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A framework to explore the effects of urban planning decisions on regulating ecosystem services in cities

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ABSTRACT

Urban planning is the most relevant decision-making process affecting urban regulating ecosystem services. However, a clear understanding of the effects of planning decisions on both the supply and demand of urban regulating ecosystem services is still lacking. To support planners in enhancing urban regulating ecosystem services, there is a need to understand what variables are at stake and how changes in planning-related variables may affect urban regulating ecosystem services. The article presents a conceptual framework that describes how capacity, demand, and flow of urban regulating ecosystem services, and related benefits, are linked to the main variables controlled by urban planning, i.e. the location, typology, and size of urban green infrastructure, and the spatial distribution and vulnerability profile of population and physical assets. The variables and links described in the framework are then detailed for seven urban regulating ecosystem services. The analysis reveals, for each service, what are the main levers on which planners can act to shape the amount and spatial distribution of urban regulating ecosystem services and related benefits across the city. Uses and limitations of the proposed framework are discussed, and some key messages are drawn for planners on how to operationalise the findings.

1. Introduction

Regulating ecosystem services (ES) are defined as the "*benefits obtained from the regulation of ecosystem processes"* (MA, 2005, p.40) and comprise the multiple ways through which ecosystems regulate environmental conditions, including soil, water, and air quality; climate variations; and the frequency and intensity of hazards (Smith et al., 2013). In urban areas, regulating ES locally produced by urban ecosystems and their components include, among others, air purification, microclimate regulation, noise reduction, and runoff mitigation (Gómez-Baggethun and Barton, 2013), which play a key role in promoting healthy, liveable, and resilient cities (McPhearson et al., 2015; van den Bosch and Sang, 2017). Despite this, regulating ES are often overlooked in current decision-making processes, due to multiple reasons recently summarised by Sutherland et al. (2018), who solicited a greater attention towards this ES category.

Among the decision-making processes affecting ES in cities, urban planning is arguably the most relevant. By deciding "where to put things" (Polasky et al., 2008), urban planning defines the dimension and location of green infrastructure components, hence the typology of ES suppliers and their distribution across the city. In the last years, the scientific literature on urban ES has grown exponentially, mostly focusing on the relation between green infrastructure and ES supply (Haase et al., 2014; Luederitz et al., 2015; Pulighe et al., 2016). At the same time, there has been a strong call to integrate innovative concepts such as green infrastructure, ES, and nature-based solutions in current urban planning practices, especially in the European Union (European Commission, 2015, 2013). As a result, planning approaches based on green infrastructure and ES have been spreading among planners and decision-makers at the municipal level (Kabisch, 2015; Mascarenhas et al., 2014; Young, 2013), and many urban plans now contain actions aimed at enhancing ES for multiple benefits, including flood control, air pollution reduction, and noise mitigation (Cortinovis and Geneletti, 2018a; Hansen et al., 2015; Rall et al., 2015).

Urban planning also affects ES by defining the spatial arrangement of land uses and functions, hence the distribution of population and physical assets that determine the demand for regulating ES (Langemeyer et al., 2016). Yet, the effects of planning decisions on ES demand are rarely explored, which somehow reflects a still limited focus of the scientific literature on this aspect (Bagstad et al., 2013; McPhearson et al., 2014; Schmidt et al., 2016). The few studies explicitly addressing the analysis of regulating ES in relation to planning

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scenarios (e.g., Kain et al., 2016; Mascarenhas et al., 2019) focus on how alterations of the green infrastructure modify ES supply, but do not consider how changes in other land uses, including e.g. urban expansions or densification, may affect the intensity and distribution of ES demand.

Overall, a complete picture of the links between regulating ES and urban planning decisions is still lacking. While methods and indicators to describe urban regulating ES are useful to assess current conditions and identify existing needs, as demonstrated by a growing number of studies (e.g., Baró et al., 2016; Derkzen et al., 2015; Holt et al., 2015; Larondelle and Lauf, 2016), they seem still unable to support planning in adopting a scientifically-based proactive approach, grounded on a clear understanding of the effects of planning decisions (Davies et al., 2017).

On a conceptual level, several authors have pointed out the gap between planning and ES assessments. Ahern and colleagues noted that ES assessments can support the definition of benchmarks, but *"they do not motivate, or support the innovations required to provide specific ecosystem services as an intentional part of routine urban and infrastructure development activity by municipalities and professionals"* (Ahern et al., 2014, p. 254). Von Haaren and colleagues noticed that the main objective of existing ES frameworks and interpretations is "explanation" rather than "application" in planning and decision-making (von Haaren et al., 2014). Similarly, with reference to monetary valuation, Wright and colleagues observed that they tend to be more "conceptual" than "instrumental", i.e. to support discussion rather than decision (Wright et al., 2017).

Operationally, this makes it hard for municipal officers and decision-makers to consider the enhancement of urban ES, particularly regulating ES, as a strategic goal to orient planning decisions. Recent reviews of planning documents reveal that regulating ES are rarely mentioned among the strategic goals of urban plans (Cortinovis and Geneletti, 2018a) and actions to strengthen the provision of regulating ES are often not supported by an appropriate knowledge base (Cortinovis and Geneletti, 2018a; Geneletti and Zardo, 2016). These findings are confirmed by the opinion of municipal officers. Interviews with urban forest managers in 15 major cities in UK revealed that, despite regulating ES provided by trees in cities are widely acknowledged, they are not considered as a relevant aspect when interventions on urban forests are planned (Davies et al., 2017).

To support planners, there is a need to identify the most relevant variables that link regulating ES with planning decisions and to understand – at least qualitatively - how the former react to the latter. This helps planners to identify the potential impacts of different strategies and to select the right type of intervention to enhance urban regulating ES. Only at a later stage, when interventions are fine-tuned and tailored to the specific local context, a detailed quantification of their expected benefits can be carried out to verify their design.

The aim of the article is to provide an overall picture of the relationship between urban planning decisions and the provision of regulating ES and associated benefits in cities. Specifically, the article has two objectives:

1. at the conceptual level, to provide an overall framework that describes how ES capacity, demand, and flow are linked to the main variables controlled by urban planning;
2. at a more operational level, to detail the links between planning variables and ES for a set of seven key urban regulating ES.

The remainder of the article is organised in four sections. Section 2 describes the approach and the methods adopted in the study. Section 3 presents the results in the form of a conceptual framework (Section 3.1) and a series of tables detailing the links between planning variables and seven urban regulating ES, including indicators suitable for urban planning purposes (Section 3.2). Section 4 discusses the main findings and limitations of the study from both a conceptual and an operational perspective. Finally, Section 5 draws some key conclusions.

2. Methods

The aim of the conceptual framework is to link the provision of urban regulating ES and related benefits to planning decisions. Hence, as a first step, relevant variables to describe both the process of ES provision and the different types of planning decisions were selected.

The main components involved in the process of ES provision were identified building on two existing models and approaches for ES assessment: the Cascade conceptual model (Haines-Young and Potschin, 2010) and the supply-demand approach for ES mapping and assessment (Baró et al., 2016; Burkhard et al., 2012). The Cascade model describes the supply side of ES, which "flow" from the structural and functional characteristics of urban ecosystems to the benefits produced. The supply–demand approach complements the Cascade by making explicit the presence of a demand side, thus allowing for the identification of the whole set of variables involved.

Following Sutherland et al. (2018), the presence of ecological pressures as a main factor determining the provision of regulating ES was also considered. For the purpose of this study, ecological pressures are defined as those conditions that are regulated by the respective urban ES, as it will be further detailed in the following section. Hence, on the ES side, the framework includes the four components that are considered fundamental to assess the provision of regulating ES, i.e., ecological pressures, ES capacity, ES demand, and ES flow (Sutherland et al., 2018), with the addition of ES benefits, coherently with the Cascade model (Haines-Young and Potschin, 2010), to indicate both the target of planning actions and a way to measure their impacts.

Each component was then broken down into at least two descriptive variables. One variable describes the component from a spatial point of view (i.e., location and size, when relevant). The other variable describes the component from a quantitative point of view (i.e., amount or intensity). A combination of the variables allows for a description of urban regulating ES that is spatially-explicit and quantitative for all components, which is considered a basic requirement to respond to the needs of urban planners (Syrbe and Walz, 2012).

To identify the relevant variables on the planning side, we distinguished between planning decisions related to urban green infrastructure and planning decisions more broadly related to the spatial distribution of land uses and functions (Saarikoski et al., 2016). The former are linked to the supply side of ES, since urban green infrastructure components act as service providing units (Vandewalle et al., 2013) that can be planned with the specific purpose of delivering ES (European Commission, 2013). The latter are linked to the demand side (Burkhard et al., 2012).

Regarding urban green infrastructure, the main planning variables relevant at the local scale were identified following Grafius et al. (2018) and include size, distribution, and composition (i.e., typology of urban green infrastructure components). Regarding land uses and functions, the main variables that affect the demand for urban regulating ES were identified in the spatial distribution of people and physical assets across the city and the resulting vulnerability profile of the different areas (Baró et al., 2016; Wolff et al., 2015).

The components of the framework and the links between them were then detailed to describe seven key regulating ES, identified among the most relevant ES supplied by urban ecosystems (Gómez-Baggethun and Barton, 2013; Haase et al., 2014; Luederitz et al., 2015). The analysed ES are listed in Table 1, together with the underpinning ecosystem functions and the respective biophysical structures and processes (Haines-Young and Potschin, 2010). The analysis was based on the review of a wide scientific literature on urban regulating ES. The selection of the literature started from the key references identified by Elmqvist et al. (2016) and Gómez-Baggethun and Barton (2013) (see Table 1) and followed a snowball search approach (Greenhalgh and Peacock, 2005) looking for publications specifically dedicated to each ES. When needed, more recent studies were included to supplement the retrieved information.

Table 1
List of the seven urban regulating ES considered in the analysis: ecosystem functions that underpin each ES, biophysical structures and processes that support the supply, and key references. Modified after Elmqvist et al. (2016), Gómez-Baggethun and Barton (2013).

urban regulating ES	ecosystem function	biophysical structure (process)	key Refs.
air purification	uptake of gaseous air pollutants	leaves	Nowak et al. (2006)
	deposition of particles	vegetation	Nowak et al. (2006)
global climate regulation	carbon sequestration	vegetation (photosynthesis) and soil	Jo and McPherson (1995), Nowak et al. (2013)
	carbon storage	vegetation and soil	Pouyat et al. (2006), Strohbach and Haase (2012)
moderation of extreme events	physical barrier (absorption of kinetic energy)	trees	Danielsen (2005), Dobbs et al. (2011)
noise reduction	reflection and diffraction of noise	vegetation and soil	Van Renterghem et al. (2012)
	noise absorption	vegetation (mechanical vibration) and soft soil	Van Renterghem et al. (2012)
runoff mitigation and flood control	water infiltration	permeable surfaces	Yang et al. (2015)
	rainfall interception	tree canopies	Xiao and McPherson (2002)
	reduction of flood velocities	vegetation	Nisbet and Thomas (2006)
	water storage	floodplains	Blackwell and Maltby (2006)
urban temperature regulation	evapotranspiration	vegetation	Coutts et al. (2012)
	shading	tree canopies	Shashua-Bar and Hoffman (2000)
	evaporation	water	Saaroni and Ziv (2003)
	heat transfer (storage and release)	*water bodies*	Saaroni and Ziv (2003)
	wind blocking	*trees*	Huang et al. (1990)
waste treatment*	removal of storm water pollutants (sedimentation, filtration, sorption, assimilation and degradation)	ponds, wetlands, vegetated surfaces	Clar et al. (2004), Hemond and Benoit (1988)
	decomposition of solid organic litter	*soil*	Vauramo and Setälä (2011)

Functions in italics are not further considered in the study.
* For waste treatment, among the high number of existing typologies of stormwater treatment and management systems, we limit our analysis to the illustrative cases of wetlands and vegetation strips.

3. Results

3.1. Linking planning variables to urban regulating ES

The framework describes, at the conceptual level, how urban planning decisions affect the provision of regulating ES and related benefits in cities (Fig. 1). We assume that urban planning acts towards the enhancement of urban regulating ES as a response to an unsatisfied demand, which arises from the exposure of population and physical assets to undesirable conditions generated by ecological pressures. Within this overall picture, urban planning can act on urban regulating ES through two main entry points: i) on the supply side, by determining the location, typology and size of urban green infrastructure, and ii) on the demand side, by defining the arrangement of land uses and functions in the city. On the supply side, conservation, restoration, enhancement, and creation of urban green infrastructure are the actions that planners can put in place to secure and enhance the provision of urban regulating ES (Cortinovis and Geneletti, 2018a). On the demand side, planners can arrange land uses and functions in a way that the demand matches the existing supply (Rodríguez-Rodríguez et al., 2015).

The characteristics of urban green infrastructure components, defined by planning, determine their capacity to supply urban regulating ES, i.e., their capacity to act as Service Providing Units (SPU). SPU are "*the components of biodiversity necessary to deliver a given ES at the level required by service beneficiaries*" (Vandewalle et al., 2013, p. 323), hence they represent the minimum units to analyse ES supply. Not all typologies of urban green infrastructure provide the same ES (Bastian et al., 2012; Zardo et al., 2017), hence, for each urban regulating ES, understanding how SPU are spatially distributed across the city involves an analysis of urban green infrastructure location and typologies.

In the case of urban regulating ES supplied by more than one typology of urban green infrastructure, different typologies are characterised by a different capacity to perform the ecological functions involved in each ES (e.g., Baumgardner et al., 2012; Farrugia et al., 2013). Moreover, the size of the SPU is a key variable affecting its performance. Hence, the specific ES capacity that characterise each SPU is a function of typology and size (Zardo et al., 2017). The relation

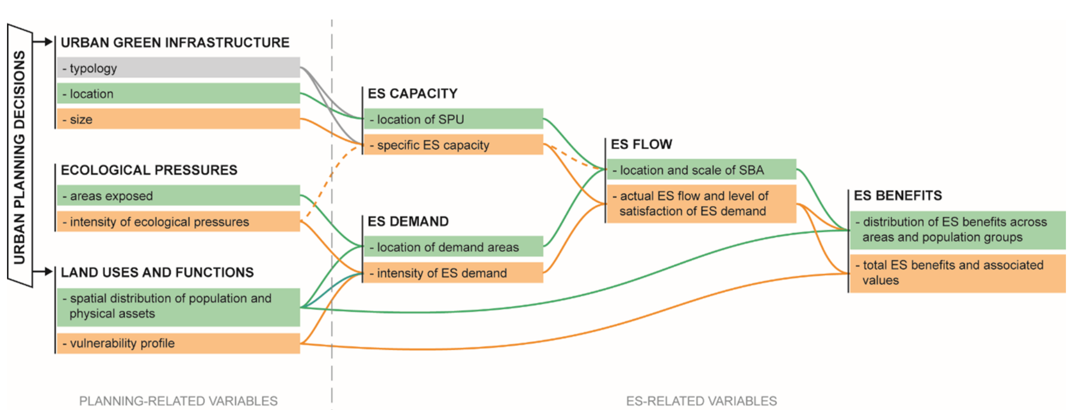

Fig. 1. The proposed conceptual framework showing the links between urban planning decisions and the provision of regulating ES and related benefits in cities. Each component of the framework is described at least by one spatial variable (green) and one quantitative variable (orange).

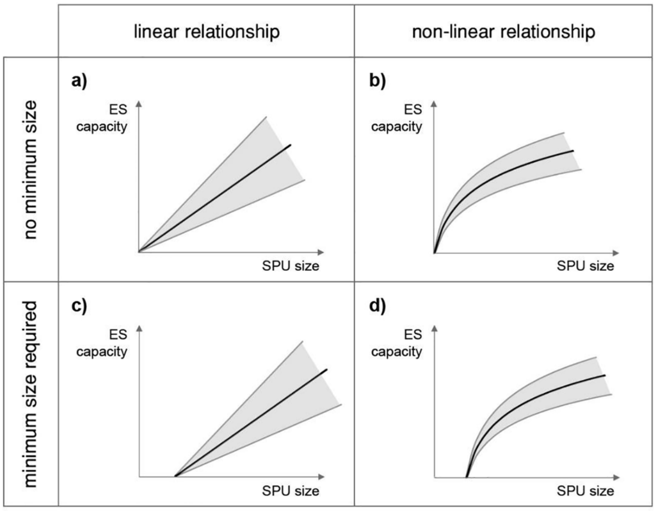

Fig. 2. Schematic representation of the possible relations between planning variables related to urban green infrastructure and ES capacity: a) linear relationship between size and ES capacity with no minimum size required for ES supply; b) non-linear relationship between size and ES capacity with no minimum size required for ES supply; c) linear relationship between size and ES capacity with minimum size required for ES supply; d) non-linear relationship between size and ES capacity with minimum size required for ES supply. Different slopes indicate differences in the ES capacity of different typologies of urban green infrastructure.

between size and ES capacity may be linear or not linear, depending on the ES, with non-linear relations often showing a decreasing efficiency.

For some ES, a minimum size of SPU is required. This is the case when the ecological processes underpinning ES capacity are emergent properties resulting from the interaction of different functions (Escobedo et al., 2011), or when individuals (e.g., single trees) do perform the underpinning ecological functions, but only the sum of multiple contributions reaches the minimum level of supply that can be perceived by beneficiaries as an actual ES. In the former case, entire ecosystems are the minimum SPU involved in the supply, while in the latter a population – in ecological terms - is required as SPU (Andersson et al., 2015). Fig. 2 summarises the possible relations between SPU size and ES capacity.

Ecological pressures linked to regulating ES are spatially and temporally variable (Andersson et al., 2015; Sutherland et al., 2018), and can be described in terms of areas exposed and respective intensity. The intensity of ecological pressures measures, in a specific place and at a specific moment in time, the level of hazard or the distance from a desirable state (Baró et al., 2016). For certain ES, the intensity of ecological pressures has a direct effect on the ecosystem functions performed by green infrastructure, ultimately increasing or decreasing ES capacity. However, the most important role of ecological pressures is in the definition of ES demand. Ecological pressures associated to urban regulating ES (e.g., air and water pollution, noise, extreme weather events) represent a risk for human health and security. Hence, they generate the need for protection and mitigation that is at the basis of the demand for urban regulating ES (Wolff et al., 2015).

Planning decisions about how land uses and functions are arranged in the city determine what types of population and physical assets (including buildings, infrastructures, and ecosystems) are located where. Two aspects must be considered to assess ES demand: the spatial distribution of population and physical assets, and their sensitivity and resilience to the ecological pressure of interest. The combined analysis of areas exposed to ecological pressures and spatial distribution of population and physical assets allows identifying where the demand is (ES demand areas) and the amount of people and physical assets exposed. The analysis of sensitivity and resilience is necessary to assess the intensity of ES demand. In the proposed framework, the intensity of demand in each area is therefore a function of three variables: i) the local intensity of ecological pressures, ii) the amount of people and assets exposed, and iii) the sensitivity and resilience of the population and physical assets in the area to the specific ecological pressure under consideration.

Once SPU and ES demand areas are identified, the actual flow of ES can be assessed. Areas where ES are actually enjoyed by beneficiaries can be defined as Service Benefitting Areas (SBA) (Burkhard et al., 2014; Syrbe and Walz, 2012) and are at the overlap between ES supply and ES demand areas (Burkhard et al., 2012). ES supply areas are those areas where environmental conditions are affected by the regulating functions performed by SPU. hence represent potential SBA. Contrarily to what happens to tradable ES (e.g., provisioning ES), ES supply areas and SBA of regulating ES are never decoupled from SPU (Burkhard et al., 2014), although man-made infrastructure may mediate between the two, as in the case of the urban water sector. Depending on the specific ES under consideration, potential SBA are characterized by different spatial relations with SPU (see Fisher et al., 2009; Syrbe and Walz, 2012) and different spatial scales, from the single household to the global scale. In some cases, the ES capacity of the SPU may also affect the scale of the potential SBA, since SPU with higher capacity can benefit wider areas (e.g. microclimate regulation or moderation of extreme events).

For each SBA, it is possible to calculate the actual flow (i.e., how much of the ES capacity is actually used) and the level of satisfaction of ES demand. Supply-demand ratios (Zhao et al., 2015) and budgets (Burkhard et al., 2012), and the amount of unsatisfied demand (Baró et al., 2016) are possible ways to measure the efficiency in the provision of ES within each SBA, although the results of such approaches, especially when applied to urban regulating ES, require careful interpretation based on a clear understanding of the underlying hypotheses (Schröter et al., 2012).

The benefits generated by the provision of urban regulating ES depend on the negative impacts of ecological pressures that are avoided thanks to ES provision. These are a function of the quantity of ES that flows to beneficiaries and of the specific exposure-response ratio that measures the expected impacts of ecological pressures considering the relevant characteristics of beneficiaries. Higher levels of sensitivity and lower levels of resilience determine greater impacts, hence a greater benefit when impacts are reduced or avoided. Since regulating ES are purely non-rival ES (Kemkes et al., 2010), benefits are not limited by crowding or congestion in SBA. Hence, in principle, a total benefit over a certain area can be calculated as the sum of the benefits experienced by each beneficiary. On the other hand, by combining the analysis of ES flow with the spatial distribution of population across the city it is possible to investigate the distribution of ES benefits across different areas and population groups, a fundamental information for urban planning to address equity in the distribution of ES (Jennings et al., 2017).

3.2. How planning decisions affect specific urban regulating ES

For the framework to become an operational tool that supports planning decisions, the variables and links described at the conceptual level need to be detailed for the specific regulating ES of interest. Hereunder we report the results of the analysis carried out for the seven key urban regulating ES listed in Table 1.

Table 2 identifies the ecological pressures linked to the analysed urban regulating ES and describes them in terms of spatial distribution and temporal variability. As it can be observed, pressures related to urban regulating ES are mostly human-induced factors, often directly related with urbanization processes, although their scale varies from local to global phenomena. An overview of the effects that they produce on urban population and physical assets, as well as on urban green infrastructure, is provided in Table S1 in the Supplementary Material.

Table 2
Ecological pressures linked to the analysed urban regulating ES, their spatial distribution, temporal variability, and possible environmental quality standards or targets to measure their intensity.

urban regulating service	ecological pressure	spatial distribution*	temporal variability**	environmental standard or target to measure intensity
air purification	concentration of air pollutants (PM_{10}, $PM_{2.5}$, NO_2, O_3, CO, SO_2)	variable	press characterised by seasonal variations	● air quality targets (e.g., European Union, 2008) (Baró et al., 2016)
global climate regulation	concentration of greenhouse gases (CO_2)	uniform	press	● emission reduction targets (e.g., Covenant of Mayors) (Baró et al., 2014) ● carbon emission offset (Zhao et al., 2015)
moderation of extreme events	storms, floods and waves	local	pulse	● acceptable risk based on the return time of the event (Liquete et al., 2013)
noise reduction	noise	local	press characterised by continuous variations but nearly-constant peaks	● target noise levels (e.g., WHO, 2009)
runoff mitigation and flood control	stormwater runoff	variable	pulse	● acceptable risk based on the return time of the event (Olsen et al., 2015)
urban temperature regulation	urban heat island and heat waves	variable	pulse	● based on an agreed-upon definition of heatwave (e.g., Fischer and Schär, 2010) (Baró et al., 2015) ● critical heat index (Bodnaruk et al., 2017)
waste treatment	concentration of stormwater contaminants	variable	pulse	● quality standards for the receiving waters (e.g. European Union, 2000) ● post-construction stormwater standards (e.g. US EPA, 2011)

* Key: uniform = affecting the whole city with the same intensity; variable = affecting the whole city with different intensities depending on the location; local = affecting only certain areas of the city.
** For more details on press and pulse pressures and their potential relation with ES capacity refer to Sutherland et al. (2018).

Table 3
Planning variables that describe urban green infrastructure (UGI) in relation to their capacity to provide urban regulating ES: UGI typologies and respective level of ecological organisation, relevant UGI size and relation with ES capacity, effect of ecological pressure.

urban regulating ES	ES capacity/flow indicator [unit]	UGI typologies and level of ecological organisation *	relevant UGI size and relation with ES capacity **	effect of ecological pressure on ES capacity ***
air purification	pollution removal [t/yr]	trees (I), shrubs (I)	area (a)	↑
global climate regulation	carbon storage [t], carbon sequestration [t/yr]	trees (I), shrubs (I), soil (E)	area (a)	↑
moderation of extreme events	wave height reduction [%]	trees (P), wetlands (E)	width of the buffer zone (d)	↔
noise reduction	excess noise attenuation [dBA]	trees (P), shrubs (P), soft soil (E)	width of the buffer zone (c/d)	↔
runoff mitigation and flood control	avoided runoff	trees (P), shrubs (P), permeable soil (E), wetlands (E)	area (interception and infiltration), volume (storage) (a/c)	↓
urban temperature regulation	Δt [°C]	trees (I), shrublands and grasslands (E), permeable areas (E), wetlands (E), water courses (E), water bodies (E)	area and shape index (b)	↓evapotranspiration, ↑ shading
waste treatment	pollution removal efficiency [%]	herbaceous vegetation (E), soil (E), wetlands (E)	wetland-to-watershed area / length of the vegetation strip (d)	↓

* Levels of ecological organisation are defined according to the following key: I = individual, P = population, E = ecosystem (modified after Andersson et al., 2015).
** Relation with size is classified as in Fig. 2.
*** Types of relation with the intensity of ecological pressures are indicated as follows: ↑ = ES capacity increases at the increase of the respective ecological pressure, ↓ = ES capacity decreases at the increase of the respective ecological pressure, ↔no effect. More details are provided in Table S2 in the Supplementary Material.

With the only exception of the concentration of greenhouse gases, all the other pressures listed in Table 2 are not uniformly distributed across the city, hence it is important to understand to which extent their variability affects the assessment of ES supply and demand.

The intensity of ecological pressures can be measured with respect to a desired state, generally defined at the institutional level by setting environmental quality standards or targets to be achieved (Geijzendorffer and Roche, 2014) at the local, national, or international levels (Table 2). The distance between the standards or targets and the actual environmental conditions measures the intensity of ecological pressures and is part of the assessment of ES demand. Most of the ecological pressures are commonly monitored in the context of spatial and sectoral plans, with the aim of assessing the quality of the urban environment (e.g., air, water, noise pollution) or the presence of risks, especially those related to climate change (e.g., heat waves, floods, extreme events) (Galler et al., 2016). Hence, related information is usually available for planning purposes.

Urban green infrastructure involved in the provision of the analysed urban regulating ES and their relevant features that affect ES capacity are described in Table 3. Typologies are based on classifications that focus on the identification of SPU, as opposed to land use-based classifications. SPU typologies usually include: woodland/forest/coarse vegetation, trees, (tall and short) shrubs, grass/herbaceous vegetation/fine vegetation, bare soil/permeable surfaces, wetlands, and water, sometimes including mixed typologies based on management, such as private gardens or urban agriculture, as a way to overcome data limitations (Baumgardner et al., 2012; Davies et al., 2011; Derkzen et al., 2015; Kremer and Hamstead, 2016; McPhearson et al., 2013). Following Andersson et al. (2015), for each ES, each typology is associated to a minimum level of ecological organisation, thus highlighting cases when populations or entire ecosystems are the minimum ecological units acting as SPU.

As shown in Table 3, while trees are the most frequently mentioned, different typologies of urban green infrastructure, sometimes performing different ecosystem functions, are involved in the supply of the same ES. This means that, in most cases, different options exist to provide the same urban regulating ES. Moreover, most of the green infrastructure typologies are multifunctional, i.e. they support the provision of a bundle of ES (Luederitz et al., 2015), thus multiple benefits can be expected from planning actions enhancing the provision of urban regulating ES.

ES capacity is also affected by the size of the SPU and, in certain cases, by the intensity of the ecological pressure to which the SPU is exposed (Table 3). Depending on the biophysical mechanisms that underpin the provision of each urban regulating ES, factors such as area, width, or length can be used to describe the size of the SPU and to calculate ES capacity, either as proxies or as inputs for production functions and models (Maes et al., 2014; Nahuelhual et al., 2015). These factors can be considered the most relevant from a planning perspective, and they can be used to compare SPU of the same typology but different spatial extent. The intensity of ecological pressure affects five out of the seven urban regulating ES, although in some cases variations are negligible (e.g., increasing vegetation growth rate due to increasing CO_2 concentration in the atmosphere does not lead to a major improvement of global climate regulating in urban environments) and effects may be contrasting (e.g. in the case of microclimate regulation).

Table 4 lists the planning variables and associated indicators that can be used to describe the arrangement of land uses and functions in relation to the demand for regulating ES. The spatial distribution of urban population and physical assets across the city can be described through data and indicators that are of common use in planning practices (e.g., population density, census data, land uses, and presence of infrastructures). The assessment of sensitivity and resilience is based on the expected outcomes of exposure (Turner et al., 2003) and considers the presence of population groups or urban areas that are highly vulnerable to the specific ecological pressure under consideration (Table 4).

The identification of demand areas requires combining information on areas exposed to ecological pressures, considering their spatial variability (Table 2), with information on the spatial distribution of urban population and physical assets (Table 4). According to the

Table 4
Planning variables that describe land uses and functions in relation with the demand for urban regulating ES: exemplary indicators to measure the spatial distribution of population and physical assets and their sensitivity and resilience to the ecological pressures under consideration.

urban regulating ES	spatial distribution of population and physical assets (ES demand areas and high exposure)	highly vulnerable population groups and urban areas (high sensitivity and/or low resilience)
air purification	• population density Baró et al. (2016), Morani et al. (2011)	• foetuses and children, elderlies, and persons with pre-existing cardiorespiratory diseases, diabetes, or asthma (Makri and Stilianakis, 2008)
global climate regulation	• census population; transportation, agricultural and industrial intensity per census tract Zhao et al. (2015)* • spatially-normalized annual CO_2 emissions per person Larondelle and Lauf (2016)*	-
moderation of extreme events	• population density, road density, percentage of artificial surfaces, number of historical and cultural sites Liquete et al. (2013)	• vulnerable areas based on the number of people and the total cost of damage (Wei et al., 2004)
noise reduction	• presence of residential and recreational areas Syrbe and Walz (2012)	• children, elderly, chronically ill (WHO, 2009)
runoff mitigation and flood control	• presence of flood-vulnerable properties Bagstad et al. (2014) density of built areas, density of households Syrbe and Walz (2012)	• vulnerable areas based on damage cost (Olsen et al., 2015)
urban temperature regulation	• census population Geneletti et al. (2016) population density Larondelle and Lauf (2016)	• infants; elderlies; people with obesity, hypertension, pulmonary, or cardiovascular disease; people with restricted mobility; people living alone and lacking social contacts; low-income groups (Basu and Samet, 2002; Kenny et al., 2010) • urban areas with more intense heat island effect based on density and lack of green spaces (EEA, 2012) • amount of elderly people (Larondelle and Lauf, 2016) • impervious cover density, children under the age of 5, adults above the age of 65 (Zidar et al., 2017)
waste treatment	• traffic load and proportion of impervious areas Nordeidet et al. (2004)*	• critical conditions of the sewage system (e.g., based on overflows and diffuse losses) (Nordeidet et al., 2004)

* In these studies, demand areas are prioritised based on the effects of land uses and functions on ecological pressures (not on exposure).

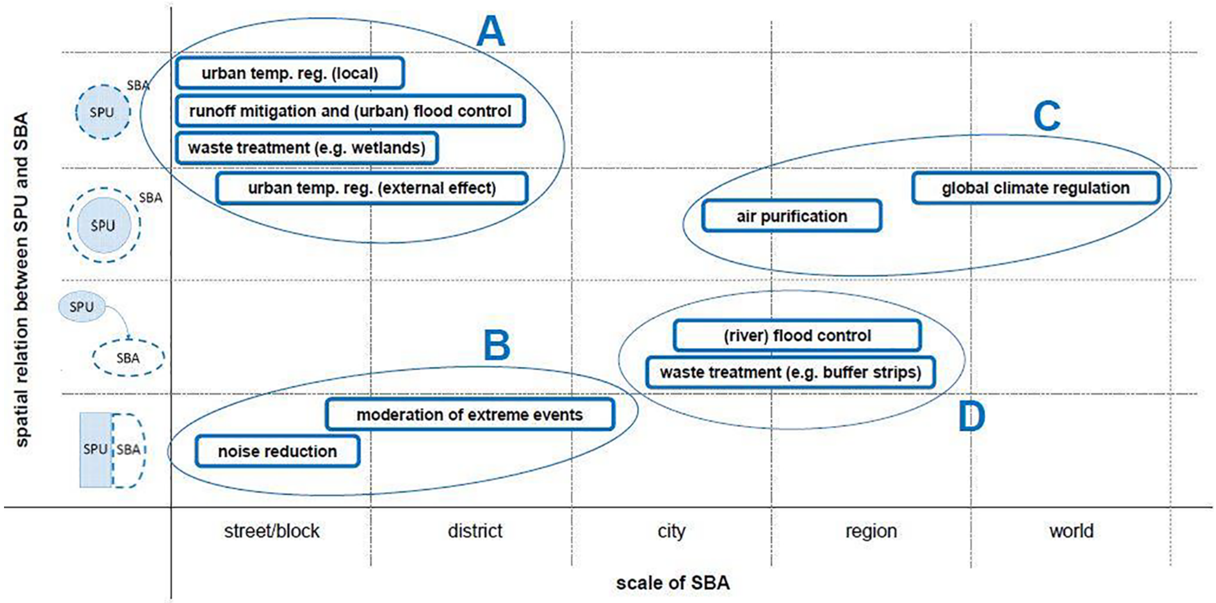

Fig. 3. Spatial scale of potential SBA (x-axis) and spatial relation between SPU and SBA (y-axis) for urban regulating ES. The categories of spatial relations between SPU and SBA follow the classification proposed by Fisher et al. (2009) and Syrbe and Walz (2012), namely (from top to bottom): in situ, omnidirectional, directional upstream–downstream, directional buffer. The scale of SBA is identified by means of five illustrative definitions. The four clusters gather: local ES with homogeneous effects (A), local ES with directional effects (B), supra-local ES with homogeneous effects (C), and supra-local ES with directional effects (D).

framework, the intensity of demand can be quantified by multiplying the intensity of ecological pressure (Table 2) and the amount of urban population or physical assets exposed, accounting for the different levels of sensitivity and resilience that characterise different areas of the city (Table 4). However, it must be noted that detailed analyses of the demand for urban regulating ES assessing all the three components of vulnerability (i.e., exposure, sensitivity, and resilience (Turner et al., 2003)) are not common. Either the intensity of ecological pressure or the spatial distribution of population and physical assets (or a combination of them) are most often adopted as proxies of ES demand (Baró et al., 2016, 2015; Burkhard et al., 2014).

Fig. 3 summarises the spatial relation between SPU and SBA and the scale of potential SBA (i.e., areas that benefit from the effects of ES supply, independently on the presence of beneficiaries). The type of spatial relation depends on the type of ecosystem function that supports ES provision (e.g., mechanical, chemical, bio-physical functions) and on the environmental component that is regulated (e.g., air, water). Four main clusters of urban regulating ES can be identified by crossing scales and types of spatial relation between SPU and SBA. Most urban regulating ES produce effects at the local scale within or in the immediate surroundings of urban green infrastructure components (Fig. 3). However, four out of the seven regulating ES analysed generate potential SBA that go beyond the boundaries of the city, thus contributing to the quality of a wider environment.

Table 5 identifies some exemplary indicators that can be used to assess benefits from urban regulating ES both in social and economic terms. Examples of economic benefits measured in monetary units have been found for all the seven analysed regulating ES, while this is not the

Table 5
Exemplary indicators for the assessment of benefits from urban regulating ES.

urban regulating ES	social benefits	economic benefits
air purification	• reduction of premature deaths and hospital admissions Mindell and Joffe (2004), Tiwary et al. (2009)	• monetary benefits based on avoided externalities (Nowak et al., 2006) • return on investment of tree planting (beneficiaries*mitigation/cost) (Kroeger et al., 2018)
global climate regulation	–	• monetary value based on carbon market prices (Zheng et al., 2013) • monetary value based on estimated marginal social costs of carbon dioxide emissions (Nowak et al., 2008)
moderation of extreme events	• reduction of human deaths Das and Vincent (2009)	• replacement cost of engineering structures (Narayan et al., 2016)
noise reduction	• number of persons with change from annoyed to not annoyed Veisten et al. (2012) dB(A) change per person/household per year Veisten et al. (2012)	• economic value of noise reduction based on hedonic pricing (Veisten et al., 2012)
runoff mitigation and flood control	• reduction of number and frequency of combined sewage overflow Zidar et al. (2017) reduction of localised flooding Zidar et al. (2017)	• avoided damage based on the total value of properties protected (Nedkov and Burkhard, 2012) • avoided damage based on specific depth-damage functions for different land use-land cover types (Olsen et al., 2015) • replacement cost of manmade substitutes (Silvennoinen et al., 2017)
urban temperature regulation	• reduction in cumulative population-risk weighted exceedance heat index Bodnaruk et al. (2017) total number of people and number of vulnerable people exposed to the cooling effect of urban green infrastructure Geneletti et al. (2016)	• return on investment of tree planting (beneficiaries*mitigation/cost) (Kroeger et al., 2018)
waste treatment	–	• savings based on replacement cost (Breaux et al., 1995)

case for social benefits. Regarding the former, it must be noted that not all of them reflect the approach proposed by the framework (Fig. 1): some, e.g. those based on replacement costs, do not consider the different level of vulnerability of beneficiaries.

4. Discussion

4.1. A Framework for a strategic approach to urban regulating ES

By developing a conceptual framework that links ES-related variables to urban planning decisions, the study responded to the growing demand for frameworks that support planners in effectively enhancing the provision of ES (Koschke et al., 2012; Langemeyer et al., 2016). In fact, good practices of planning to enhance urban ES are spreading. However, most plans still lack a strategic approach that allows linking planning decisions to their overall effects on both the supply and demand of urban regulating ES (Cortinovis and Geneletti, 2018a). As a result, planning actions that explicitly address the supply of urban ES are often not grounded on an appropriate scientific basis (Cortinovis and Geneletti, 2018a; Davies et al., 2017; Geneletti and Zardo, 2016), which may ultimately undermine their effectiveness, while the effects on demand are mostly overlooked.

Due to the high number of variables involved, complexity is a key barrier for the operationalisation of regulating ES in urban planning (Sutherland et al., 2018). In this context, providing simple and easy-to-use information, models, and tools is fundamental to guarantee a successful integration of ES knowledge (Ruckelshaus et al., 2015; Slootweg, 2015). In a review of decision-support tools to operationalise the ES concept, Grêt-Regamey and colleagues found that most of the existing tools are devoted to the assessment of regulating ES, and spatial planning is among the best supported application fields (Grêt-Regamey et al., 2017). However, even the easiest-to-use models, including for example i-Tree (Nowak et al., 2008), require so many and detailed input data that their application to everyday planning decisions is unfeasible.

Indeed, such models can produce a quantitative estimate of ES in the current and planned conditions, but this is not always needed in planning processes (Albert et al., 2014b). Before assessing the effectiveness of single actions, the "what if" relations between regulating ES and planning decisions must be made clear. To fill this gap, the approach of this study was to take a step back from methods, models, and tools; identify the main variables involved in the process of ES provision; and describe in a qualitative way the relations that link them. Identifying the links between the elements of the framework allows understanding the impact of planning and management decisions based on how their effects are expected to propagate along the process of ES provision, ultimately enhancing or reducing ES benefits (Olander et al., 2018). This way, the framework supports planners in answering questions such as: "*What kind of impacts on urban regulating ES should I expect if I take this planning decision*?", or "*On which variables should I act if I want to enhance this regulating ES in my city*?".

A key aspect of the framework is that it bridges the urban planning and the ES domains by linking the respective terminologies. As revealed by interviews with planners, the unclear relationship with other concepts that are of common use in the practice is among the barriers that prevent the adoption of ES (Albert et al., 2014a). From a planning perspective, the framework identifies two main components directly affected by planning decisions: green infrastructure and land uses, two elements that planners are accustomed to work with in their daily activities (Albert and Von Haaren, 2014). In particular, the concept of green infrastructure, explicitly linked to ES in the definition by the European Commission (2013), was selected since it is well accepted by planners and is considered a promising way to integrate concerns for biodiversity, nature conservation, and ES in planning practices (Albert and Von Haaren, 2014).

On the ES side, the framework builds on two among the most popular models and approaches that have demonstrated applicability to planning contexts: the Cascade conceptual model and the supply-demand approach for mapping ES (Burkhard et al., 2012; Potschin-Young et al., 2017; Spangenberg et al., 2014). Elements from the two are combined, thus taking a step forward to their unification, and detailed to meet the specific characteristics of urban regulating ES.

The Cascade conceptual model provides the stepwise description of the supply side of urban regulating ES, where the flow originates from the functional characteristics of urban ecosystems, and ES and related benefits are clearly distinguished (Haines-Young and Potschin, 2010). From a planning perspective, assuming the stepwise approach of the Cascade model allows navigating the framework in both directions, thus understanding not only the expected consequences of planning actions, but also what actions are needed to achieve a defined objective (Potschin-Young et al., 2017; Spangenberg et al., 2014). Furthermore, it allows distinguishing between what different authors have defined as ecosystem functions and ES, or ES capacity and actual flow, or offered and utilized ES: an aspect that is particularly relevant as far as strategic decisions are concerned (von Haaren et al., 2014).

The supply-demand approach for ES mapping and assessment provides the concept of service benefitting area. The approach was specifically formulated in the context of spatial analysis of ES (Syrbe and Walz, 2012) and a number of mapping studies has already demonstrated its applicability (Burkhard et al., 2013; García-Nieto et al., 2013; Palomo et al., 2013 among others). In the framework, the concept of service benefitting area is used to describe ES as the overlap between supply and demand, thus contributing to a spatially-explicit description that is considered critical towards the operationalization of ES in urban planning (Haase et al., 2014; Syrbe and Walz, 2012).

More in general, the framework advances the understanding of the demand for urban regulating ES by drawing a "parallel cascade" from land uses and functions to ES benefits, and detailing the links between vulnerability to undesirable environmental conditions and demand for urban regulating ES (Bagstad et al., 2013). While a poor definition of the demand side has been recognized as a key barrier to the operationalization of ES knowledge (Bagstad et al., 2014; McPhearson et al., 2014), the proposed analytical approach could help to overcome the limited availability of methods and indicators for assessing the demand for urban regulating ES (Olander et al., 2018; Schmidt et al., 2016), thus providing planners with valuable information to understand actual and potential beneficiaries.

Finally, the proposed framework explicitly acknowledges the fundamental role of ecological pressures (Sutherland et al., 2018) and describes their effects on both ES capacity and demand. Other ES conceptual frameworks mention ecological pressures in a more general definition of "drivers and pressures" affecting the provision of ES (e.g., the MAES (Maes et al., 2013), the "cascade-integrated" DPSIR (Müller and Burkhard, 2012), the EPPS (Bastian et al., 2012), and the ES-in-Planning (Albert et al., 2015) frameworks). In our framework, the inclusion of ecological pressures clarifies the use of environmental indicators when assessing urban regulating ES. In fact, environmental indicators are frequently adopted as proxies of regulating ES (see for example the list in Kandziora et al. (2013)), without specifying whether they measure demand or supply, and to what stage of the cascade they refer.

4.2. Key messages on how to operationalise the findings in urban planning

Detailing the links described in the conceptual framework for the different ES allows understanding, in each situation, what are the most relevant variables on which the results of planning actions depend, and which actions can be expected to produce the highest benefits. The information summarised in Section 3.2 for seven urban regulating ES can be navigated "service-wise", by tracking a single ES across the tables, or "transversally", by looking simultaneously at multiple ES in the same component of the framework. The two ways of reading the findings complement one another and help to answer different planning questions: in the former case, how to address a single urban regulating ES; in the latter case, how planning decisions may affect bundles of ES, thus generating synergies and trade-offs (Baró et al., 2017; Jopke et al., 2015).

Based on our findings, some key messages can be drawn to guide planners in operationalising the approach.

1. Land use-based classifications should be further detailed to identify the SPU of urban regulating ES.

Land use-based classifications do not provide a suitable baseline data to assess regulating ES in cities, for two main reasons. First, they do not account for the heterogeneity of urban green infrastructure components and do not capture patches and scattered elements that compose a large part of green infrastructure in cities (Cadenasso et al., 2007; Gómez-Baggethun and Barton, 2013; Müller et al., 2013). Second, they mask the spatial variability of ecological pressures, which causes the same typology of green infrastructure component to have different capacities when located in different parts of the city. SPU correspond to the smallest distinct homogeneous elements that can be addressed by planning and management (Andersson et al., 2015) and each of them can be analysed through the main variables proposed in the framework. Hence, an approach based on SPU could support planners in effectively addressing urban regulating ES.

2. The multifunctionality of urban green infrastructure and the synergies among multiple ES should be acknowledged and actively exploited.

Similar spatial distributions of different urban ES emerge in cities (Holt et al., 2015) and synergies rather than trade-offs can be expected among urban regulating ES, as well as between them and some cultural and supporting ES (Demuzere et al., 2014; Derkzen et al., 2015). Synergies among ES and the resulting multiple benefits are one of the main strengths of ecosystem-based approaches (European Commission, 2015; Geneletti and Zardo, 2016; Iacob et al., 2014), which planners can exploit when designing planning actions. Furthermore, accounting for synergies can improve the valuation of urban green infrastructure, and the assessment of alternative planning actions against multiple objectives (Kremer and Hamstead, 2016).

3. The demand for urban regulating ES and its variations should be assessed and monitored to understand the overall effects of planning decisions.

The assessment of ES demand is often neglected, especially in relation to multiple ES and to land-use changes (Wolff et al., 2015). Indeed, synergies and co-benefits generated by the multifunctionality of urban green infrastructure are favoured by the fact that high levels of demand for multiple ES are often concentrated in the same areas of the city. From a planning perspective, the assessment of demand, e.g. for assessing alternative scenarios or prioritizing planning interventions, is the stage where multiple objectives can be incorporated, including social and economic goals such as equity (Kabisch and Haase, 2014) and poverty alleviation (Adem Esmail and Geneletti, 2017). For example, different weights can be assigned to demand areas with disadvantaged conditions in terms of green infrastructure availability or socio-economic status, independently from the enhancement of specific urban environmental conditions (Cortinovis and Geneletti, 2018b). Data and indicators that are of common use in traditional planning practices, such as population density, census data, land uses and infrastructure can be used to analyse the demand. This should simplify the task for urban planners, and could promote the emergence of new indicators and approaches through a cross-fertilization between planning and ES science.

4.3. Limitations and caveats

Among the potential aims of conceptual frameworks listed by Potschin-Young et al. (2017), this article mainly refers to its use as an "organizing structure" that provides "*a shared language and a common set of relationships and definitions to make complex systems as simple as they need to be for their intended purpose*" (Díaz et al., 2015, p.3). Here, the intended purpose is to support effective planning decisions, and systematising the available scientific knowledge appears a first step toward its operationalization.

However, potential users of the framework should be aware of the degree of simplification that this implies. The simplification is evident in the description of the complex biophysical functions and processes at the basis of ES supply, boiled down to three key variables that describe urban green infrastructure (namely location, typology, and size). Even though this may seem a strong limitation, the three variables were identified based on a review of models, methods, and indicators available for urban planners. Specifically, the use of green infrastructure typology is coherent with classification efforts carried out in the urban planning domain (Bartesaghi Koc et al., 2016), where average performances based on typology are frequently used (e.g., Derkzen et al., 2015; Escobedo and Nowak, 2009) and the link between green infrastructure typologies and ES is considered a relevant information (Braquinho et al., 2017). Indeed, more detailed information is often unavailable for planning purposes. However, planners must be aware that differences in ES capacity can be found within the same typology due to distinctive traits at the specie or individual level, which need to be addressed in a later design stage.

Furthermore, it should be noted that the article only refers to regulating ES provided by green infrastructures within the city, and to planning processes at the urban scale. However, the availability, spatial distribution, and functionality of urban green infrastructure are also affected by planning decisions at wider scales. At the same time, a "good" urban planner should consider the effects of planning actions beyond the territorial boundaries of the city. Not only, as revealed by the analysis, the service benefitting areas of some urban regulating ES can be bigger than the city itself, or located outside its boundaries, but also the localization of land uses and functions may produce consequences on a wider scale. A "scale-sensitive integration", as defined by Faehnle et al. (2014), is therefore essential to ensure that potential synergies and trade-offs generated by planning decisions are taken into due account.

Regarding the relation with other ES, it should be kept in mind that, despite selected among the most relevant in urban contexts (Gómez-Baggethun and Barton, 2013; Haase et al., 2014; Luederitz et al., 2015), the seven regulating ES here analysed are only illustrative. Other regulating ES may be more significant depending on the context and on the planning decision in question. A preliminary scoping stage aimed at identifying the priority ES for the context and selecting those that are expected to be affected by planning decisions, including provisioning and cultural ES, is needed to ensure that the assessment of urban regulating ES conducted by following the conceptual framework can effectively support decision-making (Geneletti, 2015).

Finally, despite the effort to describe the main interactions and feedbacks, the framework schematizes only the main and most direct relations in the production of ES (Ernstson, 2013). The "urban planning" component of the framework, in particular, should be intended as a complex decision-making process (Mckenzie et al., 2014) rather than simply as its outcomes. Applications to real-world case studies are needed to test on the ground the usability of the framework in the different stages of the planning process, and to assess the benefits of its adoption compared to more traditional planning approaches (Geneletti et al., 2017).

5. Conclusions

Responding to the plea for a greater attention toward regulating ES (Sutherland et al., 2018), the aim of this study was to provide an overall picture of how urban regulating ES and related benefits are affected by planning decisions. This has been done in two consecutive steps.

At the conceptual level, a framework was developed that links the main variables controlled by urban planning (i.e., location, typology, and size of urban green infrastructure, and the distribution land uses and functions) to ES capacity, demand, and flow. The framework offers to urban planners a conceptual guidance to understand how the effects of planning decisions are expected to impact on ES, ultimately supporting them in effectively enhancing ES provision.

At the operational level, the links included in the frameworks have been explored and detailed for a set of seven key urban regulating ES. This revealed, for each ES, what are the most relevant variables affecting the provision, hence on which levers planners can act to produce the highest benefits. Suitable methods and exemplary indicators to analyse each component of the framework from a spatially-explicit perspective have been collected from the literature, thus supporting a more effective integration of ES knowledge in planning practices.

Within the context of a progressive spread of ecosystem-based actions (Cortinovis and Geneletti, 2018a; Geneletti and Zardo, 2016) and a growing policy support for nature-based solutions (European Commission, 2015; Faivre et al., 2017), the study can help planners to adopt a proactive, scientifically-based approach when integrating urban regulating ES in urban planning.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2019.100946.

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