{10}, SO_2	Dry deposition model (i-Tree Eco)	0.2–1.0 (PM_{10}) 0.1–0.6 (NO_2)	Nowak et al. (2006)
Santiago Metropolitan Region (Chile)	Metropolitan (urban trees)	CO, NO_2, O_3, PM_{10}, SO_2	Dry deposition model (i-Tree Eco)	0.6–1.6 (PM_{10}) 0.2–0.4 (NO_2)	Escobedo and Nowak (2009)
10 USA cities	City (urban trees)	$PM_{2.5}$	Dry deposition model (i-Tree Eco)	0.05–0.24	Nowak et al. (2013a)
5 EU cities (Barcelona, Berlin, Rotterdam, Stockholm, Salzburg)	City (urban trees and shrubs)	PM_{10}, NO_2, O_3	Dry deposition model (i-Tree Eco)	0.20–2.42 (PM_{10}) 0.07–0.81 (NO_2) 0.10–1.16 (O_3)	Baró et al. (2015)
Central London (UK)	Site - Street Canyon (Green roofs and walls scenarios)	PM_{10}, NO_2	Street-canyon chemistry and deposition model (CiTTy-Street)	6.4–42.9 (NO_2) 10.8–61.9 (PM_{10})	Pugh et al. (2012)
19 different real-life urban vegetation designs (Belgium and Netherlands)	Site- Street Canyon (Trees and other green barriers)	PM_{10}, NO_2 and EC	Computational fluid dynamics (CFD) model (ENVI-met)	Most part of roadside urban vegetation designs have a negative effect on air quality	Vos et al. (2013)
Pudong District, Shanghai (China)	Site (six urban parks)	TSP, NO_2 and SO_2	Empirical data (mid-flux air and passive samplers)	2–35 (TSP) 2–27 (SO_2) 1–21 (NO_2)	Yin et al. (2011)
Khulna City, Bangladesh	Site (two greenbelts)	TSP	Empirical data (active monitors)	Approx. 50–65	Islam et al. (2012)
Two Finnish cities (Helsinki and Lahti)	Site (tree-covered park areas and treeless open areas, twenty sites in total)	NO_2, VOC and TSP	Empirical data (passive samplers)	2.0–7.1 (NO_2) 36.1–40.1 (TSP)	Setälä et al. (2013)
Sydney (Australia)	Site (eleven sites in central Sydney with various green space conditions)	CO_2, CO, VOC, NO, NO_2, SO_2, TSP, PM_{10}, $PM_{2.5}$	Empirical data (active monitors)	Green space is quantifiable associated with reduced PM levels	Irga et al. (2015)

Notes: CO_2 (carbon dioxide), CO (carbon monoxide), VOC (volatile organic compounds), NO (nitric monoxide), NO_2 (nitrogen dioxide), SO_2 (sulphur dioxide), TSP (total suspended particulate matter), PM_{10} (suspended particles <10 µm in diameter), $PM_{2.5}$ (suspended particles <2.5 µm in diameter), O_3 (ground-level ozone). Estimated % air quality improvements indicate the minimum-maximum average value range (if available). In empirical studies it refers to average removal of air pollutants in green areas relative to treeless areas (see corresponding references)

9.3 The Case Study of Barcelona

9.3.1 *Case Study Area*

For the urban area of Barcelona, located northeast of Spain on the Mediterranean Sea, regulating ESS have been assessed both at the city (Barcelona municipality) and regional (Barcelona metropolitan region, BMR) scales. See Baró et al. (2014, 2016) for a complete assessment description. The BMR hosts 5.03 million inhabitants living in a total area of 3243 km^2 (Statistical Institute of Catalonia 2015). It embeds 164 municipalities, but its urban core is mainly constituted by the municipality of Barcelona (1.61 million inhabitants and 101.4 km^2) and several adjacent middle-size cities. The BMR still contains a rich variety of natural habitats of high ecological value, including Mediterranean forests (1185 km^2; 36.5%) and scrubland (449 km^2; 13.8%), extensive agro-systems (655 km^2; 20.2%) with a substantial share of vineyard, and various inland water bodies (24 km^2; 0.7%). Currently, almost 70% of the land is protected from urbanisation including, totally or partially, 14 Natura 2000 sites. In contrast, green space in the municipality of Barcelona is scarce. The total green space within the municipality of Barcelona (including urban parks, periurban forests and other green land covers) amounts to 27.2 km^2 representing 26.8% of the municipal area and a ratio of 16.9 m^2 of green space per inhabitant (based on Land Cover Map of Catalonia 4th edition[4], year 2009).

The multi-scale assessment covers two relevant regulating ESS for the case study area: air quality regulation and carbon sequestration. The city of Barcelona and other urban areas in the BMR have repeatedly exceeded the EU limit values for average annual concentrations of NO_2 and PM_{10} (both set at 40 $\mu g/m^3$) in the last decade (ASPB 2011). The City Council of Barcelona signed the 'Covenant of Mayors' initiative[5], committing to reduce 23% municipal GHG emissions until 2020 (baseline year 2008). Other municipalities in the BMR have also set similar reduction targets.

9.3.2 *Data and Main Results*

The multi-scale assessment was based on the definition and quantification of indicators of regulating ESS provision and pressure, building on different models and data sources described in Baró et al. (2014, 2016) and Baró (2015). See also an overview in Table 9.3. Pressure indicators (i.e., NO_2 pollution and carbon emissions) can be considered a proxy of regulating ESS demand since the higher the pressure magnitude, the higher the policy demand for regulating processes by ecosystems (see Burkhard et al. 2014; Baró et al. 2015; Wolff et al. 2015).

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[4] Available from http://www.creaf.uab.es/mcsc/

[5] See http://www.covenantofmayors.eu/index_en.html

Table 9.3 Overview of regulating ecosystem service indicators and related pressures calculated for the Barcelona multi-scale assessment

Regulating ecosystem service	Scale/study area	Provision and pressure indicators	Unit	Main input data	Methods	Main references
Carbon sequestration	Regional (BMR)	Carbon sequestration (Provision)	kg/ha year	National forest inventory data (IFN2 & IFN3)	Land use regression modelling	Pino (2007)
				Land use data and other spatial predictors.		Baró (2015)
	Local (Barcelona municipality)	Carbon sequestration (Provision)	t/year	Field data	i-Tree Eco Model	Nowak et al. (2008)
				Allometric equations from literature		Baró et al. (2014)
	Regional (BMR)	Carbon emissions (Pressure, demand proxy)	kg/ha year	Carbon emissions per sector and municipality (year 2012)	Available carbon inventories	Sustainable Energy Action Plans (Barcelona Regional Council data)
	Local (Barcelona municipality)	Carbon emissions (Pressure, demand proxy)	t/year	Carbon emissions per sector in Barcelona (year 2008)	Available carbon inventories	Baró et al. (2014)
						PECQ (2011)
Air quality regulation	Regional (BMR)	NO_2 removal flux (Provision)	kg/ha year	Air quality data from BMR monitoring (year 2013)	Land use regression modelling (ESTIMAP)	Zulian et al. (2014)
				Various spatial predictors (see main references)		Baró et al. (2016)
	Local (Barcelona municipality)	NO_2 removal flux (Provision)	t/year	Field data	i-Tree Eco Model	Nowak et al. (2008)
				Air quality data from Barcelona monitoring stations (year 2008)		Baró et al. (2014)
				Meteorological data (year 2008)		
	Regional (BMR)	Annual mean NO_2 concentration (Pressure, demand proxy)	$\mu g/m^3$	Air quality data from BMR monitoring (year 2013)	Land use regression modelling (ESTIMAP)	Zulian et al. (2014)
				Various spatial predictors (see main references)		Baró et al. (2016)
	Local (Barcelona municipality)	NO_2 emissions (Pressure, demand proxy)	t/year	NO_2 emissions in Barcelona and background pollution impact (year 2008)	Available emissions data	Baró et al. (2014)
						PECQ (2011)

At the level of Barcelona municipality, results show that the contribution of urban GI to climate change mitigation is very low (5187 t carbon sequestered in 2008), accounting for 0.47% of the overall city-based GHG emissions in that year. Similarly, NO_2 removal by urban GI in the municipality of Barcelona (55 t/year) only represented 0.53% of the total city-based emissions in 2008, indicating a marginal air quality improvement.

At the regional level (BMR), the provision of both regulating ESS shows similar spatial patterns (see Figs. 9.2a and 9.3a). Regulating ESS fluxes are especially relevant in periurban forest areas such as the mountain range of Collserola and other tree-covered sites located in the hinterland. However, NO_2 removal in some of these areas (e.g., Montseny massif) is relatively low because pressure (pollutant concentrations) is also moderate (see Fig. 9.2b). The lowest provision values for both regulating ESS are located in urban and agricultural land. As expected, the highest pressure values are mostly located in the municipality of Barcelona and adjacent middle-size cities (see Figs. 9.2b and 9.3b). As observed in the local scale assessment, the urban core is characterized by a compact urban form, very high population density and a relative small share of inner green areas. The other middle-size municipalities, located both along the coastline and hinterland, show mostly middle to low pressure values. The higher spatial resolution of NO_2 concentration compared to carbon emissions also reveals that high capacity roads are major sources of NO_2 pollution. The spatial indicator of pressure related to air purification (annual mean NO_2 concentration) expresses the remaining air pollution after regulating ESS provision (Guerra et al. 2014 refer to it as 'ESS mitigated impact'). Thus, the resulting map (Fig. 9.2b) indirectly shows where regulating ESS provision cannot sustain a good air quality level according to the NO_2 limit value set by the EU Air Quality Directive (40 $\mu g/m^3$). The carbon offsetting impact of urban GI is small on average (less than 5%) across BMR municipalities (see Fig. 9.3c). Only in 5 out of 164 BMR municipalities, the estimated carbon emissions are completely offset by carbon sequestration by the local vegetation. These municipalities are characterized by very low population density (less than 500 inhabitants) and predominance of forest land cover.

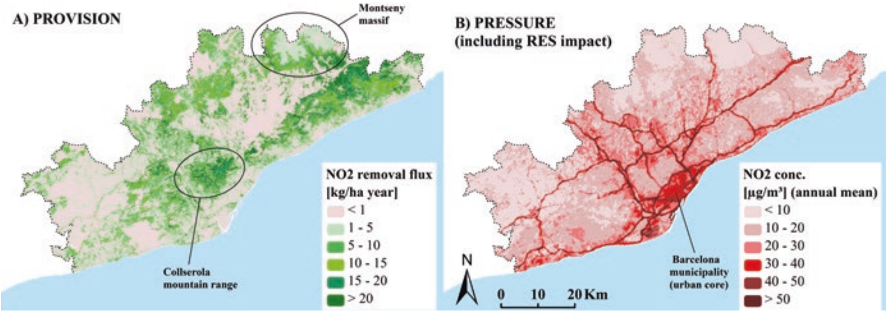

Fig. 9.2 (**a**, **b**) Provision and pressure maps related to the air purification in the Barcelona metropolitan region (Source: own elaboration building on Baró et al. (2016). Map '2a' is reused from Baró et al. (2016) with kind permission from Elsevier Ltd. See Table 9.3 for data sources)

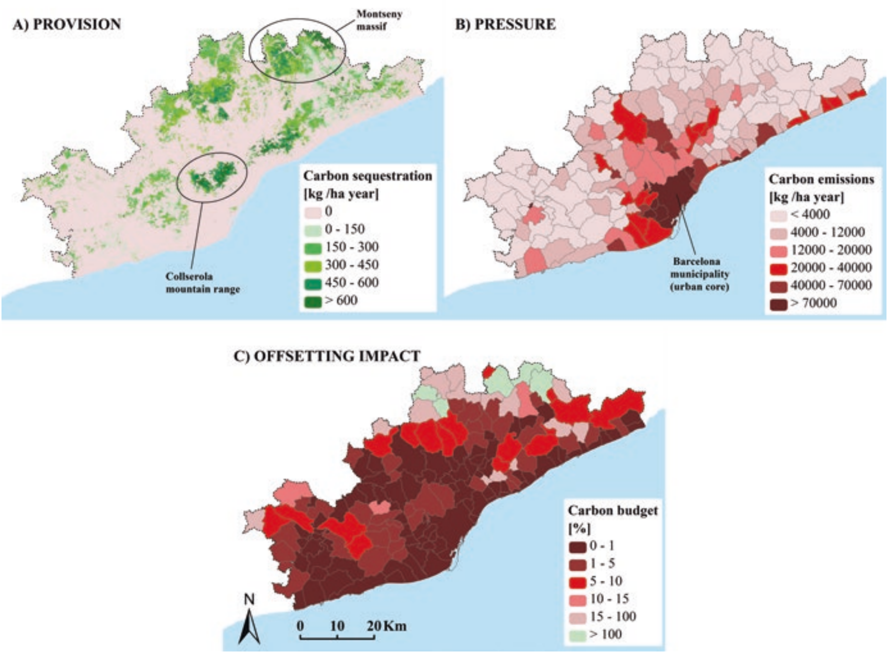

Fig. 9.3 (**a**, **b**, **c**) Provision and pressure maps related to carbon sequestration in the Barcelona metropolitan region (Source: own elaboration building on Baró (2015). See Table 9.3 for data sources)

9.4 Synthesis and Concluding Remarks

Our review indicates that the potential of regulating ESS provided by urban GI to counteract carbon emissions, air pollution and heat stress is often limited and/or uncertain, especially at the city level. In other words, most studies suggest that the magnitude of these environmental problems is usually too high at the city scale relative to the actual or potential contribution of urban ecosystems in mitigating their impacts. At the metropolitan scale, the proportion of urban GI versus built-up or urbanized land is generally substantially higher than at the core city level (e.g., see Barcelona case described above). Yet, metropolitan regulating ESS assessments also show marginal impacts in the overall carbon budgets (e.g., less than 1% in the case of Barcelona). The estimated high air purification and cooling capacities of large metropolitan GI blocks (e.g., protected natural areas) are generally ‘underused’ due to their distance from demand sites (i.e., residential areas most affected by air pollution or heat stress; see also Baró et al. 2016). This result indicates that the relevant spatial scales for NBS with respect to air pollution and cooling are probably confined to the city or site level. Results from empirical and modelling studies are largely supportive that urban GI, especially urban trees, can improve air quality, offset carbon emissions and reduce heat stress at the site level (especially within and around green spaces). Yet, factors such as species selection, design and management practices of NBS can have a critical impact on the performance of regulating ESS provision. Table 9.4 summarizes the evidence associated with the potential of the three regulating ESS considered here as NBS at three different spatial scales: metropolitan, city and site. Our findings are consistent with previous similar assessments (Pataki et al. 2011; Demuzere et al. 2014).

On the basis of current knowledge and associated uncertainties regarding the potential of regulating ESS as NBS for air quality improvement, carbon offsetting and reduction of heat stress in urban areas, we advance the following policy and research implications:

- More empirical research is needed in order to decrease the levels of uncertainty associated to the impact of regulating ESS provision on urban environmental quality, especially at the city and metropolitan scales, which mostly rely on modelling studies.

Table 9.4 Potential magnitude of the assessed regulating ESS as NBS relative to the scope of the associated urban pressure on three spatial scales

Regulating ecosystem service	Potential as NBS			
	Metropolitan (regional scale)	City (local scale)	Green space (site scale)	Street canyon (site scale)
Air quality regulation	🟥 Low to moderate	🟥 Low	🟧 Moderate	🟧 Depending on vegetation design and composition
Carbon sequestration and avoided carbon emissions	🟥 Low	🟥 Low	🟥 Moderate	🟥 Not defined
Local temperature regulation	🟥 Not defined	🟥 Low to moderate	🟩 Moderate to high	🟧 Moderate

Source: own elaboration based on the evidence discussed above (Tables 9.1 and 9.2) and Pataki et al. (2011)

Notes: The potential was considered high on a specific scale when the evidence from the reviewed studies showed that urban GI can substantially contribute to environmental quality (i.e., air quality, local temperature, carbon offsets). The regulating ESS potential was considered low when most part of studies show that urban GI has a marginal impact on environmental quality at the corresponding spatial scale. In some cases, this qualitative assessment could not be defined due to unclear, conflicting or even lacking evidence. Additionally, grid colours correspond to the current level of uncertainty (considering both empirical and modelling analyses) associated to the potential magnitude of regulating ESS at the different spatial scales: low (*green*); moderate (*orange*) and high (*red*)

- Urban climate change and air pollution mitigation policies should primarily focus on the sources of pollution (built infrastructure and transport systems), not on the sinks (urban GI absorbing carbon and pollutants). Our assessment clearly shows that air pollution problems and local GHG reduction targets are to be dealt with emission reduction policies (e.g., road traffic management, energy efficiency measures). The role of urban GI strategies can be complementary to these policies, but not alternative. Additionally, carbon offsets associated to GI can be fostered by local and metropolitan authorities beyond urban boundaries (see Seitzinger et al. 2012).
- Urban GI can contribute to site-scale strategies related to air quality and heat stress. For example, urban parks, street trees or green roofs/walls can act as clean air/cool zones and corridors within cities. The potential of green roofs and walls can be particularly relevant due to lack of available land in urban cores (see Enzi et al., this volume).
- Trade-offs and disservices related to NBS should be considered in planning and management in order to estimate ‘net’ contributions to environmental quality. Even if most urban GI elements, such as urban trees, are multi-functional in relation to the three regulating ESS considered in this analysis, some trade-offs have been identified in the literature. For example, dense tree canopies provide a high shading effect, but they are also associated to lower dispersion rates of air pollution in street canyons (e.g., Jin et al. 2014).

The scope of this analysis is limited to three tested regulating ESS (air quality regulation, local climate regulation and global climate regulation through carbon sequestration and avoided emissions) in urban areas, while obviously urban GI can also provide additional ESS and benefits to the urban population, such as water regulation, health and social benefits (see chapters in this issue and other synthesis reviews, e.g., Pataki et al. 2011; Demuzere et al. 2014). Unlike standard ‘grey’ or technological infrastructures that are normally designed as single-purpose, an added value of urban GI resides on its multi-functionality (see Demuzere et al. 2014 for a comprehensive analysis of synergies or co-benefits associated to different types of urban GI). Therefore, we contend that planning and managing urban GI in the context of NBS for climate change mitigation and adaptation requires an holistic approach, considering the whole range of ESS potentially provided by different types of urban GI and the interactions between them, together with the different spatial scales at which these ESS can be relevant for the resilience, sustainability and safety of urban areas. This calls for a strong multi-scale institutional coordination between all the authorities dealing with urban and environmental policy and for the harmonization of planning and management instruments at different levels.

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