

Exploring Urban Metabolism Through Ecosystem Services Mapping: The Case Study of Turin (Italy)

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Abstract. In a scenario of global urbanization and increasing impact of cities on climate change and loss of biodiversity, urban planning has a critical role in the path towards sustainability. The pathway towards climate neutrality requires novel tools and approaches for accounting for different components of urban metabolism relating cities to the surrounding territories. This paper explores the integration of a climate neutrality framework to address climate and biodiversity challenges in urban planning. Through the mapping of crucial ecosystem services (ES), the study presents a methodology to account for the (Eco)system capacity of the urban system, stimulating considerations in respect of urban impact towards inland territories in the case study of Turin, Italy. The study reveals the critical role of ES in enhancing urban sustainability and resilience, offering valuable insights for policymakers toward achieving climate neutrality.

Keywords: Urban Metabolism · Ecosystem Services · Climate neutrality

1 Introduction

Global policy is in a critical race to find strategies for addressing the escalating climate and biodiversity emergencies. Although urban areas are smaller in size compared to forests and agricultural lands, they account for over 70% of global emissions and cities are in urgent need to adopt low-carbon and resilient urban development strategies to mitigate climate change emissions and adapt to its impacts (Rezvani et al. 2023). This challenge is addressed in European policies through the concept of climate neutrality, which aims for net-zero greenhouse gas emissions by balancing emissions with their removal from the atmosphere (IPCC 2014). Within the EU Mission "Climate-Neutral and Smart Cities", the commission aims to deliver 100 climate-neutral and smart cities by 2030 (European Commission 2021), aligning with the broader objectives of the European Green Deal to achieve climate neutrality by 2050 (Salvia et al. 2023).

To address this challenge, urban planning is encouraged to utilize Nature-Based Solutions (NBS) for mitigating the urban heat island effect or using a less intrusive engineering approach to drainage management (Albert et al. 2019; Pauleit et al. 2019;

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Ronchi et al. 2020). Among regulatory and planning solutions, Urban Green Infrastructure represents a network of green spaces and ecological systems planned with the scope of supporting the delivery of multiple Ecosystem Services (ES) such as water purification, air quality improvement, and climate mitigation and adaptation, vital for achieving climate neutrality (Ronchi et al. 2020).

Analyzing and managing the flow of energy and materials within cities concerns the concept of Urban Metabolism (Rosado et al. 2016; Perrotti and Stremke 2020) that transform these inputs into growth, energy, and waste. This approach can be applied to the development of strategies that address energy efficiency, waste reduction, and resource conservation in urban areas, thereby contributing to the achievement of climate neutrality. In the context of urban planning, this study considers cities as dynamic systems that both contribute to mitigation and adaptation to climate change. It advocates for actions that not only mitigate climate change by reducing emissions but also enhance the city's resilience and adaptability to climate-related challenges and extreme events. This approach ensures that efforts towards climate neutrality also contribute to the broader goal of sustainable urban development (Perrotti and Stremke 2020). A metabolic perspective can help decision-makers understand the socio-technical processes associated with the harvesting and using resources (especially natural) in cities. Enhanced awareness can facilitate a more resource-efficient urban planning.

Adaptation to foster resilience requires measurable targets and means of improving the efficiency and effectiveness of using resources, including energy. As mentioned above, reduction remains a pivotal aspect, encompassing minimizing waste from environmental pollution and reducing greenhouse gas emissions, among others (Lampinen et al. 2022). Additionally, optimizing water consumption and promoting sustainable transportation practices are integral facets of fostering resilience in resource management. The adaptive approach in urban planning requires the adoption of a multidisciplinary perspective accounting the relation between urban poles and the surrounding territory (Giacomelli et al. 2023) Specifically, a climate-neutral approach considers urban metabolism assessment in cities to define spatial policies and adaptive solutions should take into account the input-output flow of natural resources involving urban poles. Moreover, specific actions/urban design solutions should be socially inclusive and integrate the needs of urban stakeholders as well as vulnerable groups for urban planning solutions put in place (Lampinen et al. 2022; Giacomelli et al. 2024). However, increasing the adaptation of the system means developing an in-depth knowledge of the multiple dimensions that involve urban metabolism.

At the core of this framework is the notion that urban planning must balance between enhancing the system's capacity for reducing emissions and augmenting the ecosystem's capacity for offering benefits to people (among others, carbon sequestration and pollutant reduction). In this sense, through the concept of ES, it highlights the critical role of natural processes in improving air quality, regulating water, and supporting biodiversity within urban environments.

Considering this theoretical framework, the research aims to test and practically apply a methodology for urban metabolism assessment in the case study of Turin, Italy. Five regulatory ES were mapped within urban environments to inform urban planning and promote climate neutrality and draw consequences with respect to the relationship

between the city of Turin and neighboring natural ecosystems. In this sense, the research aims to bridge the gap between theoretical ES assessment and practical urban planning needs, providing actionable insights applicable to other cities.

The study is organized as a research paper, the methodology introduces the study area and the models used for ES mapping and assessment. The results illustrate the distribution of the mapped ES (Carbon sequestration; Habitat Quality; Cooling Capacity; Water Regulation) and the total values for Air Purification. Within the discussion, a series of considerations on urban metabolism are developed in order to offer insights to urban planning. The last paragraph aims to offer shortcomings and draw directions for future researches.

2 Methodology

2.1 Study Area

The city of Turin (Piedmont, North-west of Italy) extends for 130.2 km^2, with 878,074 inhabitants (ISTAT, 2021). It is located in the Po Valley and develops over a flat urban area (239 m a.s.l.) and in a hilly area that reaches an altitude of 715 m. The choice as a case study is related to its unique environmental challenges, as the city has high levels of air pollution, with an average PM10 of 2018 measured in the center of Turin of 33.0 $\mu g\ m^{-3}$, and the maximum daily value, set at 50 $\mu g\ m^{-3}$, exceeded 55 times. Urban planning faces the challenges of managing urban sprawl, addressing the urban heat island effect, towards the improvement of an Urban Green Infrastructure supporting biodiversity and ES provision (Vitulano 2024).

Turin's historical and contemporary urban development presents an ideal context for applying and evaluating the developed methodology as the city is now working on the new land use plan (Piano Regolatore Generale). Furthermore, the city recently approved the Climate Resilience Plan (2020) and the strategic plan of Green Infrastructure (2021), showing a strong commitment to the integration of environmental and ES subjects into urban planning. Among the aspects taken into account by urban policies, it is well-known that imperviousness, among compactness, salinization, desertification, or the loss of organic matter, is a cause of degradation that the soil can receive from a land-use alteration reducing ecological functions (Salata et al. 2021). The so-called "land take" is defined as an unsustainable kind of land use alteration that compromise the possibility of the soil returning to its original natural properties (European Environmental Agency, 2019). Therefore, urbanization and the related sealing process is considered an irreversible dynamic since it does not allow to return to natural conditions while maintaining the initial stock of the (limited) soil resource (Fig. 1).

Turin is a deep "compact" urban catchment since the soil sealing rate for each land use demonstrates that the city has been subject to a concentrated anthropic transformation while creating a densely built-up core urban area with a low rate of permeability. Despite the eastern hilly area, the "Parco del Valentino" and the confluence between the Po and Stura rivers, the remaining areas have fewer natural unsealed areas. This distinctive characteristic is confirmed by the Natural Difference Vegetation Index (NDVI), which assesses the "health" of the vegetation even inside the compact built-up area. Recent research based on this indicator demonstrates that a few urban districts are "porous"

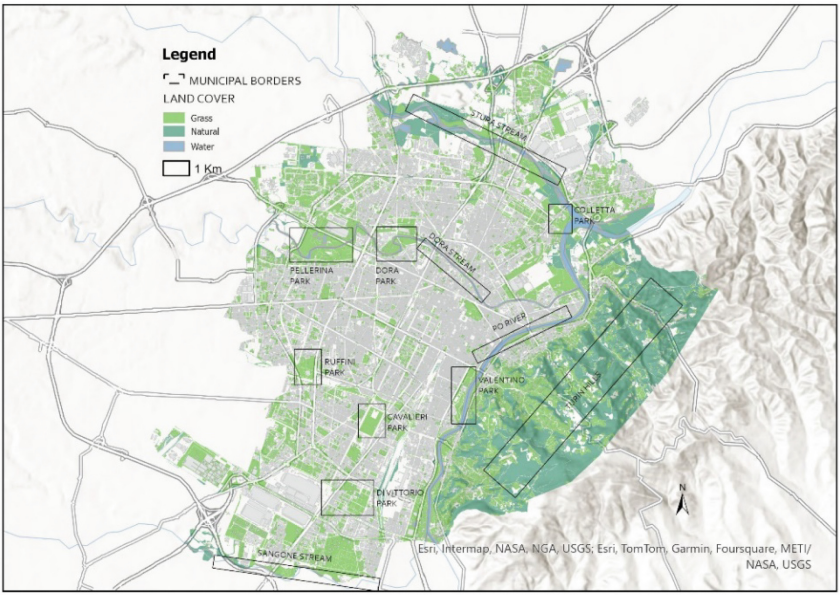

Fig. 1. City of Turin and location of the major streams and green areas. Authors own elaboration.

with healthy vegetation in the private space such as the Vanchiglia, the Vanchiglietta, Crocetta, and Borgo San Secondo.

Urban adaptation can be realistically pursued if the capacity to measure and evaluate the urban system is precise and reliable while reaching an accurate comprehension of the biophysical performance of the urban environment.

2.2 Ecosystem Services Mapping

The analysis of ES capacity for the city of Turin was developed through the mapping of four regulative ES: Carbon sequestration; Habitat Quality; Cooling Capacity; Water Regulation. The spatial assessment was developed through available data using the software Integrated Evaluation of ES and Tradeoffs (InVEST) (Natural capital project, 2024). InVEST is a suite of free, open-source software used to map and assess the goods and services from nature that sustain and fulfill human life. If properly managed, ecosystems yield a flow of services that are vital to humanity, including the production of goods (e.g., food), life-support processes (e.g., water purification), and life-fulfilling conditions (e.g., beauty, opportunities for recreation), and the conservation of options (e.g., genetic diversity for future use). In this sense InVEST aims to support assessments towards scarcely monitored natural capitals and, in many cases, undergoing degradation and depletion.

The methodology integrates InVEST's models with a novel approach to derive LULC data. The model employs land cover data derived from the digital topographic dataset (BDTRE 2023) of the city freely available at Geoportale Piemonte. To reach an updated and more grounded evaluation of this model, we self-produced an NDVI index of the city from an original acquisition of Copernicus L2A image processed on the 04 of

January 2024. We used the NDVI value to integrate LULC classes with the degree of soil permeability important for the assessment of ES provision.

ES1 Carbon Storage: The Carbon Storage model focuses specifically on quantifying the amount of carbon stored in vegetation and soils within a given landscape. It utilizes various data inputs such as land cover, vegetation types, soil types, and climate data to estimate carbon storage in different pools, including aboveground and belowground biomass, and soil organic carbon. By conducting spatial analysis, the model generates maps and tabular outputs that support efforts to prioritize conservation and restoration actions for climate change mitigation.

ES2 Habitat quality: InVEST's Habitat Quality model combines information on LULCs and biodiversity threats to create habitat quality maps. This approach produces two main sets of information that are useful for making an initial assessment of conservation needs: the relative size and degradation of different habitat types in an area,

Table 1. List of mapped Ecosystem Services (ES) and input data

ES	Ecosystem Service	Input	Source
ES1	Carbon Sequestration	-Amount of carbon stored in 4 different carbon pools	-Italian National Inventory of Forests and Forest Carbon Sinks
ES2	Habitat Quality	-Land Use/Land Cover	-BDTRE 2023
		-Anthropic threats (LULC)	-BDTRE 2023
		-Sensitivity of each land use to anthropic threats	-Based on Arcidiacono et al. 2015; Salata et al. 2017
ES3	Cooling Capacity	-Land Use/Land Cover Shade (%)	-BDTRE 2023
		-Evapotranspiration (mm)	-Ministry of Agriculture, Food and Forestry database
		-Albedo (K)	-Copernicus Global Land Services
		-Air temperature (°C)	-ARPA Piemonte
		-Imperviousness (K)	-High resolution layer – ISPRA
ES4	Water regulation	-Land Use/Land Cover	-BDTRE 2023
		-Map of soil hydrologic groups (USGS soil groups)	- Regional geological map
		-Map of average annual precipitation (10 years)	-ARPA Piemonte Regione Piemonte
		-Stormwater runoff and percolation coefficients for each Soil group (CN K)	-Map of soil protection capacity

and changes over time. This approach also allows rapid assessment of habitat status and trends as a proxy for more detailed measurements of biodiversity status.

ES3 Heat mitigation: Based on the InVEST Urban Cooling model, the indicator identifies the contribution of vegetation in reducing urban temperatures, which is crucial for enhancing urban resilience against climate-induced temperature increases. The model calculates an index of heat mitigation based on shade, evapotranspiration, and albedo, as well as distance from cooling islands (e.g. parks). The index is used to estimate a temperature reduction by vegetation. Finally, the model estimates the value of the heat mitigation service using two (optional) valuation methods: energy consumption and work productivity.

ES4 Water regulation: The urban flood risk mitigation InVEST model addresses cloudburst impacts, particularly in densely populated hillside cities. It calculates the runoff reduction, i.e. the amount of runoff retained per pixel compared to the storm volume, based on land cover, soil type, and rainfall data. Key inputs include watershed delineation, rainfall depth, land use/cover maps, soil hydrologic groups, and biophysical values for land classes. The model integrates various datasets, including imperviousness levels and tree cover density, to classify urban areas and assess their vulnerability to flooding, aiming to inform urban planning and mitigation strategies (Table 1).

2.3 Air Purification Assessment

The assessment of the **ES5 Air Purification** is based on the I-Tree Eco model, which allows to estimate the urban forest structure and its function on air pollutant removal. (i-Tree, n.d.). The software allows to estimate the grass effects on air pollutant removal and specifically CO, NO2, SO2, O3 and PM10. For running the Air Purification assessment, the Turin tree cataster has been collected and codified according to the I-tree model. The GPS coordinates of the individual trees were also entered to spatialize the outcome subsequently. Furthermore, some limited simplifications and adjustments were done for records missing any land registry data. The reference year for the meteorological and pollutants data is 2015, with data up to 2021 used for the models, excluding the

Table 2. Input data for Air Purification assessment

ES	Ecosystem Service	Input	Source
ES5	Air Purification	-Species (Identify and record the species and genus names of each tree assessed) -Diameter at breast height - DBH (Measure and record the tree stem diameter at breast height for each tree) -Total tree height (Height from the ground to the top (alive or dead) of the tree)	-Tree Cataster, Città di Torino

years impacted by the COVID-19 pandemic (2020, 2021) due to significant pollution reductions (Table 2).

3 Results

In this section, we present the findings of the assessment exploring the distribution and significance of selected regulating ES, identified as crucial for urban sustainability and climate resilience. The analysis encompasses four spatial mappings (Carbon Storage, Habitat Quality, Heat Mitigation, and Water Regulation) (Fig. 2) and one quantitative evaluation (Air Purification) (Table 3). By examining the results in the perspective of Urban Metabolism, we aim to provide valuable insights into the environmental dynamics of Turin and inform evidence-based urban planning strategies aimed at promoting climate neutrality and enhancing the city's ecological resilience.

3.1 The Distribution of Ecosystem Services

ES 1 Carbon Storage: The Carbon Sequestration model calculated an average pooling capacity of Turin urban soils to store 47 tons per hectare, including both soil and vegetation functions. The maximum pooling capacity, as expected, is recorded in the hills (see Fig. 2) with a maximum pooling capacity of 218 tons per hectare. This first result demonstrates the crucial role of seminatural areas surrounding cities, accounting the main share of CO2 absorption and oxygen generation.

ES 2 Habitat Quality: The Habitat Quality index in Torino presents a minimum value of 24.29 and a maximum value of 92.17. Well-maintained habitats are mainly distributed in the hills and along the main tributaries of the Po Rives that create an ecological connection between the western and eastern borders of the city (Dora and Stura). Although the hill displays higher values, it is noticeable how they are clusterized and not diffused, meaning that the area is a highly anthropized system with threats for the environment. The Dora Stream displays good values of Habitat Quality around the Pellerina and Parco Dora parks, but except from here, there is no trace of higher values, possibly meaning that the Riverbed has been highly channelized and heavily anthropized, leaving no space for natural habitats. Differently, the Stura stream is more natural, and along its course, it can be well-recognized as a higher Habitat Quality.

ES 3 Heat mitigation: As for heat mitigation, Torino presents a minimum value of 27.92 and a maximum value of 92.87. Four main core mitigation areas can be detected as hotspots to cool down temperatures during hot days. The hills are first, including the northeastern part where the Stura tributary reaches the Po River. Parco della Colletta also plays a vital role in connecting the natural areas of the hill with the peri-urban agricultural system. Also, the Basse di Stura cluster can be recognized as a strong mitigation point. In the south, Sangone Park seems to have a dimension that provides enough cooling capacity, thus representing the fourth hotspot of the city. It should be mentioned that, for this specific ES, the Po River creates a channel that crosses the city from south to north and provides air circulation with a freeze even during hot, stagnant days. Unfortunately, here the model does not account for wind interaction because it has been designed only



Fig. 2. Mapping of four Ecosystem Services for the City of Turin. Carbon Storage, Habitat Quality, Heat Mitigation, and Water Regulation. Authors elaboration

to assess the capacity of natural soil features (such as vegetation) to provide cooling capacity.

ES 4 Water regulation: As for heat mitigation, the Urban Flood Risk Mitigation integrates the information on land uses with soil hydraulic conductivity. The retention index indicates, for each pixel, the amount of total yearly water volume that can be retained by soil. Of this amount a small fraction goes to recharge the aquifer (percolation) while the remaining part evapotranspirates through roots absorption. In Turin, the model indicates that the 54% of the annual rain volume infiltrates on soil, while the 46% goes on runoff. Only a fraction of 1,34% of the infiltrated soil percolates and recharge the deep acquifer of the city (this amount correspond to 1.636.020 cube meters which is a valuable measure that can be used to see if the water demand is satisfied by the infiltration). Other studies on the city of Turin (Salata et al. 2020, 2021) show how the average infiltration capacity in the dense urban areas is lover of the average, often falling below the 10%. This might suggest that the large majority of the rainwater goes on runoff in the urban catchment. As expected, the hill has in general a good retention capacity, even though the soils are not performing well in terms of water conductivity.

3.2 The Assessment of Air Purification

The **ES Air Purification** Model estimated the pollution removal by the urban forest of Turin composed by 116.300 trees with a cover of 594.48 ha (Table 3). The most common

species of Trees are Oriental planetree, Basswood, European hackberry. The estimation of pollution removal is 55 tons/year including Ozone (O3), Carbon monoxide (CO), Nitrogen dioxide (NO2), Particulate matter less than 2.5 microns (PM2.5), Particulate matter less than 10 microns and greater than 2.5 microns (PM10), and sulfur dioxide (SO2). In Turin, the carbon storage (i.e. the amount of carbon bound up in woody material above and below ground) is 40.59 thousand tons, the trees are estimated to store 40,600 tons of carbon. Oriental planetree stores and sequesters the most carbon, accounting approximately 16.1% of the total carbon stored and 20.5% of all sequestered carbon. Finally, according to I-Tree the removal of carbon (in the form of carbon dioxide) from the atmosphere through the process of photosynthesis is 1.566 thousand tons of carbon per year.

Table 3. Summary of Urban Forest effects and values from i-Tree Eco assessment.

Number of trees: 116.372
Tree Cover: 1471 acres
Most common species of trees: Oriental planetree, Basswood spp, European hackberry
Pollution Removal: 55.82 tons/year
Carbon Storage: 40.61 thousand tons
Carbon Sequestration: 1.568 thousand tons
Oxygen Production: 4.18 thousand tons/year
Avoided Runoff: 12.33 million gallon/year

4 Discussion

4.1 Urban Metabolism and Ecosystem Services Relationships

The application of the Urban Metabolism approach to the city of Turin can provide insights into the values of the urban environment and its implications for climate-neutral urban planning. Specifically, the framework can support the integration of system dynamics in addressing urban challenges and can help moving towards a knowledge base tool to support urban planners (Elliot et al. 2019). Knowledge on Ecosystem capacity can support the definition of spatial actions towards NBS designed to address site-specific situations (Salata and Grillenzoni 2021).

In this discussion, we address the implications of the ES assessment findings by comparing them with data on actual urban consumption. The analysis revealed significant patterns in the distribution of ES across Turin as the city benefits from substantial carbon storage capacity, particularly in semi-natural surrounding areas, which play a role in environmental regulation and habitat quality.

As concerns water balance, statistics indicate that the daily water consumption per inhabitant in the City of Turin stands at 197 L/day (Comune di Torino, 2016). Comparing

this with the infiltration capacity of the urban ecosystem reveals a significant disparity, as only approximately 2.6% of the annual water usage by the urban population is actually infiltrated into the city's ecosystem.

In terms of CO_2 emissions, our assessment indicates that the Carbon Sequestration capacity of the urban ecosystem accounts for roughly half of the total greenhouse gas (GHG) emissions (Comune di Torino 2021). This contrast between urban ecosystem capacity and actual consumption underscores an unbalanced metabolism, where the demand for ES far exceeds what urban ecosystems can currently provide.

These disparities underscore the need for strategic interventions to rebalance the urban metabolism and enhance the resilience of Turin's urban ecosystem. Fostering greater integration of nature-based solutions within urban planning frameworks can help bridge the gap between demand and supply of ES, ultimately promoting a more sustainable and resilient urban environment.

4.2 Urban Planning Towards Climate Neutrality

The mapping exercise highlights environmental challenges in the context of Turin, including habitat degradation and flood risk. To address these issues, information on ES presents a possible base for developing targeted interventions that enhance the city's ecological resilience (Ronchi et al. 2020).

In response to the challenge of stormwater mitigation in the flat areas of Turin, proactive measures in the upslope regions are crucial. Establishing NBS, such as water reservoirs and seminatural basins with Bioretention systems, before streams reach densely populated settlements can significantly mitigate flood risks (Rezvani et al. 2023). Accompanying these measures with a comprehensive afforestation program in the upslope areas aligns with broader objectives of creating afforestation initiatives in peri-urban zones, acting as a natural buffer against urban sprawl (Salata and Grillenzoni 2021).

Moreover, re-naturalizing the riverbeds of the Po, Dora, Stura, and Sangone rivers offers an opportunity to create a natural pedestrian and slow-mobility connection between the urban fringe and central areas of the city. This approach seamlessly integrates peri-urban spaces with the urban context, fostering connectivity and enhancing biodiversity corridors (Salata et al. 2020). In densely urbanized zones where establishing seminatural water reservoirs may pose challenges, repurposing areas along streams for rainwater harvesting systems, filter strips, and green roofs can be explored as alternative solutions (Manes et al. 2016).

Integration of spatial urban information in the habitat quality allows defining ecological hotspots while supporting a new perspective for an ecosystem-oriented planning (Salata, 2020). Furthermore, confirming findings for other urban contexts (Manes et al, 2016), the urban forest of Turin contributes significantly to air purification, with specific tree species playing key roles in pollution removal. Manes et al (2016) further demonstrates how PM10 deposition on forests mainly depends on Leaf Area Index (LAI) while O3 absorption is mainly influenced by forest functional diversity. This information may be useful to manage urban green spaces more efficiently.

Initiating a sponge district necessitates a meticulous assessment of the natural drainage pattern using basic GIS tools like Digital Elevation Models for catchment areas (Salata et al. 2020). Visualizing streams with flow direction and accumulation

tools aids in understanding topography and ground conditions, informing the identification of suitable areas for infiltration. Defining surface water sub-catchments involves considerations of flow routes and development clusters, ensuring strategic placement of parks and open spaces downstream to accommodate surface water attenuation and controls. These measures aim to integrate surface water conveyance paths harmoniously with the landscape, prioritizing integrated storage and treatment to maximize benefits while minimizing disruptive infrastructure.

4.3 Shortcomings and Further Research

The analysis relies on available data at the city level and the impact of some physical factors are not included. It's important to acknowledge that the analysis overlooks the influence of construction materials as the reflectivity of sealed vertical surfaces in tall buildings, which can significantly affect urban microclimates and contribute to the urban heat island. Future research should explore how these factors impact the urban climate.

Furthermore, while we assessed overall pollution removal by trees in Turin, extra research could spatialize the Air Purification model to identify areas within the city benefiting most from urban forests. Mapping pollutant removal rates across neighborhoods can inform targeted tree planting initiatives for improving air quality. In this context, investigating the relationship between urban parameters (e.g., land use, vegetation cover) and ES could provide insights into effective heat mitigation strategies. Understanding how socioeconomic factors and land use policies influence cooling capacity can guide interventions to enhance urban resilience to heat stress.

Finally, the urban metabolism perspective could be further explored by mapping the demand for ES, identifying matches and mismatches with areas of supply. The widening of the study area to the metropolitan region would allow to map ES budget in a larger territory, allowing to draw implications in terms of environmental and spatial justice.

5 Conclusions

In conclusion, this study bridges the gap between theoretical ES assessment and practical urban planning needs, providing actionable insights applicable to other cities. By embracing an urban metabolism approach and integrating ES considerations, cities like Turin can pave the way towards sustainable and resilient urban development, aligning with broader global objectives of climate neutrality and biodiversity conservation.

The disparities between the ecosystem capacity and the emission budget highlight the need for strategic interventions to rebalance urban metabolism and support the resilience of its ecosystem. Integrating nature-based solutions more extensively into urban planning frameworks can serve as a crucial step in bridging this gap, ultimately fostering a more sustainable and resilient urban environment. By integrating system dynamics and ecosystem capacity assessments, urban planners can develop knowledge-based tools to address urban challenges. Integrating NBS within urban planning frameworks can bridge the gap between demand and supply of ecosystem services, addressing pressing environmental challenges in Turin such as habitat degradation and flood risk. Proactive measures, including establishing NBS in upslope regions for stormwater mitigation and

afforestation initiatives in peri-urban zones, can mitigate flood risks and act as natural buffers against urban sprawl. Renaturalizing riverbeds offers opportunities for creating connectivity between peri-urban and central areas, enhancing biodiversity corridors. In densely urbanized zones, repurposing areas along streams for rainwater harvesting systems and green infrastructure can provide alternative solutions. Integrating spatial urban information in habitat quality assessment supports ecosystem-oriented planning, while efficient management of urban green spaces contributes to air purification.

Although the analysis provides valuable insights, certain factors such as construction materials and vertical surface reflectivity's influence on urban microclimates require further exploration. Future research should spatialize air purification models to identify areas benefiting most from urban forests and inform targeted tree planting initiatives. Investigating the relationship between urban parameters and ES can provide insights into effective heat mitigation strategies, considering socioeconomic factors and land use policies.

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