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"Environmental Assessment of Nature-Based Solutions in Turin, Italy: A Case Study within the GREEN-INC European Project"

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Abstract

This thesis studies the environmental dimensions of Nature-Based Solutions (NbS) implementation in Turin, Italy, within the framework of the GREEN-INC European Project. The thesis focuses on assessing the sustainability of NbS initiatives, the research employs a multidisciplinary approach to evaluate their environmental impacts. the study examines NbS projects in Turin spanning various environmental domains such as gray water management, green infrastructure, and biodiversity. Through quantitative analysis and qualitative assessment, the thesis explores the effectiveness of NbS in enhancing urban water systems, ecosystem services and Air temperature. By using digital visualization tools, including GIS and dashboards, the research presents a comprehensive analysis of NbS performance and its implications for environmental sustainability and in Turin. The findings illustrates to a deeper understanding of NbS as a tool for building more resilient cities in the face of climate change and urban challenges.

Keywords: Nature-Based Solutions, environmental sustainability, circularity, Turin, Italy, GREEN-INC European Project, urban resilience.

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Chapter 1. Introduction

Nature-based Solutions (NbS) emerged in the late 2000s to highlight the role of biodiversity conservation in climate change. NbS was introduced as a comprehensive approach to address global challenges. This thesis demonstrates the assessment of environmental indicators in Turin, Italy as part of the GREEN-INC European Project. GREEN-INC will evaluate inclusive climate actions addressing both climate change and urban inequalities. The unique combination of climate and hydrology and urban features in Turin makes it an excellent location to study the intricate effects of Nature-Based Solutions. This research investigates the environmental advantages of these solutions through a multidisciplinary method to evaluate their effectiveness in five main environmental indicators. This study conducts an extensive environmental performance evaluation of Turin's existing NbS through systematic assessment methods and quantitative analytical techniques. The research evaluates particular environmental indicators to establish evidence-based insights about NbS effectiveness in urban areas. The research aims to enhance knowledge about NbS performance in Mediterranean urban settings while providing evidence to support future urban planning and environmental management choices for Turin and comparable cities.

Duty of the Project

The duty of the GREEN-INC European Project is to provide a comprehensive framework for implementing and evaluating NbS in urban context all though 5 European cities. The project has several key aspects:

1. 1.Design and Implementation: Developing and implementing NbS interventions that actually fit the specific environmental, social, and economic realities of each urban area.
2. Monitoring and Assessment: Tracking how these natural solutions perform over time by gathering real data on their environmental effects, benefits to local communities, and economic value.
3. Stakeholder Engagement: Building partnerships between different local groups - from government officials and neighborhood residents to city council members and academic experts.
4. Policy Recommendations: Using research findings to create practical policy suggestions that help city officials implement nature-based approaches more effectively and expand them to more neighborhoods.
5. Knowledge Dissemination: publishing the findings and best practices with other cities and regions to promote the wider adoption of NbS and support global sustainability goals.

This research falls under task 2: Monitoring and Assessment. The specific contribution involved implementing a five-indicator environmental assessment framework to evaluate Nature-Based Solutions in Turin. The methodology included developing standardized assessment templates for each indicator and conducting the practical evaluation of Turin using quantitative analytical methods. This assessment focused specifically on the environmental dimension of NbS performance, generating empirical evidence about their effectiveness in the urban context of Turin.

1.1 Problem Statement and Background

Cities around the world are facing increasing environmental challenges, some of the main important challenges are air and noise pollution, urban heat islands and biodiversity loss. These issues threaten public health, lower the quality of life, and test the sustainability of urban ecosystems (Lee et al., 2021). In the old times engineering solutions often had problems addressing these complex problems in a sustainable way, leading to a rise in the use of Nature-Based Solutions (NbS). NbS uses natural elements to tackle environmental issues, offering a comprehensive approach to urban planning (Commission et al., 2015; Norton et al., 2015). NbS are now seen as one of the most important urban strategies rather than just environmental add-ons. By using natural elements in the city, NbS can influence reducing air pollution and urban heat Island, also restoring the natural habitats, at the end leading to boosting biodiversity. This approach promotes ecological resilience, supports sustainability, and enhances urban living conditions, making cities more adaptable to climate change (Tzoulas et al., 2007). The impact of urban environmental challenges, such as air pollution and noise, on public health and well-being is well-documented. Urban heat islands, for example, increase city temperatures, leading to higher energy use in buildings and more deaths during heatwaves (Lafortezza et al., 2009) . Biodiversity loss in the cities also hampers the ability of natural systems to provide needed services like water purification and carbon sequestration, adding more strain to urban environments.

Nature-Based Solutions (NbS) involve bringing natural elements into the cities to deal with environmental, social, and economic problems. These approaches take their cues from nature itself, and t meant to protect biodiversity, lead to a better ecosystem, and give people green areas to gather. It's about finding ways to work with nature instead of against it (Cohen-Shacham et al., 2016). The environmental benefits of NbS are extensive. By increasing green spaces such as plants and trees, cities can improve air quality as these natural elements filter pollutants and fine particulates (Escobedo et al., 2011; Nowak et al., 2006a). Green spaces and water bodies can also reduce urban heat islands, where city areas become warmer than their rural surroundings due to human activities and concentrated energy use (Akbari et al., 2001a; Santamouris, 2014a). NbS also offers significant social advantages, such as enhanced aesthetic value, more recreational opportunities, and improved mental health through contact with nature (Hartig et al., 2014). Economically, NbS delivers tangible financial benefits. Properties near green spaces typically increase in value, healthcare costs tend to decrease as residents are having better physical and mental wellbeing, and the due to natural elements enhancement creates meaningful local jobs (Kuo et al., 1998; Wolch et al., 2014). A key role of NbS is enhancing urban resilience to extreme weather conditions. Green roofs, urban forests, and wetlands can absorb excess rainfall, reduce flood risks and provide habitats for urban wildlife (Gill et al., 2007; Young, 2011). These features help cities adapt to extreme weather conditions, promoting sustainability (McPhearson et al., 2016; Raymond et al., 2017). Urban green spaces also serve as refuges for species displaced by urban development, helping maintain and enhance urban biodiversity, which supports ecosystem functionality and resilience (Aronson et al., 2017a; Dearborn & Kark, 2010).

Turin located in northern Italy's Piedmont region, facing many Mediterranean urban challenges. It is known for its industrial history like Fiat and other automotive enterprises, Turin faces significant environmental issues like air pollution and urban heat islands (Benedini & Rossi, 2020). The city's specific geography, like the Alps and the Po River, affects local weather patterns and pollution dynamics due to temperature inversions and limited air circulation. Turin's industrial activities have caused its air quality problems, such as emissions from manufacturing and automotive sectors often exceeding European Union air quality standards. Turin's environmental challenges reflect broader patterns seen in Mediterranean cities, which are particularly vulnerable to climate change impacts same as increased temperatures and extreme weather events (Giorgi, 2006; Lionello et al., 2006). Turin's situation is representative of many Mediterranean cities, where the regional climatic conditions intensify typical urban environmental issues, highlighting the need for localized solutions.

Despite the potential of Nature-Based Solutions (NbS) to address urban environmental issues, there isn't enough research on their impact in Mediterranean climates, especially in southern European cities like Turin. There are many studies on NbS Implementation in Northern Europe and North America, but unfortunately, they aren't applicable in Southern cities in Europe considering the unique geographical features (Langergraber et al., 2020). Most existing research on NbS in Europe is either theoretical or based on case studies from temperate regions, which do not adequately represent Mediterranean conditions. This lack of site-specific, empirical research hinders the development of policies that reflect the local environmental, social, and economic realities (Lee et al., 2021). Detailed environmental assessments based on data of NBS are a key to provide data-driven insights into their specific benefits and limitations. The lack of studies in current literature with robust methodologies to measure these impacts, creating a big gap in knowledge necessary for effective urban planning and policymaking (Braubach et al., 2017). Without this specificity, there is a risk that NbS implemented in southern European cities may not achieve their intended environmental, social, and economic outcomes, leading to inefficient resource use and missed opportunities for improving urban sustainability (Benedini & Rossi, 2020; IEA, 2021).

This thesis aims to fill these gaps by conducting an environmental assessment of NBS in the specific context of Turin, Italy, as part of the GREEN-INC European Project. It will quantify and elucidate the environmental impacts of NBS implementations, assess their contribution to urban system circularity. The study will use a multidisciplinary approach, integrating quantitative data analysis and qualitative evaluations, to provide a comprehensive view of the sustainability and effectiveness of NbS in enhancing urban resilience and achieving environmental goals in Turin.

1.2 Research Objectives

The main objective of this research is to assess the environmental aspect of Nature-Based Solutions (NbS) in the city of Turin, within the framework of the GREEN-INC European Project. Specifically, the research aims to achieve the following objectives:

1. To develop and implement a standardized methodology for quantifying the environmental performance of NbS.
2. To evaluate the diverse environmental impacts of Nature-based Solutions in Turin.

1.3 Research Questions

Adding to the research objectives mentioned above, the following key research questions will guide the thesis:

1. How have the current nature-based solutions in Turin affected environmental parameters?
2. What methodological approaches are most effective for quantifying and evaluating the environmental performance of NbS in Turin?

Chapter 2. Literature Review

2.1 Definition of Nature-Based Solutions (NbS)

Nature-Based Solutions (NbS) represent an emerging paradigm in addressing complex varied challenges throughout the ecological approaches. As described by Cohen-Shacham et al. NBS are defined by the International Union for Conservation of Nature (IUCN) as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." (Cohen-Shacham et al., 2019). Adding on this topic, the European Commission conceptualizes NbS as solutions "inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience" (Commision, 2021).

Building on these main definitions, Chairat and Gheewala identify four core features of NbS as interventions are inspired and powered by nature; address societal challenges or resolve problems; provide multiple services/benefits, including biodiversity gain and are of high effectiveness and economic efficiency. They also establish eleven criteria that exclude green/blue interventions from being considered NbS, including "lack of functioning ecosystems," "random actions," "post-implementation goal(s)," and "negative/no impact on biodiversity." Chairat & Gheewala (Chairat & Gheewala, 2024) highlight that NbS address environmental issues while pursuing conservation and natural resource management missions, emphasizing the need for comprehensive quantitative assessment frameworks to evaluate their performance across environmental, social, and economic aspects. Lemes de Oliveira examines the conceptualizations of nature in NBS, noting that while the place-specificity of NbS is recognized in the literature, local definitions and values of nature are not sufficiently included, which can compromise long-term uptake(Lemes de Oliveira, 2025).

Policymakers across Europe and internationally have established Nature-based Solutions (NBS) as a strategic priority to tackle a range of pressing societal issues, including vulnerability to natural disasters, climate change impacts, sustainability imperatives, and progress toward fulfilling the United Nations' Sustainable Development Goals (SDGs)(Faivre et al., 2017)

NbS as an Umbrella Concept

Nature-based Solutions function as an umbrella concept includes multiple ecosystem-based approaches. As shown in Figure 1 (Commision, 2021), NbS incorporate various established practices including ecosystem-based adaptation (EbA), ecosystem-based disaster risk reduction (Eco-DRR), green and blue infrastructure (GI/BI), urban forestry (UF), sustainable urban drainage systems (SuDS), ecological engineering (EE), and ecosystem services (ESS). Albert et al. organize these approaches into five categories: "Restorative; Issue-specific; Infrastructure; Management; Protection" (Albert et al., 2021). This conceptual organization demonstrates how NbS strategically integrate existing approaches across "spatial planning, soft engineering, and performance dimensions".

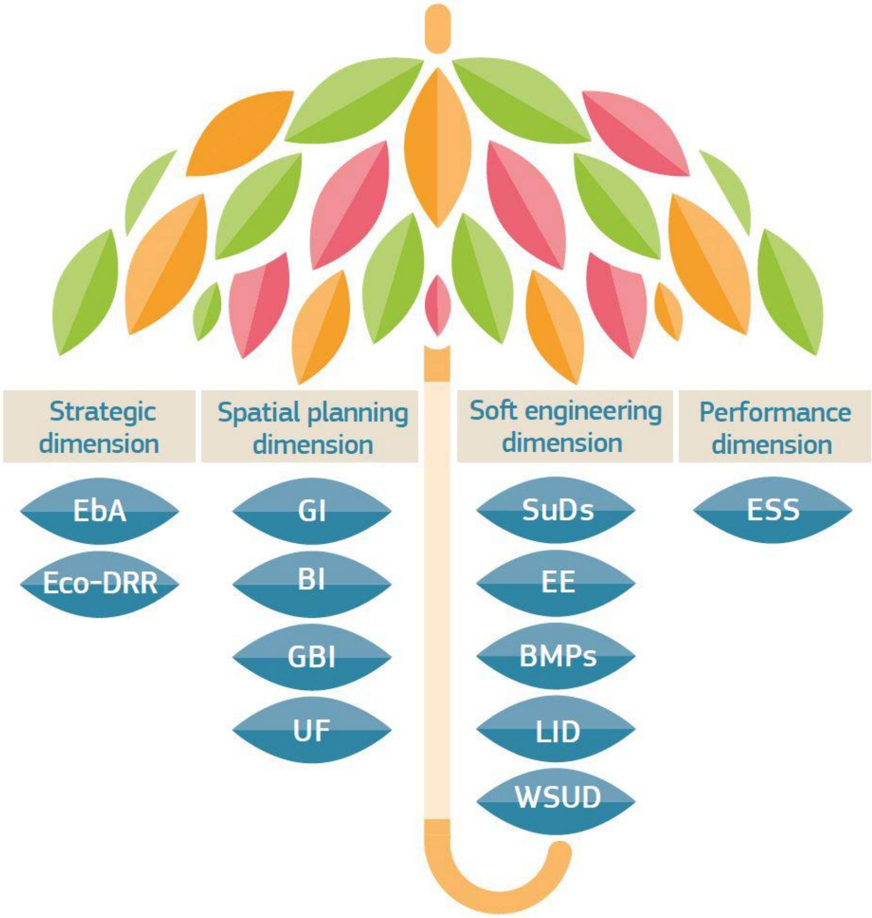

Figure 1 Nature-based solutions as an umbrella concept and the relation of NBS to key existing concepts (Source:(Commision, 2021))

According to Cohen-Shacham, three essential criteria define Nature-based Solutions:

1. **Challenge-orientation**: NbS must address well-defined societal challenges. These challenges span multiple dimensions as depicted in the Handbook, including climate resilience, water management, natural hazards, biodiversity enhancement, air quality, and social dimensions such as health and wellbeing (Commision, 2021).

2. **Ecosystem process utilization**: NbS leverage ecological processes and functions. As Albert et al. note, "The application of NbS is the deliberate inclusion of natural system processes within human environments to obtain relevant outcomes in the form of ecosystem services" (Albert et al., 2021). The degree of human intervention may vary from protection of existing ecosystems to hybrid solutions.

3. **Practical viability**: NbS must be embedded within appropriate governance and business models. As Cohen-Shacham emphasize, "To be viable, NbS need to be considered an integral part of governance models" (Cohen-Shacham et al., 2019).

2.2 Environmental Impact of Nature-Based Solutions (NbS)

Nature-based solutions is a strategic policy to address the following cities' challenges by working with natural processes and not against them. NbS utilize the functionality of living systems to deliver multiple environmental services while, at the same time, addressing society needs. NbS operates on all environmental aspects, delivering restoration, protection, and improvement of natural systems that form the foundation of human health and biodiversity conservation.

One of the most important environmental benefits of NbS is that it can enhance ecosystem resilience. Unlike traditional engineering strategies, NbS increases the resilience of natural systems to repair the disturbances by rendering landscapes more resilient to environmental change. When implemented based on ecological principles, NbS defends and recovers vital ecosystem services with the original resilience of natural systems. For instance, restoring and preserving coastal wetlands generates natural buffers for storm progression with support for a variety of ecological communities and improved water quality through the natural filtering process (Seddon et al., 2020). Multi-functional wetland systems like these far outcompete one-purpose engineered structures in terms of overall environmental gain created.

Nature-based solutions are critical in the ecological restoration, where human degradation is countered. Ecological restoration employing NbS aims at restoring degraded, damaged, or destroyed ecosystems to the point where self-sustaining ecosystem processes take place. Professionally well-designed restoration projects, according to Cohen-Shacham et al., yield important environmental gains, including improved soil formation, nutrient cycling, and habitat (Cohen-Shacham et al., 2019). For example, restoration of China's Loess Plateau natural herbaceous and shrub-land vegetation reduced soil erosion to a much greater extent than tree plantations without sacrificing soil water holding capacity (Seddon et al., 2020). This shows how nature-based solutions with an ecological focus can outperform unsubstantiated interventions not based on natural ecosystem dynamics.

In land management, NbS offers enormous advantages by agroecological approaches. These approaches integrate natural processes into farming systems, enhancing environmental quality without a loss of productivity. Agroforestry, cover crops, and conservation agriculture enhance soil health, increase water infiltration, reduce erosion, and enhance beneficial organisms. Studies in Europe have shown that agroforestry systems reduce erosion and increase soil fertility, with greatest impact in warmer, drier locations where soil is experiencing increased aridity because of global climate change (Seddon et al., 2020). Such systems demonstrate the potential of joining up with natural processes to create environmental benefits in addition to assisting agricultural production.

The environmental value of NbS extends to urban areas, that helps mitigate the ecological footprint of cities. Urban NbS like green roofs, bioswales, and urban forests make habitat for wildlife, improve soil and water quality, and create ecological connectivity in landscapes. Research shows that urban forests reduce urban heat island, effect and absorb air pollutants, while green spaces increase permeable surfaces that reduce stormwater runoff and associated pollution (Commision, 2021) These environmental improvements happens alongside social and economic benefits, increasing the multifunctional nature of NbS.

Nature-based solutions deliver better environmental performance than traditional "grey" infrastructure. While engineered solutions typically address specific environmental issues with fixed capacities, NbS respond dynamically to changing conditions and tend to improve their performance over time as ecosystems mature. In the words of Nesshöver et al., NbS promote "transformation in the ecosystem management paradigm". with approaches that build on maintaining ecological resilience considering the multi-functionality of landscapes and ecosystems." This change reflects a basic difference in the way environmental problems are framed and tackled, a shift from reactive control to proactive support for ecosystem function (Nesshöver et al., 2017).

NbS' environmental performance depends significantly on the ecological composition and arrangement of NbS. “Seddon et al. point out that NbS with high native species richness yield superior environmental benefits compared to simplified systems like monoculture plantations (Seddon et al., 2020).” NbS with high biodiversity are more resilient to pests, diseases, and climate factors, and possess a greater range of ecosystem services. This highlights the importance of ecological knowledge in NbS design and application, so that interventions work with rather than against nature (Albert et al., 2021). In accordance with ecological principles, NbS can realize long-term environmental gains across many spheres.

When applied at landscape levels, NbS yield environmental benefits that go beyond the edges of single sites. Albert points out that NbS function optimally when "applied at a landscape scale," forming networks of connecting natural and semi-natural locations that enhance ecological processes across larger regions (Albert et al., 2021). This landscape level enables NbS to address environmental concerns that extend beyond single sites, for example, watershed management, habitat connectivity, and regional climate regulation. For example, protection of the forest and restoration in headwaters has environmental services downstream like improved water quality, reduced flooding, and enhanced aquatic habitat (Commision, 2021).

Table 1 consolidates a broad array of environmental assessments of Nature-based Solutions for the period 2001-2023. The studies employ diverse methodological procedures, including quantitative analysis, simulations, reviews, surveys, and framework development. Nowak et al. and Escobedo et al. studies indicated remarkable removal of air pollution by urban forests, where the U.S. urban trees removed 711,000 metric tons annually and Santiago's urban forests removed 1,000 tons annually (Escobedo et al., 2011; Nowak & Crane, 2002). Temperature studies confirm green infrastructure's cooling ability, with Santamouris finding that green roofs can lower ambient temperature by 2°C and surface temperature by 30°C (Santamouris, 2014a), while Akbari et al. stated strategic planting of trees could lower urban temperatures by 4°C (Akbari et al., 2001a). Water management research indicates that green roofs can hold 75% of rainfall annually (Czemiel Berndtsson, 2010) and constructed wetlands can remove as much as 90% of water pollutants (Vymazal, 2011a). Conceptual theory of NbS is mapped through various frameworks to arrive at the use of IUCN Global Standard in marine aquaculture (Gouvello et al., 2023) This body of evidence demonstrates NbS effectiveness across several environmental areas across various testing methods.

Project/Paper	Year	Companies/Countries	Methodology	Result
Urban trees air pollution removal study (Nowak et al.)	2006	United States	Quantitative analysis of urban tree pollution removal	Urban trees remove approximately 711,000 metric tons of air pollution annually, providing an estimated $3.8 billion in value
Urban forests air quality improvement study (Escobedo et al.)	2008	Chile (Santiago)	Analysis of urban forest pollution removal	Urban forests remove about 1,000 tons of air pollutants each year, significantly improving local air quality
Green roofs temperature reduction study (Santamouris)	2014	Not specified	Review of green roof cooling effects	Green roofs can reduce ambient temperatures by up to 2°C and surface temperatures by up to 30°C compared to conventional roofs
Urban temperature reduction strategies (Akbari et al.)	2001	Not specified	Analysis of tree planting and cool surfaces implementation	Strategic planting of trees and implementing cool surfaces can reduce urban temperatures by up to 4°C
Green cover impact on urban temperatures (Gill et al.)	2007	UK (Manchester)	Simulation of increased green cover	Increasing green cover by 10% could reduce surface temperatures by up to 2.5°C
Urban biodiversity study (Aronson et al.)	2017	Global	Review of urban green spaces and biodiversity	Well-managed urban green spaces can support biodiversity levels comparable to natural habitats
Green roof biodiversity study (Kadas)	2006	UK (London)	Survey of green roof fauna	Green roofs in London supported over 10 species of spiders and beetles
Green infrastructure stormwater management (Fletcher et al.)	2015	Global	Review of green infrastructure effectiveness	Green infrastructure can reduce stormwater runoff by up to 90%, significantly mitigating flood risks
Constructed wetlands water treatment (Vymazal)	2011	Global	Review of constructed wetlands effectiveness	Constructed wetlands can remove up to 90% of pollutants like nitrogen, phosphorus, and heavy metals from stormwater
Green roof rainwater retention (Berndtsson)	2010	Not specified	Analysis of green roof water retention capacity	Green roofs can retain up to 75% of annual rainfall, reducing runoff and burden on urban drainage systems

Nature-Based Solutions definition and framework (Cohen-Shacham et al.)	2016	Global (IUCN)	Conceptual framework development	Defined NbS as actions that work with and enhance nature to address societal challenges, providing benefits for human well-being and biodiversity
Evolution of Nature-Based Solutions concept (Eggermont et al.)	2015	Europe	Review and conceptual analysis	NbS evolved from earlier ideas of ecosystem services and green infrastructure, integrating these concepts into a holistic framework
Nature-Based Solutions in the EU (Faivre et al.)	2017	European Union	Policy analysis and review	NbS recognized as essential strategies for sustainable urban development, enhancing urban resilience and quality of life
Co-benefits framework for Nature-Based Solutions (Raymond et al.)	2017	Urban areas globally	Framework development	Developed a framework for assessing and implementing co-benefits of nature-based solutions in urban areas
Nature-Based Solutions for marine aquaculture (Le Gouvello et al.)	2023	Global	Application of IUCN Global Standard	Demonstrated the use of IUCN Global Standard for NbS as a tool for enhancing sustainable development of marine aquaculture

Table 1 Environmental Analysis of Nature-based Solutions

2.2.1 Air Quality Improvement

Nature-Based Solutions (NbS) play a critical role in mitigating the air quality challenges faced by cities. Vegetation, including trees and shrubs are capable of removing pollutants such as particulate matter (PM), nitrogen dioxide (NO2), and sulfur dioxide (SO2). Nowak et al. mentions the economic value associated with urban tree plantings, which remove around 711,000 metric tons of pollution yearly in the US, along with providing $3.8 billion value (Nowak et al., 2006). Treed areas not only act as natural filters for capturing PM but also aid in remediating stagnant air masses through their role in biometeorology through rain out scavenging processes. Urban forests have also shown substantial benefits elsewhere; to illustrate, Escobedo et al. estimates that urban forests in Santiago Chile removes roughly 1,000 tons annually (Escobedo et al., 2011).

In addition to directly improving air quality, NbS also helps reduce the urban heat island effect which has a secondary benefit on air quality. Reduced temperatures from vegetation lead to increased emissions efficiency from power plants that were used for cooling purposes leading cold air discharges to be warmed by cooler heats and therefore decreased expenditure for global warming gases. Roof gardens as well assist these objectives; Santamouris reported adding green roofs resulted in an overall -2°C ambient temperatures while reducing power requirement for energy consumption for associated pollutions lowering its release drastically up to five ton per year (Santamouris, 2014a).

In terms of public health and overall well-being, integrating NbS into urban planning can greatly improve air quality. Enhancements to the public's health indicators would be a welcome development for the populace.

2.2.2 Reduction of Urban Heat Islands

The urban heat island (UHI) effect, where urban areas experience higher temperatures than their rural surroundings, is a significant environmental challenge that NbS can address effectively. Vegetation and green infrastructure, such as parks, green roofs, and urban forests, provide shade and release moisture through evapotranspiration, which cools the air. According to Akbari et al. strategically planting trees and implementing cool surfaces can reduce urban temperatures by up to 4°C. This cooling effect not only makes cities more comfortable but also reduces the demand for air conditioning, leading to lower energy consumption and greenhouse gas emissions (Akbari et al., 2001b).

Green roofs are particularly effective in mitigating the UHI effect. A study by Santamouris found that green roofs could reduce surface temperatures by up to 30°C compared to conventional roofs (Santamouris, 2014b). This significant temperature reduction helps lower indoor temperatures, reducing the need for artificial cooling. Additionally, green spaces can create microclimates that further enhance urban cooling. Gill et al. demonstrated that increasing green cover in Manchester, UK, by 10% could reduce surface temperatures by up to 2.5°C. By incorporating NbS into urban design, cities can effectively combat the UHI effect, leading to more sustainable and livable urban environments (Gill et al., 2007).

2.2.3 Enhancement of Biodiversity

NbS play a crucial role in enhancing urban biodiversity by providing habitats for various species and promoting ecological connectivity. Urban green spaces, such as parks, gardens, and green corridors, offer refuge for wildlife and support diverse plant and animal communities. Aronson et al. highlighted that urban areas with well-managed green spaces can support a high level of biodiversity, comparable to natural habitats (Aronson et al., 2017b). These green spaces serve as critical habitats for pollinators, birds, and small mammals, contributing to the overall ecological health of urban areas.

Moreover, NbS can restore degraded ecosystems and create new habitats. For example, the restoration of urban wetlands can provide breeding grounds for amphibians and birds, while green roofs and walls can support a variety of plant species and insects. A study by Kadas found that green roofs in London supported over 10 species of spiders and beetles, demonstrating their potential to enhance urban biodiversity . By integrating NbS into urban planning, cities can create multifunctional landscapes that support biodiversity, improve ecosystem services, and enhance the resilience of urban environments to environmental changes.

2.2.4 Water Resource Management

NbS are highly effective in managing urban water resources by enhancing stormwater management, reducing flood risks, and improving water quality. Green infrastructure, such as permeable pavements, rain gardens, and constructed wetlands, can absorb and filter stormwater, reducing runoff and preventing flooding. A study by Fletcher et al. found that green infrastructure could reduce stormwater runoff by up to 90%, significantly mitigating flood risks in urban areas (Fletcher et al., 2015). These systems also help recharge groundwater, ensuring a sustainable water supply for urban populations.

Constructed wetlands are particularly effective in improving water quality. They can remove pollutants such as nitrogen, phosphorus, and heavy metals from stormwater through natural processes like sedimentation, filtration, and microbial activity. Vymazal reported that constructed wetlands could remove up to 90% of these pollutants, providing a cost-effective and sustainable solution for urban water management (Vymazal, 2011b). Additionally, green roofs can retain a significant amount of rainwater, reducing the volume of runoff and the burden on urban drainage systems. Berndtsson found that green roofs could retain up to 75% of annual rainfall, highlighting their potential in urban water management (Czemiel Berndtsson, 2010). By incorporating NbS into urban planning, cities can enhance their water resource management, reduce flood risks, and improve water quality, contributing to more resilient and sustainable urban environments.

2.3 Common Challenges/Gaps

While greater recognition is being given to the capabilities of Nature-Based Solutions, relatively little is known about how they perform in Mediterranean urban areas like Turin. Past work has largely focused on Northern European cities with no consideration for typical constraints of Mediterranean weather that come with hot, dry summers and cool, wet winters (Langergraber et al., 2020). This geographical skew is also compounded by methodological variation, with most studies reliant on qualitative or theoretical assessments rather than standardized quantitative indices that are able to compare effectively between interventions within different contexts. In filling these gaps, the study will help improve available methods and create new applied tools that better measure how climate risks affect the environment and how NbS can make a difference when deployed.

Chapter 3. Methodology

This chapter presents the methodological framework developed to assess the environmental performance of Nature-based Solutions (NbS) in Mediterranean urban contexts, with specific focus on Turin, Italy. The assessment structure follows a three-phase approach:

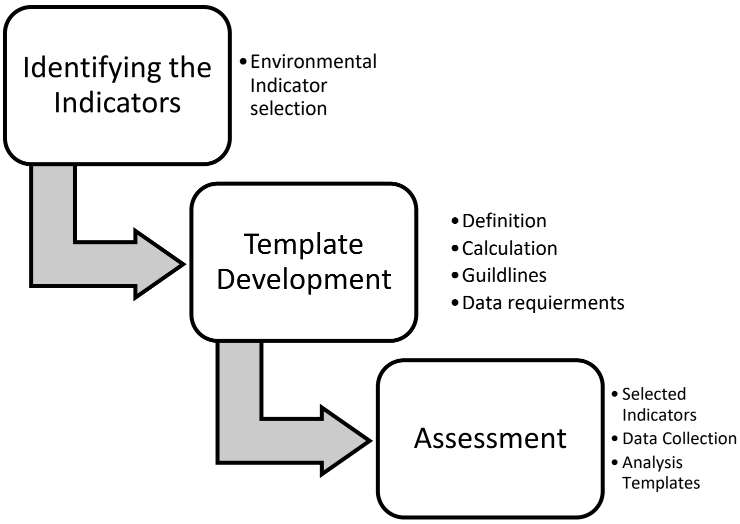

Figure 2 Methodology

3.1 Identification of Environmental Indicators:

First step identifying the most relevant environmental key performance indicator based on Pellerey & Torabi Moghadam's study (Pellerey & Torabi Moghadam, 2025).

The environmental indicators selected for this study are as following:

1. **Air Temperature**
2. **Annual CO2 Equivalent Emissions**
3. **Rainwater and Graywater Capture and resuse**
4. **People Adversely Affected by Natural Disasters**
5. **Structural and Functional Connectivity**

The five environmental indicators were chosen specifically for their relevance to the research's objective: evaluate the diverse environmental impacts of Nature-based Solutions in Turin.

3.2 Methodological Template Development:

For each indicator, comprehensive assessment templates were created incorporating:

- Standardized Definition: precise scope and parameters for each environmental metric
- Calculation Protocols: detailed quantification methods including formulas and software
- Guidelines Implementation: specifying the templets to the case study
- Data Requirements: A structured table listing the necessary data, sources, and benchmarks or target data (if available)

These templates establish a reproducible methodology that can be applied across different NbS interventions while maintaining scientific rigor and comparability.

3.3 Field Implementation and Assessment:

The final step involves applying the developed templates to evaluate the selected indicators within the Case study (Turin). The methodologies for assessing were implemented using the data and tools outlined in the templates. The results of this assessment, including key findings and implications, will be presented and discussed in **Chapter 5.**

Chapter 4. Case Study

This research is examining Turin as a primary case study for the GREEN-INC European project. Turin, Italy's fourth-largest city, is situated in the Graian Alps foothills of northwestern Piedmont. Turin has been recognized as one of the European municipalities participating in major sustainability initiatives.

Turin's policy frameworks are the context required for this research, establishing the strategic framework for Turin's adoption and evaluation of Nature-Based Solutions. Reading from these frameworks provides insight into the rankings of environmental interventions, which considers both the existing presence of current NbS projects and the probable route for future adoption. These policies also position Turin's specific environmental issues (particularly urban heat, water management, and biodiversity) within the environmental indicators assessed in this thesis. Additionally, understanding Turin's policy landscape enables us to place this research within actual municipal decision-making exercises, making our findings more practically applicable in the real world for local stakeholders.

1. Piano d'Azione per l'Energia Sostenibile e il Clima (PAESC)

Turin's Sustainable Energy and Climate Action Plan is the city's commitment to the Covenant of Mayors initiative, with ambitious goals of carbon neutrality by 2050 and a 40% reduction in emissions by 2030. The plan explicitly states NbS as priority climate adaptation measures, for which the following are targeted:

- Increasing urban forests for carbon sequestration and cooling
- The use of sustainable urban drainage systems to minimize flooding hazard
- Establishing green corridors along the four rivers of Turin (Po, Dora Riparia, Stura di Lanzo, and Sangone)

The PAESC methodology report reveals Turin's strict methodology to track energy consumption and emissions by detailed sectoral analysis, building a base-line essential for evaluating NbS effectiveness.

2. Piano del Verde (Green Plan)

Redone in 2021, Turin's Green Plan is a comprehensive vision for developing green infrastructure in the city. The plan identifies particular environmental challenges created by the geographical position of Turin and detects:

- Strategic priorities of increasing per capita green space to 25m² by 2030 from the existing 20m²
- •Conservation and promotion interventions for Turin's 110,000 city trees and 230,000 hillside woodland trees
- Priority areas for urban cooling measures through targeted vegetation placement
- Proposals for enhanced vegetation on valley corridors to further improve air circulation

3. Piano di Resilienza Climatica

Turin Climate Resilience Plan combats two key threats to the climate of Turin: heat waves/urban heat islands and heavy precipitation/flooding. Guided by the DERRIS project, the plan analyzes climate vulnerability, with a focus on Turin's 130 km^2 area where 37% is green urban area.

The plan classifies 78 adaptation measures into two general approaches:

- Preparation measures: Developing administrative capacity and emergency management systems.
- City adaptation measures: Practicing physical adjustments via NbS and infrastructure improvement.

The plan harmonizes soft (policy), green (nature-based), and grey (infrastructure) measures, with interdepartmental coordination and ecosystem service assessment set as a priority to guide implementation. It accelerates the main actions that include urban canopy cover expansion, rain garden creation, cool material adoption, and revising urban planning regulations to ensure Turin is climate-resilient by 2030.

4. Torino 2030

This is a comprehensive action plan for Turin's development to 2030, produced in 2018-2019 by City Departments. The strategy is centered on four founding principles:

- Participatory Turin: Creating participatory citizenship, digitalization, and active neighborhood involvement through initiatives such as civic design coordination, co-management of public space, and digital citizen participation platforms.
- Dynamic Turin: Making a city that is marked by culture, innovation, and talent through building innovation districts, strengthening the university system, developing tourism, and offering opportunities to start-ups and enterprises.
- Livable Turin: Making Turin an accessible, circular, green and healthy city by developing sustainable mobility policies, waste prevention, building green infrastructures, and climate adaptation.
- Supportive Turin: Creating Turin as a city of rights with social inclusion policies, housing policies, education support and equality and intercultural dialogue ones.

Each area of intervention has specified objectives and concrete actions connected with UN 2030 Sustainable Development Goals. The document also has stakeholders' inputs gathered by community meetings, which represent the collaboration in building a solid and sustainable Turin in 2030.

Chapter 5. Results

5.1. Indicator selection

This section presents the five key indicators selected to evaluate Nature-Based Solutions (NbS) in Turin, chosen for their specific relevance to Mediterranean urban contexts and Turin's environmental challenges. Following the indicators have been selected based on the requirements of the GREEN-INC project, the indicators include: Air Temperature , which measures NbS cooling effects in urban settings; Annual CO_2 Equivalent Emissions , quantifying greenhouse gas impacts and carbon sequestration potential; Rainwater and Graywater Capture and Reuse , assessing water management improvements through collected and reused water volumes; People Adversely Affected by Natural Disasters (number of people), evaluating resilience by quantifying population vulnerability to climate-related hazards; and Structural and Functional Connectivity , measuring ecological network enhancement between green spaces. These indicators were selected based on their scientific validity, measurability in urban contexts, and particular relevance to Turin's specific environmental priorities as identified in the GREEN-INC European Project framework.

5.2. Template development

The following are the templates that have been used for this research:

5.2.1. Air Temperature

Short Description: measures variations in air temperature to evaluate the thermal conditions of urban environments.

Macro-category: Environmental Impacts

Sub-category: Public health and safety

Scale: Urban

Background information: Recent journal articles have illuminated valuable insight into world air temperature changes, forecasting increased knowledge of climatic change tendencies. Morice et al. in their Journal of Geophysical Research: Atmospheres paper presented the HadCRUT5 dataset, which gives a better estimate of near-surface temperature history since 1850 (Morice et al., 2021a). This paper plugs earlier gaps and uncertainties in data and provides a clearer image of global temperature trends.

Pfleiderer et al., in their Nature Climate Change article, discussed three landmark events in climate change science that focused on the necessity of long-term temperature records to see global climate patterns (Pfleiderer et al., 2019). Their research indicates the role of human influences in warming trends as observed and bridges the gap between modeled and observed tropospheric temperature changes.

Nature-based solutions (NbS) are significant in reducing urban air temperatures through several cooling mechanisms. Urban green spaces have been shown to reduce ambient temperatures by as much as 0.94°C during daytime (Bowler et al., 2010), with cooling effects up to 240m beyond park boundaries and with maximum cooling intensities of 6.72°C (Feyisa et al., 2014). Trees provide significant cooling impacts individually, with air temperatures 2-3K lower in canopies over trees compared to open spaces, with canopy density controlling most (Rahman et al., 2020). Green infrastructure performance varies by context; for instance, green roofs may reduce ambient temperatures by up to 2°C in the urban setting (Santamouris, 2014c). In particular, the cooling effect is largely influenced by the size and configuration of green spaces, with specific threshold values necessary for optimal comfort cooling effect (Yu et al., 2020).

These studies collectively demonstrate ongoing efforts to refine our understanding of global temperature trends, improve data quality, and reconcile observations with climate models considering the role of NbS in air temperature. They underscore the complexity of Earth's climate system and the challenges in accurately measuring and interpreting temperature changes across different atmospheric layers and time scales and effect of NbS.

Used in:

1. HadCRUT5dataset (Morice et al., 2021b)
2. Observed temperature changes in the troposphere and stratosphere (Steiner et al., 2020)
3. Key events in climate change science (Santer et al., 2019)

Key Performance Indicator: KPI

CALCULATIONS

Assessment method: Air temperature as a climatic indicator is a fundamental measuring tool used to record and monitor the changes in the Earth's climate system over time. It provides important information regarding long-term climate trends, variability, and potential impacts of global warming. Air temperature as an indicator calculation involves a series of operations that transform raw temperature observations into quantitative usable data which can be compared among regions and across different intervals(Klein Tank & Zwiers, 2009).

1. Data Collection:
   - Gather temperature measurements from weather stations, satellites, or other reliable sources.
   - Ensure data is collected at consistent intervals (e.g., hourly, daily) over a specified time period.

2. Data Quality Control:
    - Remove outliers and erroneous data points.
    - Apply statistical tests to identify and correct for instrument biases.

3. Temperature Conversion:

    Convert all temperature data to a consistent scale (Celsius or Fahrenheit). Formula:

    $°F = (°C \times 9/5) + 32$ *or* $°C = (°F - 32) \times 5/9$

4. Calculation of Daily Mean Temperature:

    For each day, calculate the average of maximum and minimum temperatures. Formula:

    $T_{mean} = (T_{max} + T_{min}) / 2$

    Where: T_{mean} = Daily mean temperature T_{max} = Daily maximum temperature T_{min} = Daily minimum temperature

5. Monthly Average Temperature:

    Calculate the average of daily mean temperatures for each month. Formula:

    $T_{monthly} = \sum(T_{mean}) / n$

    Where: $T_{monthly}$ = Monthly average temperature $\sum(T_{mean})$ = Sum of daily mean temperatures n = Number of days in the month

6. Annual Average Temperature:

    Calculate the average of monthly temperatures for each year. Formula:

    $T_{annual} = \sum(T_{monthly}) / 12$

7. Temperature Anomaly Calculation:
    - Choose a baseline period (2001 to 2023).
    - Calculate the long-term average temperature for each month using the baseline period.
    - Subtract the long-term average from each monthly temperature to get the anomaly. Formula:

      $T_{anomaly} = T_{observed} - T_{baseline}$

    Where: $T_{anomaly}$ = Temperature anomaly $T_{observed}$ = Observed temperature $T_{baseline}$ = Long-term average temperature for the corresponding month.

Temperature anomalies yield precious advantages over temperature readings not corrected for anomalies in climate studies, particularly in urban context like that of Turin. Through the computation of differences relative to a baseline period of record (*T_anomaly = T_observed - T_baseline*), anomalies really cancel out regional influences, seasonality, and site-specific biases that can conceal subtle but significant climate signals. Based on the Statistical Climate Science study at the University of Washington, "Anomalies better describe climate variability over broader regions than absolute temperatures do, and they provide a frame of reference permitting more useful comparisons between places and more accurate estimates of temperature trends." (Tingley, 2012).

8. Visualization:

visual representations of temperature trends

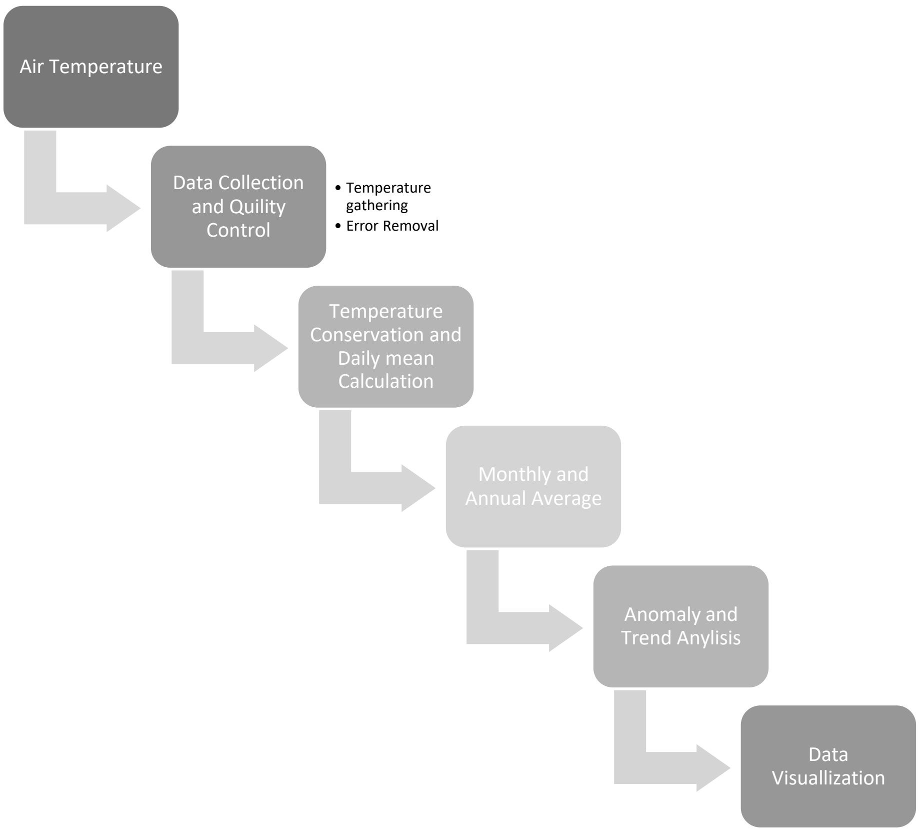

Figure 3 Assessment methodology for Air Temperature

Input data	Data Source In Turin	Data format	Elaboration
Raw temperature measurements	Arpa	Numerical data (°C)	Collected at consistent intervals (daily)

Table 2 Necessary data for air temperature analysis.

BENCHMARKS

Global References:

- "Comparison of homogenization methods for daily temperature series against an observation-based benchmark dataset" (Squintu et al., 2020) establishes methodological benchmarks for temperature data quality. The study found that in high-quality monitoring networks, effective homogenization methods achieved relative Root Mean Square Error (rRMSE) values of 0.73-0.96°C for maximum temperatures with 50-65% of daily values showing differences less than 0.5°C. For challenging European datasets with lower station density, performance decreased to rRMSE values of 1.16-1.35°C, establishing reference thresholds for temperature data quality assessment in urban monitoring networks.
- "Evaluation of trends in extreme temperatures simulated by HighResMIP models across Europe" (Squintu et al., 2021) provides quantitative temperature trend benchmarks across European regions. The study documents observed minimum winter temperature trends of 0.3-0.4°C per decade (1970-2014) and summer maximum temperature trends of 0.2-0.5°C per decade, with Mediterranean regions showing the strongest warming. For extreme indices, warm extremes (TX90p-JJA) increased by 1.5-2.5% per decade in Mediterranean areas, including northern Italy, with urban centers showing 30-45% higher trends than surrounding regions.

Local References:

- "Analysis of two-decade meteorological and air quality trends in Rome (Italy)" (Bernardino et al., 2022) provides critical benchmarks for temperature patterns in Italian urban environments comparable to Turin. This 20-year analysis (2000-2020) revealed a statistically significant positive trend for average air temperature of 0.07°C/year in both urban and coastal sites in Rome. Maximum temperatures increased more rapidly in urban areas (0.10°C/year) than in coastal locations (0.01°C/year), while minimum temperatures showed an even stronger warming trend in the city center (0.12°C/year). The heat index, which combines temperature and humidity to measure thermal comfort, increased at 0.11°C/year in Rome's center compared to 0.06°C/year in coastal areas. Seasonal analysis demonstrated that statistically significant upward temperature trends were most pronounced during summer and autumn months, with the urban heat island effect particularly evident in the nighttime minimum temperature differences between urban and surrounding areas. These findings establish reference values for expected temperature change rates in Mediterranean urban contexts similar to Turin, providing essential benchmarks for evaluating both regional climate change signals and local urban heat island effects.

TARGETS

Global Targets:

- Glasgow Climate Accord (COP26): The Glasgow Climate Accord reaffirms the Paris Agreement's temperature goals in stronger and more urgent terms. It is even stricter and more harmful yet, in the opinion of the IPCC, because avoiding global warming to 1.5°C, rather than 2°C, would indeed reduce the threat and consequences of climate change. The Pact acknowledges that to reach this objective will "need rapid, deep and sustained reductions in greenhouse gas emissions", globally such as lowering carbon dioxide emissions by 45% in 2030 from 2010 levels (Lyster, 2023).
- The Paris Agreement chapter: the Agreement established a definitive temperature goal to hold global warming "well below 2°C" and "pursuing efforts to limit such a rise to 1.5°C" over pre-industrial levels. It refers to it as a "top-down" element that gives a "ambitious direction" for countries' climate efforts. The document states that achieving this temperature goal entails a transition to a "net zero" economy in the second half of this century(Delbeke et al., 2019).

Local Targets:

- Turin's "Piano del Verde" (Green Plan) sets clear goals and key priorities for the city's green infrastructure, which affects temperature control. The plan highlights how crucial Turin's 18.2 million m^2 of public green spaces are (about $20m^2$ per person) to reduce urban heat island effects. It points out the need to boost the city's 110,000 urban trees and 230,000 trees in hillside woods to cool down areas in crowded parts where lowering temperatures matters most. The plan also aims to create green paths along Turin's four rivers (Po, Dora Riparia, Stura di Lanzo, and Sangone) to improve ecological links while providing natural cooling.

5.2.2. Annual CO2 Equivalent Emissions

Short Description: the total annual emissions of greenhouse gases (GHGs) expressed in terms of their CO2 equivalent.

Macro-category: Environmental Impacts

Sub-category: Climate Change

Scale: Urban

Background information: Nature-based Solutions (NbS) have substantial potential for reducing CO2 emissions through both direct and indirect mechanisms. NbS can sequester vast amounts of CO2, and store it as carbon in plants, soils, and sediments, when conserving, restoring, or better managing ecosystems including forests, wetlands, and farmland. Effective NbS strategies that aid in carbon removal and storage include afforestation, reforestation, and the restoration of coastal wetlands (Debele et al., 2023). NbS can also include urban strategies including green buildings, urban green spaces and preserved natural habitats, and may reduce emissions generated by the transport, residential, and industrial sectors by up to 25% (acting on savings from reduction in emissions) (Pan et al., 2023). These solutions not only lock away carbon, but also nudge pro-environmental behaviour, limit resource consumption, and improve human well-being to create climate-resilient sustainable urban places. The right policies and practices, at all levels, can create a supporting environment for raising the ambitions of NbS for climate action, and close the knowledge gap between scientists, policymakers, and practitioners to create a level playing field of NbS knowledge. To be effective, NbS must be implemented alongside rapid cuts to greenhouse gas emissions from other sectors in order to achieve global climate goals.

The Annual CO2 Equivalent Emissions indicator is a critical tool for understanding and managing the impact of human activities on climate change. This indicator aggregates the emissions of various greenhouse gases (GHGs), such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), into a single metric expressed in terms of CO2 equivalents. This standardization allows for a comprehensive assessment of the total GHG emissions, facilitating comparisons across different sectors and regions. The intent of this indicator is to provide a clear and quantifiable measure of the contributions to global warming, enabling policymakers, researchers, and businesses to track progress towards emission reduction targets. The importance of this indicator is underscored by its widespread use in international climate agreements, such as the Paris Agreement, where countries commit to reducing their national GHG emissions to mitigate global temperature rise.

Writing on the existing knowledge around the Annual CO2 Equivalent Emissions Indicator, existing Inquiry can see that it is a climate monitoring and reporting indicator. It fits squarely into national GHG inventories (submissions) to the the United Nations Framework Convention on Climate Change (UNFCCC), and subsequently national GHG inventories are incorporated to the Intergovernmental Panel on Climate Change (IPCC) guidance for accounting for GHGs. Companies use this indicator in sustainability reports, and carbon footprinting and climate impact studies. A recent article published by Le Quéré et al. in Nature Climate Change showed that transformative change to energy-related CO2 emissions is required from our energy systems, to emissions related to industrial processes, and land-use emissions if we want to make significant reductions (Quéré et al., 2020). Another discussion paper by Rogelj et al. in Nature reviews the pathways for getting to 'net-zero' emissions, also reiterating the importance this indicator for shaping and guiding policy and investment actions (Rogelj et al., 2021). With the Annual CO2 Equivalent Emissions indicator, various stakeholders can identify, design and implement actions specific to emissions reductions and carbon sinks, leading to sustainable development, and transitioning toward a resilient and climate-stable future.

Used in:

1. Global Carbon Budget 2021 (Friedlingstein et al., 2022)
2. Global Warming of 1.5°C (IPCC, 2022)
3. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement (Le Quéré et al., 2020)
4. Net-zero emissions targets are vague: three ways to fix (Rogelj et al., 2021b)
5. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018 (Maiorano et al., 2007)

Key Performance Indicator: KPI

CALCULATIONS

The calculation of Annual CO2 Equivalent Emissions involves converting the emissions of various greenhouse gases (GHGs) into a common unit, CO2 equivalent (CO2e), using their respective Global Warming Potentials (GWPs). This allows for a standardized measure of the total impact of all GHGs emitted (WRI et al., 2014).

1. First begin by identifying all the greenhouse gas (GHG) emissions that fall within the scope of the analysis and are specifically those emissions that occur within the city of Turin. This includes emissions from the generation of energy, transportation, industrial processes, agriculture, waste, and any other relevant sectors in this region.

2. Then Get quantitative data on the emission of each GHG from the identified sources. It is usually stated in units of metric tons per year. Common GHGs include carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and fluorinated gases.

3. Global Warming Potentials (GWPs) will be applied: Convert each GHG's emissions to CO2 equivalents (CO2e) by their respective Global Warming Potentials (GWPs). The GWPs are the multiples which define the relative role of each GHG with respect to CO2 over a specified timescale, usually 100 years. Multiplying the amount of each GHG by its GWP to obtain the CO2e in the end.
4. Last step all the GHGs' CO2e values will be added to get the total annual CO2 equivalent emissions. This total is the sum effect of all the GHG emissions in terms of CO2e. It is one measure through which total GHG emissions from different sources or over different spans of time can be assessed and compared.

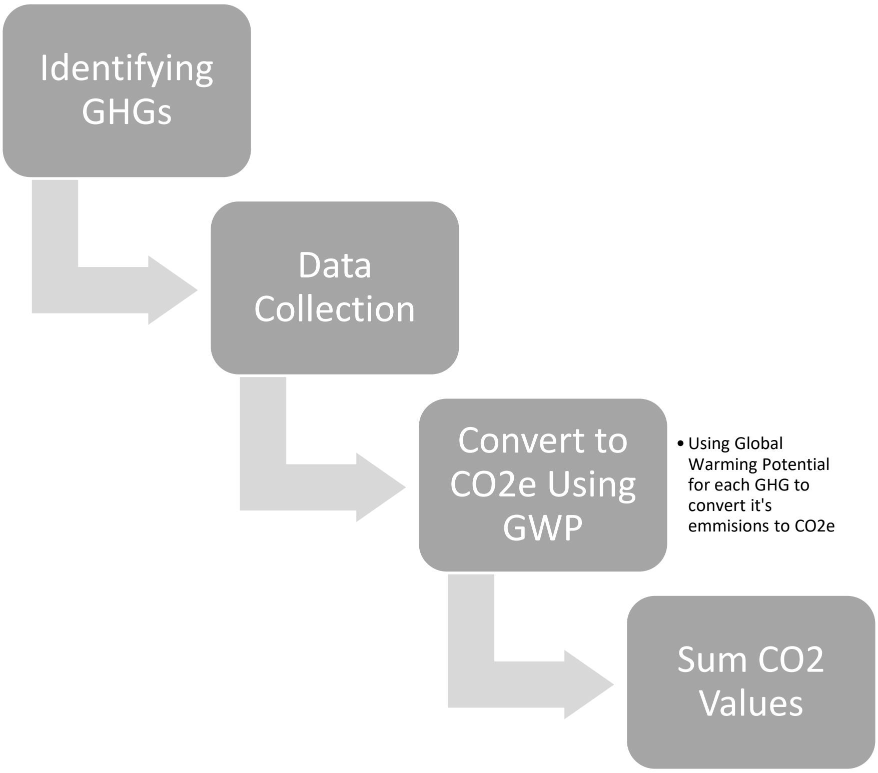

Figure 4 Assessment methodology for CO2 emissions

Input data	**Data Source in Turin**	**Data format**	**Elaboration**
Sources of Greenhouse Gas (GHG) Emissions	Arpa	Quantitative data in metric tons per year	Collecting data from emissions data from power plants, vehicles, factories, farms, and waste disposal sites. Data can be obtained from national inventories, industry reports, and environmental monitoring agencies.
Quantitative Data on GHG Emissions	Arpa	Metric tons per year for each GHG	Gathering quantitative emissions data for each GHG from the identified sources. This data is typically reported annually.
Global Warming Potentials (GWPs)	Intergovernmental Panel on Climate Change (IPCC) reports	GWP values (dimensionless) for each GHG	Obtaining the GWP values for each GHG from the latest IPCC assessment reports. GWPs are factors that describe the relative impact of each GHG compared to CO2 over a specific time period, usually 100 years. These values are essential for converting the emissions of each GHG into CO2 equivalents (CO2e).

Table 3 Necessary data for CO2 emissions

BENCHMARKS

EU-27 references:

- Eurostat Data: Eurostat estimates the EU-28's carbon footprint at 7.2 tonnes CO_2 per person in 2017, providing a vital benchmark for per capita emissions assessment. This data reveals that services account for 23% of the total carbon footprint while representing only 7% of direct CO_2 emissions (with transport, construction, and real estate services accounted for separately). The majority of emissions originate from EU production activities rather than imports. Eurostat uses a modeling approach to compile these estimates, based on economic information and air emissions accounts (AEA). These carbon footprints represent one particular analytical application of AEA, which include a range of greenhouse gas emissions data suited for integrated environmental-economic analyses and calculating emission intensities (Eurostat, 2020; Mr. Tobias N. Rasmussen, 2006)

- Global Carbon Budget 2021: The Global Carbon Budget has released expansive tracking metrics for carbon emissions. Friedlingstein et al. discussed that global fossil CO_2 emissions (EFOS) in 2020 were, 9.5±0.5 GtC yr^{-1} (9.3±0.5 GtC yr^{-1} including the cement carbonation sink), a decrease of 5.4% from 2019. With the addition of land-use change emissions, (ELUC), of 0.9±0.7 GtC yr^{-1}, total anthropogenic CO_2 emissions were 10.2±0.8 GtC yr^{-1} (37.4±2.9 $GtCO_2$), meaning that the atmospheric CO_2 plus emissions in 2020 was the following: atmospheric CO_2 growth rate (GATM) was 5.0±0.2 GtC yr^{-1} (2.4±0.1 ppm yr^{-1}), ocean CO_2 sink (SOCEAN) was 3.0±0.4 GtC yr^{-1} and terrestrial CO_2 sink (SLAND) was at 2.9±1 GtC yr^{-1}. For carbon dioxide concentrations in the atmosphere globally we have an annual mean of, 412.45±0.1 ppm. With the first look at 2021 we see that EFOS were rebounding to the 2019 levels with a +4.8% (4.2% to 5.4%) year on year compared to 2020. This information provides important reference points for fluxes across the atmosphere, ocean and terrestrial biosphere that we can properly assess the contribution of CI cities and regional urban contexts as a global carbon cycle (Friedlingstein et al., 2022)

Local references:

- Greenhouse gas emissions reduced in 2019: According to the National Inventory Report 2021 and Information Inventory Report 2021 of ISPRA on April 15-16, Italy's greenhouse gas emissions decreased by 19% in 2019 compared with 1990, from 519 to 418 million tonnes of CO2 equivalent. The report notes a decline of 2.4% compared to 2018 levels too. This downtrend is because of a variety of reasons: higher production of energy from renewable resources, greater industrial process energy efficiency, and lower coal consumption. Despite the fact that such progress is being made, the energy production and transportation sectors are still responsible for producing approximately half of country greenhouse emissions. The decrease in emissions from the energy industries sector was especially dramatic, falling by 33% in 2019 compared to levels in 1990. This drop is especially noteworthy because it was noted even as thermoelectric power generation increased from 178.6 Terawatt hours (TWh) to 195.7 TWh and electricity consumption increased from 218.7 TWh to 301.8 TWh during the same period.

TARGETS

EU-27 References:

- European Green Deal: The European Commission has established binding climate targets through the European Climate Law, requiring the reduction of net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, with the ultimate goal of making Europe the first climate-neutral continent by 2050. This framework is implemented through a comprehensive package of policies including: a strengthened EU Emissions Trading System with a lower cap and expanded scope; the Effort Sharing Regulation assigning tailored national targets for non-ETS sectors; a renewable energy target of 40% by 2030; stronger CO_2 emissions standards requiring new cars to reduce emissions by 55% by 2030 and 100% by 2035; and a target for carbon removals by natural sinks equivalent to 310 million tonnes of CO_2 by 2030. To ensure social fairness, the Commission has proposed a €72.2 billion Social Climate Fund to support vulnerable households during the transition.

Local references:

- Rome's SECAP: As a consequence of resolving the Assembly of Rome no. 78 of 14 November 2017, Rome officially adhered to the Covenant of Mayors on climate and energy and audit their territory's greenhouse gases emissions at least 40% by 2030. Since attachment to the Covenant of Mayors on climate and energy, Rome will make a Sustainable Energy and Climate Action Plan(SECAP) that studies climate altering emissions in other sectors like waste, green areas, mobility, residential, and tertiary. The SECAP concludes with other strategies for the city like a description in the Urban Plan for Sustainable Mobility, recycling and managing post-consumer materials, and Smart City plan. Accentuating that Rome's vision is that of a sustainable, resilient, and inclusive city.
- Milan's Climate Action Plan: The Air and Climate Plan (PAC) was approved by the City Council of Milan, marking the completion of the first action in an integrated planning process that aims for complete carbon neutrality by 2050, with clear interim targets, like a reduction of fossil fuel use by up to 50% by 2030 and more than 60,000 m^2 of installed photovoltaic panels on public buildings. The plan aims to change the transport system (a cycle pedestrian city with in-depth 30 km/h speed limits), refurbish public buildings with energy efficiency, cool the city with urban greening to reduce heat islands, and raise awareness about climate change with citizens. This strategic document was not prepared in isolation, but was the result of a large process of participation with citizens, associations and businesses, and further assured by Milan's participation in the European Commission's Mission on Climate-Neutral and Smart Cities and their NetZeroCities program which is run by EIT Climate-KIC, helping to provide important support for implementing the PAC.
- Turin 2030: Turin has set a bold CO2 reduction target. While building its climate targets onto the growing public awareness captured in the Climate Resilience Plan survey results, the City of Turin aims to reduce GHG emissions by at least 40% by 2030 from the baseline, and ultimately achieve carbon neutrality by 2050. The City is developing a framework that includes both mitigation efforts to reduce emissions from economic

sectors (buildings, transportation, waste, industrial processes) and adaptation strategies to address climate impacts that have begun impacting their residents, such as the increased heat waves that residents refer to as intractable.

5.2.3. Rainwater and Graywater Capture and Reuse

Short Description: Volume of rainwater and graywater captured and reused annually

Macro-category: Water Management

Sub-category: Urban Water Reuse

Scale: Urban

Background information: Rainwater and graywater harvesting and reuse systems are now integral components of sustainable city water management worldwide. Such systems have the advantage of addressing growing problems with water shortages, urban flooding, and the need for resource efficiency during climate change. It has already been demonstrated through research that there are various benefits to having such systems in urban cities.

A systematic review by de Sá Silva et al. explored environmental, economic, and social impacts of rainwater harvesting systems. From the studies, the authors established that the systems can significantly reduce stormwater runoff, reduce energy consumption for water treatment and supply, and enhance urban green parks. In addition, rainwater harvesting systems have been reported to have the ability to mitigate severe climate effects such as floods and droughts through the modification of hydrological cycles in urban settings (de Sá Silva et al., 2022).

Graywater reuse systems have also been under consideration to conserve potable water resources. In recent years, studies have been focused on the establishment of potent treatment technologies to enable the safe reuse of graywater. For instance, Çiftçioğlu-Gözüaçık et al. discussed the use of electrooxidation integrated with nanofiltration/reverse osmosis to recover wastewater, yielding promising results in meeting agricultural water reuse requirements (Çiftçioğlu-Gözüaçık et al., 2023). These technological advancements are key to the expansion of the use of graywater reuse systems to most urban setups.

Used in:

1. Fifteen Fifty Mission building, San Francisco
2. Park Habitat, San Jose, California
3. 601 W. Beech Street, San Diego
4. Piedmont Atlanta Hospital's WaterHub

Key Performance Indicator: KPI

CALCULATIONS

The research offers a detailed, step-by-step approach to calculating potential water savings through rainwater harvesting, which directly aligns with this research's need for a robust, scientifically grounded method of assessing water resource management.
To calculate the Water Savings Percentage (WSP) for rainwater and graywater capture and reuse systems, it's better to follow these steps (Bertuzzi & Ghisi, 2021):

1. Calculate Potential Water Capture (PWC):

$PWC = PRH + PGW$

Where: PRH (Potential Rainwater Harvesting) = A × R × C

a. A = Catchment area (m^2)
b. R = Annual rainfall (m)
c. C = Runoff coefficient (typically 0.8 for roofs)

PGW (Potential Graywater) = P × W × D

- P = Number of building occupants
- W = Average daily water use per person (L/day)
- D = Percentage of water that becomes graywater (typically 50-80%)

2. Determine System Efficiency (SE):

$SE = E \times M$

Where:

- E = Collection and storage efficiency (typically 0.8-0.95)
- M = Treatment and distribution efficiency (typically 0.7-0.9)

3. Calculate Actual Water Saved (WS):

$WS = PWC \times SE$

4. Estimate Total Water Use without the system (TWU) (for annual calculation) :

$TWU = P \times W \times 365$

5. Calculate Water Savings Percentage (WSP):

$WSP = (WS / TWU) \times 100$

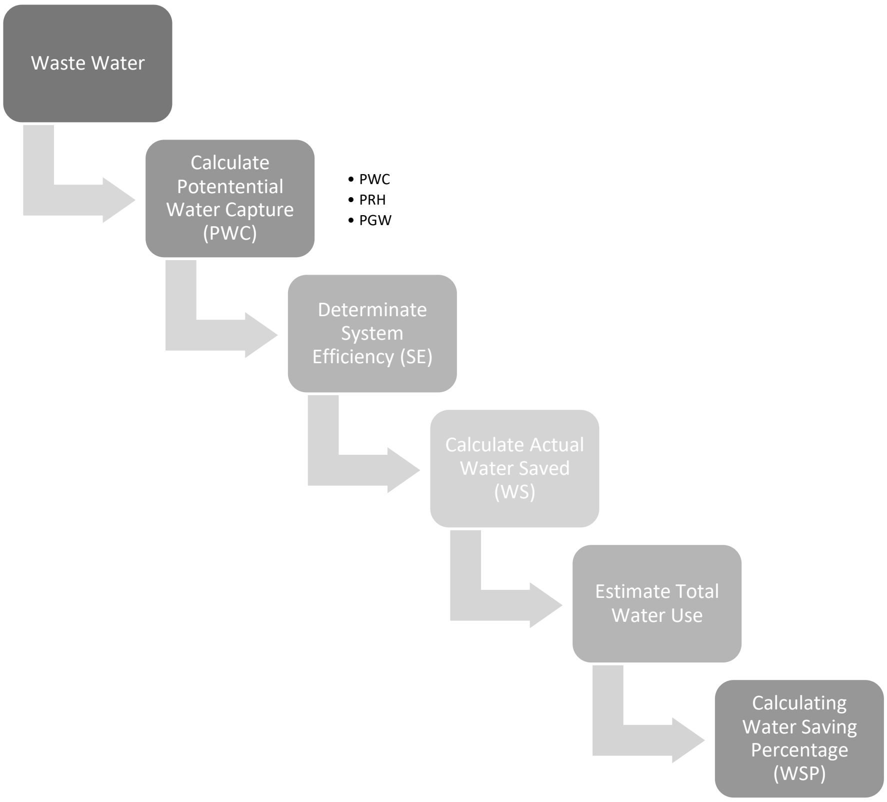

Figure 5 Assessment methodology for RainWater and Gray Water Capture and Reuse

Input data	Source	Data format	Elaboration
Catchment area (A)	Building architectural plans or municipal records for Torino	m²	Total roof area available for rainwater collection
Annual rainfall (R)	ARPA Piemonte (Regional Environmental Protection Agency) or Torino Meteorological Station	m/year	Average annual precipitation data for Torino (approximately 982 mm/year or 0.982 m/year)
Runoff coefficient (C)	Technical building standards for Italian roofing materials	Dimensionless (0.0-1.0)	Value depends on roof material (typically 0.8-0.9 for tiled roofs common in Torino)
Number of building occupants (P)	Municipal census data or building management records	Number of people	Total number of residents in the target building(s)
Average daily water use (W)	SMAT (Società Metropolitana Acque Torino) or national statistical data	L/person/day	Average per capita water consumption in residential buildings (approximately 150-175

			L/person/day for Italian urban areas)
Percentage of water becoming graywater (D)	Literature values or water use audits	%	Percentage of indoor water that can be recovered as graywater (typically 50-80%)
Collection efficiency (E)	System technical specifications	Dimensionless (0.0-1.0)	Efficiency of the collection system based on design (typically 0.8-0.95)
Treatment efficiency (M)	Treatment system technical specifications	Dimensionless (0.0-1.0)	Efficiency of the water treatment and distribution system (typically 0.7-0.9)

Table 4 Necessary data for Rainwater and Gray Water Capture Reuse

BENCHMARKS

EU-27 references:
no available benchmarks were found for this indicator

Local references:
no available benchmarks were found for this indicator

TARGETS

EU-27 References:

- Water Reuse Regulation (WRR): The European Union has established the Water Reuse Regulation (WRR) of June 2023, which gives a general framework for the water reuse to be enhanced in member states. The regulation sets down the harmonized minimum rules concerning water quality, monitoring, and risk management aspects solely for the safe reuse of reused urban wastewater in agriculture irrigation. With current EU-wide reuse of treated wastewater at approximately 1 billion m^3 annually, the new regulation aims to increase the level six times greater as it is recognized that at least 11% of Europeans have water scarcity. Permitting conditions and openness measures involving public access to information on schemes of water reuse are required under the system. This regulation is a pillar of the EU climate change adaptation policy, water security enhancement, and circular economy principles promotion by extending the life of water resources and giving flexibility to member states to tailor implementation in accordance with their specific geographical and climatic conditions. no available targets were found for this indicator.

5.2.4. People Adversely Affected by Natural Disasters

Short Description: number of people who have been adversely affected by natural disasters, including those who have been injured, displaced, or have suffered significant economic losses

Macro-category: Social Impact

Sub-category: Disaster Response and Recovery

Scale: Urban

Background information:
Natural disasters have a direct and major immediate effect on the lives on millions of people worldwide, with more devastating repercussions for developing countries. According to UNISDR and CRED (Economic, 1998) there were nearly 7,250 disasters reported worldwide between 1998 and 2017, which resulted in over 1.3 million deaths and impacted approximately 4.4 billion people. The predominant events responsible were flooding and storms in terms of numbers of events, but earthquakes single-handedly accounted for the most deaths in excess of 750,000 deaths over the research period.

The arbitrary of developing nations was stark as three-quarters of global disaster events and 99 percent of total number of individuals affected occurred in developing countries between 1970-2004 (Economic, 1998). On average more than 2 percent of the population on an annual basis are impacted by a natural disaster because most developing country reports are based on disasters affecting populations more than 500; while damage costs are on average equivalent to more than 0.5 percent of GDP - which are on average ten times higher than developed countries (Economic, 1998) .

As Hardoy, Pandiella and Velásquez Barrero point out, disasters occur at the local level where lives and livelihoods are lost, houses and infrastructure damaged or destroyed, and health and education services affected. Their work points out that hazards and vulnerability interact to form specific risk conditions that are socially and geographically framed(Hardoy et al., 2011). Analysis of disasters between 2000-2017 shows that in poor countries, 130 died on average per million potentially exposed population compared to just 18 in rich countries – making those in poor countries seven times more likely to die being equally exposed to the same hazard(Economic, 1998)

This disparity can best be attributed to the tendency of poorer societies to reside in high-risk areas, utilize poor infrastructure, and practice weather-sensitive livelihoods. Additionally, climate change is apt to increase the prevalence and magnitude of extreme events, which may again increase the vulnerability of these groups over the next several decades (Economic, 1998).

Nature-Based Solutions (NbS) are crucial to reduce the risks posed by disasters by harnessing the services of ecosystems to protect populations from climatological and hydro-meteorological threats. Robust ecosystems provide a variety of regulating services such as coastal and surface flood regulation, temperature regulation, and erosion regulation at lower costs compared to traditional engineered methods. In densely urbanized, highly exposed, and constricted spaces, hybrid systems merging ecosystem services with engineered elements (e.g., bioswales, rain gardens, green roofs) have been particularly effective. These practices not only counteract near-term disaster risks but have ancillary co-benefits of improved air quality, enhanced biodiversity, and recreational functions representing low-regret, adaptive climate adaptation strategies. Although solely green-based solutions may fall short for heavily urbanized cities at certain times, strategic injections of nature-based solutions into urban design offer a sustainable path for creating long-term immunity to aggressively growing climate challenges(Depietri & McPhearson, 2017).

Used in:

1. Economic development and the impacts of natural disasters (Toya & Skidmore, 2007)
2. Leader Survival and Natural Disasters (Flores & Smith, 2013)
3. The political economy of natural disaster damage (Neumayer et al., 2014)
4. Institutions and the losses from natural disasters (Raschky, 2008)

Key Performance Indicator: KPI

CALCULATIONS

A combination of data collection, validation, and analysis approaches should be applied to achieve reliable results regarding the number of people adversely affected by natural disasters (Guha-sapir, D., Hoyois & Below, 2015). Accordingly, the assessment of this indicator requires an integration of two diverse approaches: official reporting and statistical estimation. Official reporting is used to ensure high accuracy and compatibility in data collection from national and international organizations documenting disaster impacts (Wirtz & Below, 2009a). On the other hand, statistical estimation methods are used to support and supplement evidence generated through official reports. As such, they should strengthen and complement the evidence generated from direct reporting (Wirtz et al., 2014).

The following steps for the assessment methodology (summarized in Figure 6) combine the methodologies proposed by Guha-Sapir et al. (P. et al., 2015), Below et al. (Wirtz & Below, 2009b), and Wirtz et al. (Wirtz et al., 2014b), with the intent to assess the number of people adversely affected by natural disasters in a given region or globally over a specified time period.

1. Data Collection

- Acquired existing heat island intensity shapefiles from municipal/regional authorities
- Obtained flood risk probability shapefiles from water management authorities
- Downloaded Turin municipal boundary shapefile
- Obtained Turin's overall population density figure (people/km²)

2. Data Preparation

- Imported all shapefiles into QGIS software
- Verified coordinate reference systems and reprojected if necessary
- Clipped both risk layers to Turin municipal boundaries

3. Risk Classification

- Maintained original heat island classifications
- Preserved flood risk probability categories
- Assigned appropriate color schemes to each classification

5. Map Creation

- Set up map layout in QGIS with Esri Grey (light) base map
- Added both risk layers with transparent fill to allow overlay visibility
- Created comprehensive legend showing both risk classifications
- Added scale bar, north arrow, and title to complete the map

6. People Affected Calculation

- Applied Turin's overall population layer
- Intersect total population with heat island effect
- Determined total population exposed to flood risk the same as heat island
- Compiled final values as "People adversely affected by natural disasters" indicator

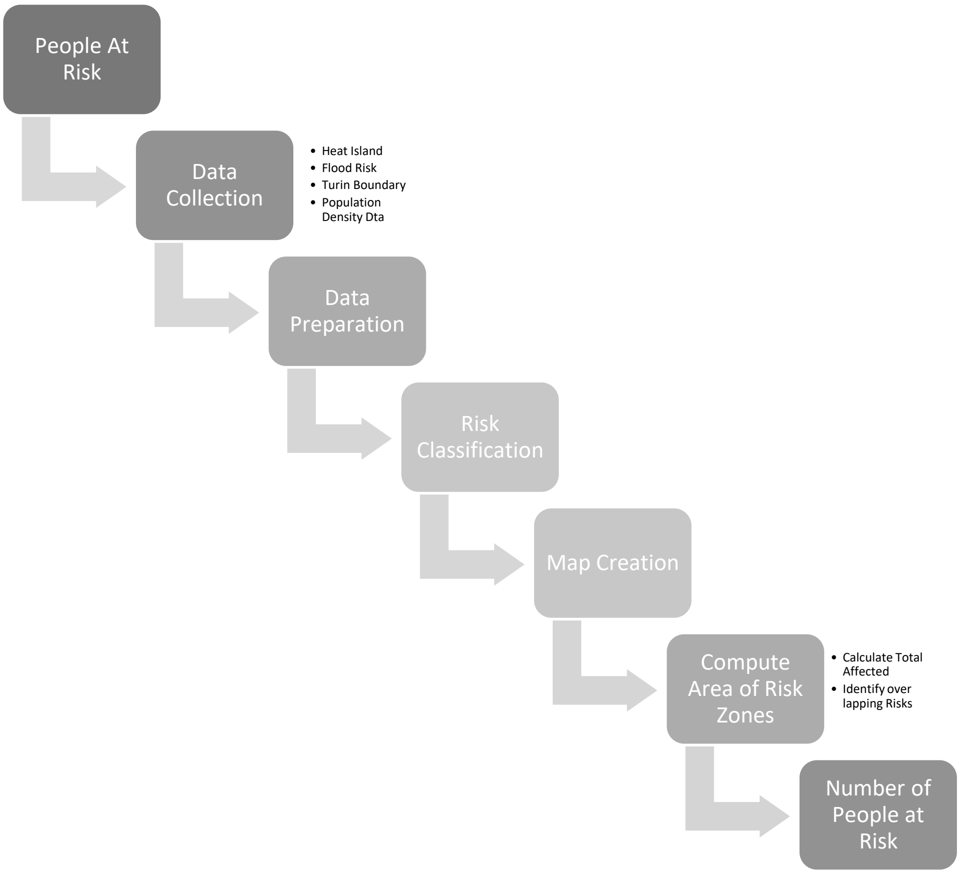

Figure 6 Assessment methodology for People Affected by Natural Disasters

Input data	Data Source In Turin	Data format	Elaboration
Heat Island Risk	geoportale.piemonte.it	Vector data (.shp)	Classified intensity zones (Bassa, Media, Medio-Alta, Alta, Molto Alta)
Flood Risk Probability	geoportale.piemonte.it	Vector data (.shp)	Three probability levels based on return periods (10/20, 100/200, and 500 years)
Turin Municipal Boundary	geoportale.piemonte.it	Vector data (.shp)	Used to clip risk layers to the study area
Turin Population Density	citypopulation.de	Statistical value	Overall population density figure (people/km²) for calculating people in risk zones
Base Map	Esri	Raster tiles	Grey (light) base map for visual context
Population	Istat	Numerical data	Turin's zonal population to calculate number of people at risk

Table 5 Necessary data for People Affected by Natural Disasters

BENCHMARKS

EU-27 references:

- The ESPON-TITAN study provides a critical benchmark for European territorial vulnerability by proving that 22% of the European population resides in high-vulnerability areas, primarily in Romania, Italy, Bulgaria, and Greece. This ground-breaking estimate surpasses economic factors, since it covers multidimensional indicators such as susceptibility, governance, social capital, and risk perception. By mapping vulnerability by region, the research presents a generalized framework for disaster risk comprehension, identifying significant differences in Central, Southern, and Eastern European countries, and outlining some of the high-risk NUTS3 regions by coastal regions of the United Kingdom, Ireland, Denmark, France, and Spain.

- ESPON NATURAL HAZARDS Project (2006): The ESPON NATURAL HAZARDS Project (2006) established an innovative benchmark for assessing territorial vulnerability in 32 European countries via the development of a new indicator-based method on the NUTS3 level. Vulnerability was addressed in the project with an integrated method and considering damage potential indicators like regional GDP, population density, and natural area fragmentation, alongside coping capacity indicators. Through creating a composite vulnerability assessment of 1,395 regions, the study provided a baseline with which to consider how different regions are vulnerable to and able to manage natural hazard risks, with significant variability in vulnerability across European terrains.

Local references:
no available benchmarks were found for this indicator

TARGETS

EU-27 References:

- European Disaster Risk Management: The European Union, in its efforts to drastically reduce the human loss due to natural disasters, is to follow a comprehensive, multi-dimensional strategy embraced by the Sendai Framework for Disaster Risk Reduction 2015-2030. This objective intends to systematically decrease disaster-induced human loss by at least 50% by 2030, such specific ones as: developing efficient national and local disaster risk reduction plans; improving early warning systems; making communities resilient; utilizing integrated risk assessment techniques; and creating adaptive mechanisms to cope with increasing natural hazard complexity.

- EU Adaptation Strategy: The EU Adaptation Strategy imposes a broad goal for Europe to become a climate-resilient society by 2050, with three overarching goals: smarter, more systemic, and faster adaptation. It aims at strengthening adaptive capacity by improving knowledge, enabling policy making, and accelerating implementation of climate change response measures. Its objective is to systematically reduce vulnerability at the sectoral and regional levels, with particular emphasis on supporting the most exposed people, strengthening regional action, and connecting international climate action. With its vision by 2050, the plan seeks to create a robust, resilient European system able to effectively respond to foresee, respond to, and mitigate the impacts of climate change, and ultimately to guarantee the continent's environmental and social resilience.

Local references:

- The National Recovery and Resilience Plan (NRRP): investing €1.53 billion directly in managing flood risk and fighting hydrogeological risks by 2026. The plan is addressed directly to territorial, generational, and gender inequalities with a specific emphasis on increased resilience through investment in green infrastructure, sustainable mobility, and community-based infrastructure at the local level. This is an all-encompassing approach that is a strategic reiteration of commitments to vulnerability reduction and increasing the capacity of local populations to resist and recover from natural disaster.

5.2.5. Structural and Functional Connectivity

Short Description: physical and ecological links between green spaces and natural elements within an urban environment, facilitating the movement of species, energy, and matter.

Macro-category: Ecosystem Services

Sub-category: Biodiversity and Habitat

Scale: Urban and neighborhood

Background information: Ecological connectivity is the central theme of landscape ecology and consists of two related dimensions: structural and functional connectivity. These are inherent dimensions for characterizing how ecological systems maximize biodiversity and resilience, particularly in urban areas.

Structural connectivity refers to the actual physical spatial arrangement of landscape features. It refers to the actual, quantifiable connections between different green locations, e.g., the presence of physical connections, corridors, or neighboring spaces which could potentially enable movement of species (Hyseni et al., 2021). It considers the actual physical elements enabling or restricting an interconnected nature landscape, e.g., forests, water bodies, and human populations.

On the other hand, functional connectivity is with the actual ecological functioning of these physical links. It measures how effectively animals can move through a landscape and considers aspects such as species behavior, habitat quality, and landscape feature openness (Croeser et al., 2024a). Functional connectivity is beyond physical proximity to determine how effectively species can move and interact in an environment, e.g., seed dispersal, breeding migration, and gene exchange.

Structurally and functionally was here totally explored for structural and functional connectivity to gain a complete perspective on ecological networks.

Used in:

1. NetworkNature project
2. Using landscape connectivity to identify suitable locations for nature-based solutions to reduce flood risk (Kalantari et al., 2022).
3. Landscape elements affect public perception of nature-based solutions managed by smart systems (Li et al., 2022).
4. What are Nature-based solutions (NbS)? Setting core ideas for concept clarification (Sowińska-Świerkosz & García, 2022).
5. Nature-based solutions for urban biodiversity: Spatial targeting of retrofits can multiply ecological connectivity benefits (Croeser et al., 2024b).
6. Wetlands as large-scale nature-based solutions: Status and challenges for research, engineering and management (Thorslund et al., 2017).
7. Uptake and implementation of Nature-Based Solutions: An analysis of barriers using Interpretive Structural Modeling (Sarabi et al., 2020).

Key Performance Indicator: KPI

CALCULATIONS

The assessment of structural and functional connectivity follows a multi-step process combining circuit theory with GIS analysis as described by Hyseni (Hyseni et al., 2021). This approach treats the landscape as an electrical circuit where species movement is analogous to current flow, with natural areas acting as conductors and urban structures as resistors. Using Circuitscape software, resistance surfaces are created from land cover data, with resistance values optimized using genetic algorithms. The model calculates current density maps that visualize movement corridors and bottlenecks, separately analyzing blue (water-based) and green (vegetation) connectivity before combining them into an integrated index. This methodology proved superior to traditional connectivity measures, explaining 7.8% of community composition variance in urban ecosystems and providing a quantitative tool for prioritizing conservation efforts.

1. Data Collection and Preparation
   - Obtain land cover maps from regional geoportals (e.g., SIRA Piemonte)
   - Acquire species distribution data on 5km grids for flora and fauna
   - Collect shapefiles for ecological elements from geoportale
   - Import Turin municipal boundary shapefile
   - Ensure all data layers share the same coordinate reference system
   - Clip all layers to the study area boundary

2. Resistance Surface Creation
   - Reclassify land cover types into resistance categories based on habitat suitability
   - Assign resistance values to landscape features:
   - Natural vegetation and forests: lowest resistance (50)
   - Mixed-use areas: medium resistance (75)
   - Urban areas and infrastructure: highest resistance (90)
   - Create resistance surfaces using habitat suitability as the foundation
   - Process landscape to identify barriers and corridors

3. Circuit Theory Application
   - Import resistance surfaces into GIS software
   - Identify habitat patches (source/destination nodes)
   - Calculate effective distances between patches
   - Generate connectivity map using the modified habitat suitability approach
   - Convert into a normalized connectivity index (0.47-1.0 scale)
   - Identify key connectivity corridors and zones of high connectivity (0.89-1.0)

4. Connectivity Index Calculation
   - Calculate effective mesh size using the formula:

     $$m_{eff} = (1/A_{total}) \times \sum(A_i^2)$$

     Where:
     m_eff = effective mesh size
     A_total = total landscape area
     A_i = area of each connected habitat patch

   - Normalize connectivity values to 0-1 scale:

     $$CI_{norm} = (CI - CI_{min}) / (CI_{max} - CI_{min})$$

   - Classify normalized values into connectivity categories

5. Connectivity Classification and Mapping

- Import normalized connectivity values into GIS software
- Apply color gradient scheme for visual interpretation (white to dark green)
- Generate connectivity maps with legend, scale, and orientation
- Map areas of high functional connectivity (0.89-1.0)
- Identify areas with medium connectivity (0.79-0.89)
- Highlight areas of lower connectivity (0.47-0.58)
- Delineate the Torino boundary on all maps

6. Validation and Analysis
   - Compare connectivity maps with habitat suitability maps
   - Identify critical connectivity corridors, especially in eastern Torino
   - Calculate percentage of landscape in each connectivity category
   - Identify priority areas for conservation or enhancement
   - Determine urban areas that could benefit from connectivity interventions

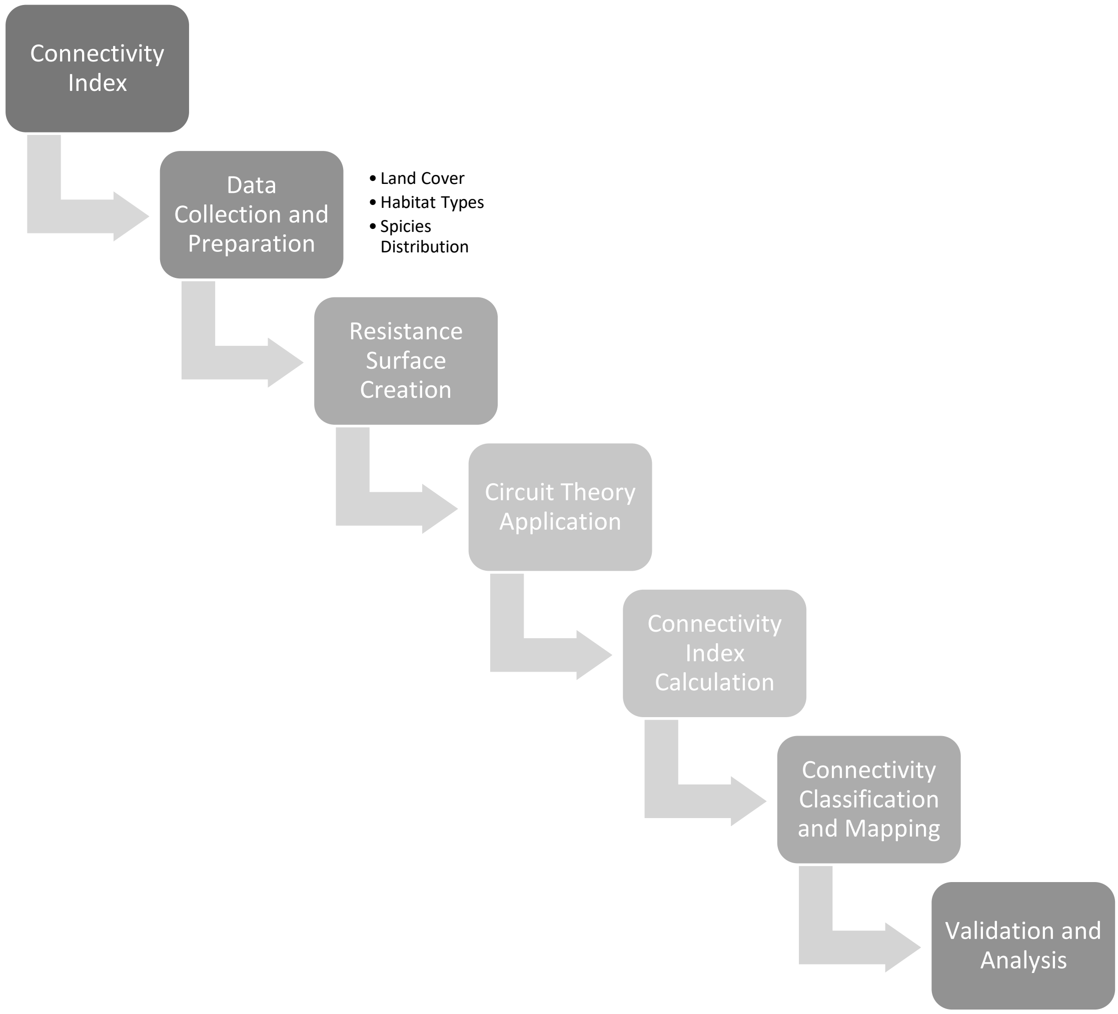

Figure 7 Assessment methodology for Structural and Functional Connectivity

Input data	Data Source In Turin	Data format	Elaboration
Fauna species distribution	SIRA Piemonte	Vector data (.shp)	BDN - Distribuzione Specie Fauna su Griglia 5 km used to identify habitat areas and target species
Flora species distribution	SIRA Piemonte	Vector data (.shp)	BDN - Distribuzione Specie Flora su Griglia 5 km used to assess natural vegetation corridors and patches
Ecological elements	Geoportale Piemonte	Vector data (.shp)	Key ecological components used to identify core habitat patches and potential corridors
Land cover map	Geoportale Piemonte	Vector data (.shp)	Classification of land use types for resistance surface creation
Habitat suitability	GIS analysis	Raster data	Classified into three categories (50, 75, 90) representing suitability for species movement
Torino municipal boundary	Geoportale Piemonte	Vector data (.shp)	Used to clip analysis layers to study area
Connectivity analysis	GIS processing	Numerical data	Calculation of effective mesh size and normalization to 0-1 scale
Base Map	Esri	Raster tiles	Grey (light) base map for visual context of final maps
Functional connectivity zones	GIS analysis	Vector data (.shp)	Classification into three categories

Table 6 Necessary data for Structural and Functional Connectivity

BENCHMARKS

EU-27 references:

- The Natura 2000: network is Europe's standard of ecological connectivity, covering 18% of the EU territory with 27,000 sites. Well-connected Natura 2000 sites tend to have connectivity index scores between 0.75 and 0.95, with a network mean of 0.78. Sites with connectivity indices above 0.80 have 30-40% higher species richness than isolated sites (below 0.50). Urban ecological networks tend to be less well connected, with values between 0.40 and 0.65. Functional ecological corridors within Natura 2000 sites have minimum widths of 50-100m and a habitat suitability score of more than 75.

Local references:
no available benchmarks were found for this indicator

TARGETS

EU-27 References:

- The EU Biodiversity Strategy to 2030 sets key connectivity targets such as: the conservation of 30% of EU land using ecological corridors as part of a coherent Trans-European Nature Network; 25% reduction in landscape fragmentation; restoration of 25,000 km of free-flowing rivers; and inclusion of urban green infrastructure standards. For connectivity indicators, member states ought to increase connectivity measures at least by 15% by 2030, with at least minimum levels of connectivity of 0.65 in urban areas and corridors between protected habitats being maintained at more than 0.75 levels.

Local references:

no available Targets were found for this indicator

5.3. Assessment

This chapter presents a comprehensive evaluation of NbS implementations in Turin, employing a systematic, multi-indicator approach developed through the GREEN-INC European Project. By applying a rigorous methodological framework, the research aims to provide empirical insights.

5.3.1. Air Temperature

Air Temperature was assessed using temperature anomaly analysis, an extremely robust technique for the detection of climate signals by calculation of deviations from a baseline reference period. Temperature observations over the city of Turin were collected from local weather stations every regular day, with quality control procedures applied to remove outliers and adjust for instrumental biases. Mean daily temperature was calculated using the formula $T\_mean = (T\_max + T\_min) / 2$ and then added to months and years.

Temperature anomalies were computed by the formula $T\_anomaly = T\_observed - T\_baseline$, with 2001-2023 employed as the baseline period. This approach removes geographic effects, seasonality, and local site bias that would otherwise mask significant climate signals and facilitate better detection of temperature trends for Turin's city environment.

Examination of temperature anomalies during the 2001-2023 period in Turin (Figure 8) reveals many dramatic patterns:

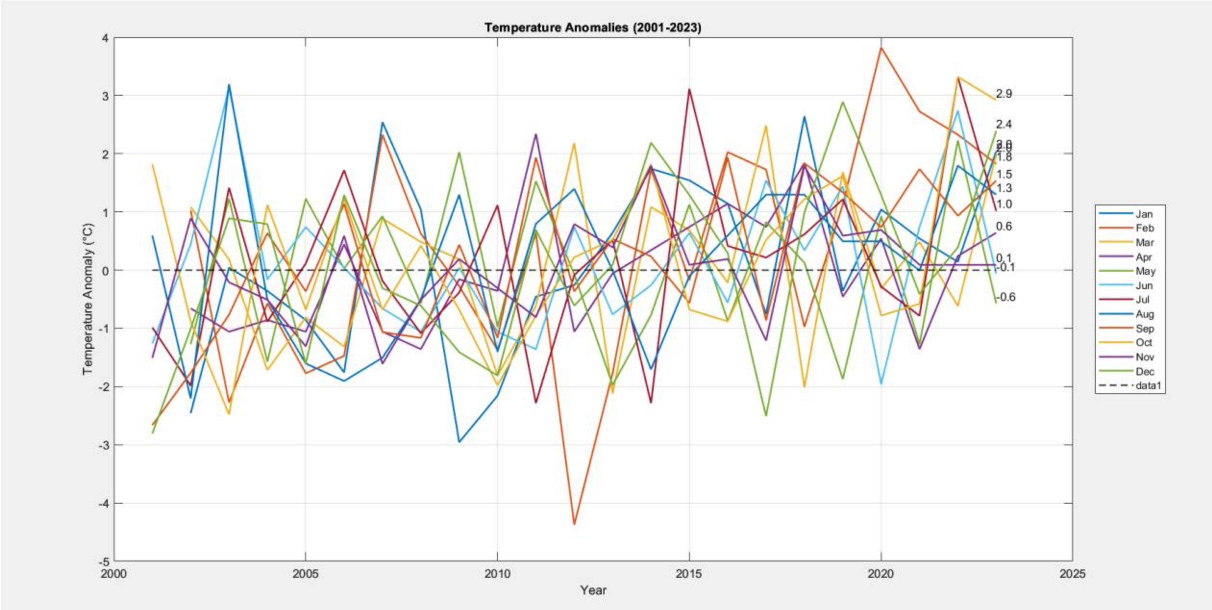

Figure 8 The analysis of temperature anomalies

1. **Progressive Warming Trend:** There is a clear trend of warming across the 22 years with the temperature anomalies shifting from mostly negative in the early 2000s to being consistently positive post-2015. This is consistent with warming trends across European cities as reported by Squintu et al.
2. **Acceleration in Recent Years:** The most pronounced warming has occurred since 2018, with multiple months showing anomalies exceeding +2.0°C. February 2023 recorded the highest anomaly in the dataset at +2.9°C, indicating significant deviation from historical norms.
3. **Seasonal Variations:** Summer months (June-August) show particularly strong warming signals in recent years, with anomalies frequently exceeding +1.5°C since 2018. This seasonal trend is especially concerning given Turin's situation within a mountain basin where urban heat island effects can be compounded during summer months.
4. **Increasing Variability:** In addition to demonstrating warming, the data indicate a rise in temperature variability, such that there is more variability in the month-to-month and year-to-year swing, particularly since 2015. This confirms the predictions from climate models for more erratic temperature behavior over the Mediterranean climate areas (Morice et al., 2021a).
5. **Reduction in Negative Anomalies:** The frequency of negative temperature anomalies has considerably reduced in the latter half of the study duration with fewer months being lower than the baseline after 2015. Negative anomalies became even rarer in the years 2020-2023, pointing towards a climatic shift in Turin's temperature pattern.

These results provide final proof that Turin is experiencing serious warming outside of natural fluctuation, both in agreement with global climate change trends and local urban heat island effects. The intensity of warming, particularly during the most recent years, emphasizes the urgency of efficient cooling actions by way of Nature-Based Solutions to urban development in Turin. Results obviously indicate Turin is undergoing severe urban warming, driven by the interaction of global climate change processes and intense localized urban heat island effects.

The results indicate a strong need for aggressive urban planning strategies, particularly Nature-Based Solutions that can exert potent resistance to rising temperatures and accumulating urban resilience against ongoing climate pressures.

5.3.2. Annual CO2 Equivalent Emissions

The Annual CO_2 Equivalent Emissions indicator was assessed using a standardized greenhouse gas (GHG) accounting protocol based on Intergovernmental Panel on Climate Change (IPCC) guidelines. This approach involved three key steps:

1. **Data Collection**: Quantitative emissions data was gathered for three primary greenhouse gases (CO_2, CH_4, and N_2O) in Turin for the years 2013, 2015, and 2019(the only data available).
2. **GWP Application**: Each GHG was converted to CO_2 equivalent (CO_2e) using the 100-year time horizon Global Warming Potentials (GWPs):
    - CO_2: GWP = 1
    - CH_4: GWP = 28
    - N_2O: GWP = 265
3. **Aggregation**: The CO_2e values for all three gases were summed to determine the total annual CO_2 equivalent emissions for each year.

Calculation Steps

For each year, the following calculation process was applied:

2013 Calculations:

- CO_2: 3,519.61 metric tons × 1 = 3,519.61 tCO_2e
- CH_4: 4,428.92 metric tons × 28 = 124,009.76 tCO_2e
- N_2O: 0.92 metric tons × 265 = 243.80 tCO_2e
- Total (2013): 3,519.61 + 124,009.76 + 243.80 = 127,773.17 tCO_2e

2015 Calculations:

- CO_2: 4,830.26 metric tons × 1 = 4,830.26 tCO_2e
- CH_4: 288.72 metric tons × 28 = 8,084.16 tCO_2e
- N_2O: 0.90 metric tons × 265 = 238.50 tCO_2e
- Total (2015): 4,830.26 + 8,084.16 + 238.50 = 13,152.92 tCO_2e

2019 Calculations:

- CO_2: 3,687.45 metric tons × 1 = 3,687.45 tCO_2e
- CH_4: 3,073.63 metric tons × 28 = 86,061.64 tCO_2e

- N_2O: 0.38 metric tons × 265 = 100.70 tCO_2e
- Total (2019): 3,687.45 + 86,061.64 + 100.70 = 89,849.79 tCO_2e

The calculations reveal significant variations in Turin's GHG emissions profile across the three assessment years:

1. **Total Emissions Trends**:
   - 2013: 127,773.17 tCO_2e
   - 2015: 13,152.92 tCO_2e (89.7% decrease from 2013)
   - 2019: 89,849.79 tCO_2e (583% increase from 2015, but still 29.7% below 2013)
2. **Methane Dynamics**: The most dramatic changes occurred in methane emissions:
   - 2013: 4,428.92 metric tons (124,009.76 tCO_2e)
   - 2015: 288.72 metric tons (8,084.16 tCO_2e) - a 93.5% reduction in raw emissions
   - 2019: 3,073.63 metric tons (86,061.64 tCO_2e) - a 965% increase from 2015
3. **CH_4 Contribution to Total Emissions**:
   - 2013: 97.1% of total emissions
   - 2015: 61.5% of total emissions
   - 2019: 95.8% of total emissions
4. **CO_2 Emissions Pattern**:
   - 2013: 3,519.61 metric tons
   - 2015: 4,830.26 metric tons (37.2% increase)
   - 2019: 3,687.45 metric tons (23.7% decrease from 2015)
5. **N_2O Emissions Trend**:
   - 2013: 0.92 metric tons (243.80 tCO_2e)
   - 2015: 0.90 metric tons (238.50 tCO_2e)
   - 2019: 0.38 metric tons (100.70 tCO_2e)

   Consistent reduction over the period, with a 58.7% decrease from 2013 to 2019

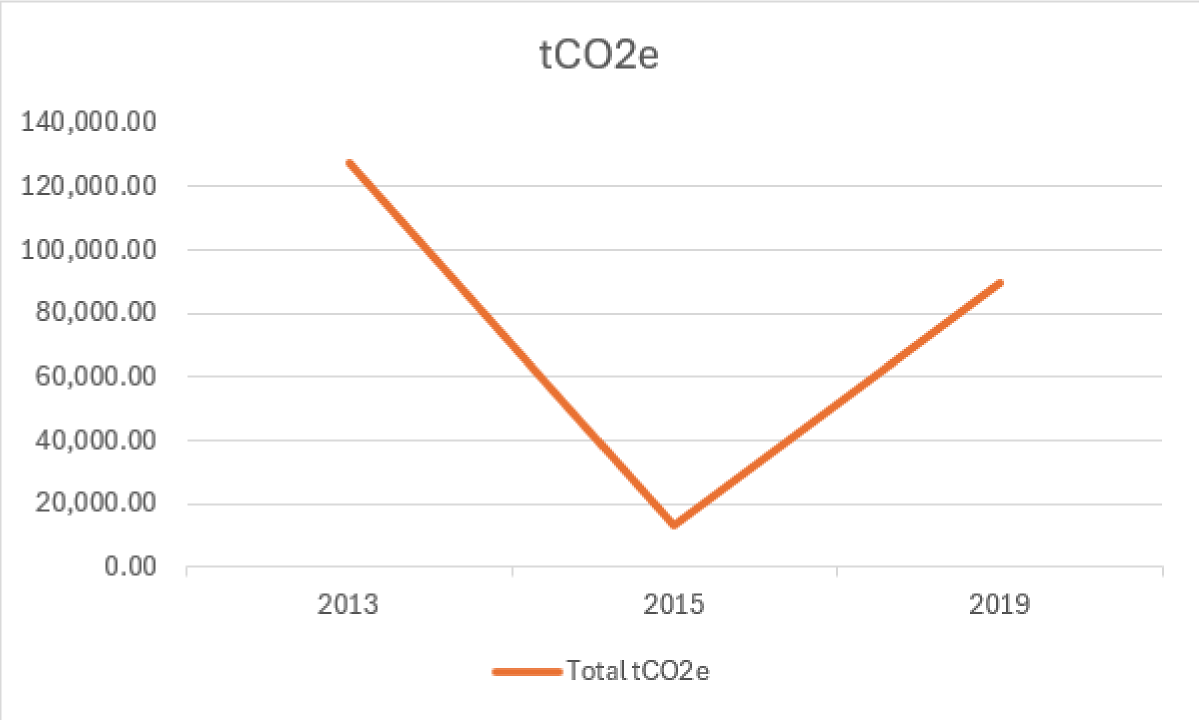

Figure 9 Total CO2e in years 2013, 2015 and 2019

These results highlight several key observations:

1. The dramatic decrease in total emissions between 2013 and 2015 was primarily driven by a substantial reduction in methane emissions, suggesting potential implementation of targeted methane control measures during this period.

2. Despite the significant reduction in 2015, methane emissions rose substantially again by 2019, though remaining below 2013 levels. This shows either temporary methane mitigation measures were employed or incremental alterations to methane-producing activities in Turin.

3. CO_2 emissions displayed an entirely different pattern than methane, namely they increased between 2013 and 2015 before decreasing again by 2019. This suggests very different factors polymerize between these two pollutants.

4. Even though co-emissions occurred, methane emissions comprised the overwhelming majority of Turin's GHG emissions profile throughout each of the years. In particular, the significant decrease in methane emissions in 2015 from the previous two years was apparent, even with its subsequent increase in 2019, this indicates that methane emissions, as a particular GHG source is high volatile.

5. The continuing declining trend in N_2O emissions, even with softly, represented a smaller portion of total emissions to indicate a respective source for long-term management of this greenhouse gas.

This study exemplifies a complex urban GHG emissions profile and reinforces the need for localized sectoral strategies for each GHG, particularly methane emissions that represent the majority of Co_2 equivalent emissions for Turin.

5.3.3. Rainwater and Graywater Capture and Reuse

Despite developing a comprehensive assessment methodology for the Rainwater and Graywater Capture and Reuse indicator (measured in m^3/year), we were unable to implement it due to insufficient data availability in Turin. While the indicator was included in our framework for its relevance to Mediterranean urban water management challenges, the current monitoring infrastructure for water reuse systems in the study areas does not yet provide reliable measurements of captured and reused volumes. This data gap represents not only a limitation for this research but also highlights a broader challenge in quantifying the hydrological benefits of Nature-Based Solutions in Turin. The methodological framework developed, based on Bertuzzi & Ghisi, remains valuable for future assessments once appropriate monitoring systems are implemented within the GREEN-INC project sites.

5.3.4. People Adversely Affected by Natural Disasters

The People Adversely Affected by Natural Disasters indicator was assessed through a GIS-based spatial analysis that integrated natural hazard risk zones with population density data. Following the methodology outlined by Guha-Sapir et al. a six-step process was implemented that combined official risk mapping with statistical estimation techniques.

Using spatial data from geoportale that were retrieved in 2021, two primary natural hazards affecting Turin were analyzed: urban flooding and heat island effects. Risk zone shapefiles were processed in QGIS, maintaining the original classifications for heat island intensity (Low, Medium, Medium-High, High, Very High) and flood risk probability levels (based on return periods of 10/20, 100/200, and 500 years).

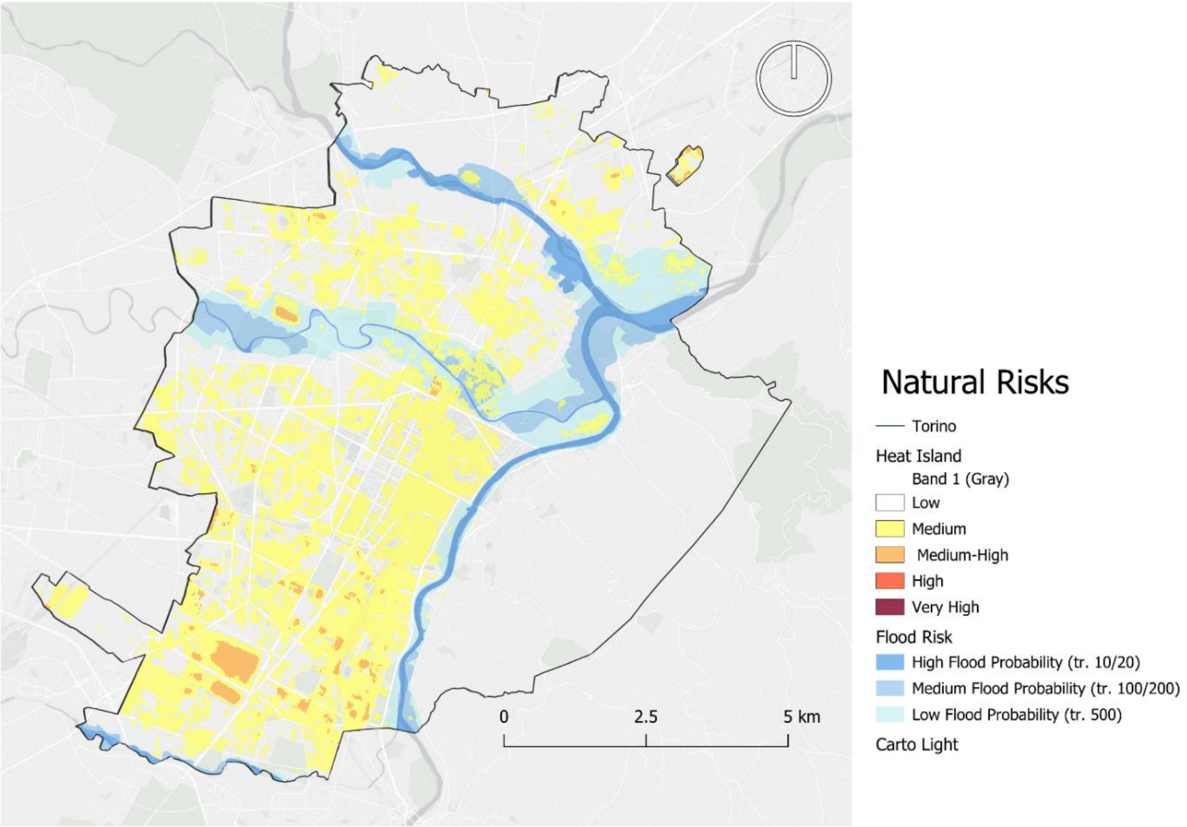

Figure 10 Natural Risks Map

The calculations estimated the area of every risk zone to determine the population within every risk zone:

People in risk zone = Population layer intersecting with the heat island layer the results indicated:

1. **Flood Risk Exposure**:

- Total area affected: 15,926,083 square meters (15.92 km²)
- Estimated population at risk ≈161,689 people

2. **Heat Island Exposure**:

- Total area affected: 90,658,226 square meters (90.65 km²)
- Estimated population at risk ≈ 817,391 people

The evaluation of the spatial distribution, as indicated by the risk map, shows that such hazards affect different parts of the city with partial overlap. Heat island effects (as indicated by yellow to red gradient) pervade the urban area, particularly in highly urbanized areas with very minimal green cover. Flood hazard (as indicated by the blue gradient) prevails along the Po River belt and tributaries, with the most probable sites (darkest blue) directly bordering watercourses.

These findings reveal that approximately 45.20% of Turin's population are exposed to significant heat island effects, and 8.93% are exposed to flood risk. In terms of EU benchmarks Turin's high heat island risk (45.20%) aligns with ESPON TITAN's emphasis on urban climate vulnerability.

5.3.5. Structural and Functional Connectivity

The Structural and Functional Connectivity indicator was assessed using a circuit theory approach integrated with GIS analysis, following the methodology described by Hyseni et al. This approach conceptualizes the urban landscape as an electrical circuit where species movement resembles current flow, with natural areas serving as conductors and urban infrastructure as resistors (Hyseni et al., 2021).

The assessment followed six methodological steps:

1. **Data Collection and Preparation**: Land cover maps and species distribution data were obtained from SIRA Piemonte, along with ecological elements from Geoportale Piemonte. These datasets were standardized to a common coordinate reference system and clipped to Turin's municipal boundary.
2. **Resistance Surface Creation**: Land cover types were reclassified into resistance categories based on habitat suitability, with values assigned on a scale where natural vegetation received the lowest resistance (50), mixed-use areas medium resistance (75), and urban infrastructure highest resistance (90).
3. **Circuit Theory Application**: Using the resistance surfaces, habitat patches were identified as source/destination nodes, and effective distances between patches were calculated. The analysis generated a connectivity map that was normalized to a 0.47-1.0 scale.
4. **Connectivity Index Calculation**: The effective mesh size was calculated using the formula:

   $$m_{eff} = (1/A_{total}) \times \sum(A_i^2)$$

   where A_{total} represents the total landscape area and A_i the area of each connected habitat patch. Values were then normalized using:

   $$CI_{norm} = (CI - CI_{min}) / (CI_{max} - CI_{min})$$
5. **Connectivity Classification**: The normalized connectivity values were classified into three categories: lower connectivity (0.47-0.58), medium connectivity (0.79-0.89), and high functional connectivity (0.89-1.0).
6. **Validation and Analysis**: Connectivity maps were compared with habitat suitability assessments to identify critical corridors and priority areas for enhancement.

The spatial analysis of structural and functional connectivity in Turin reveals distinct patterns of ecological connectivity across the urban landscape:

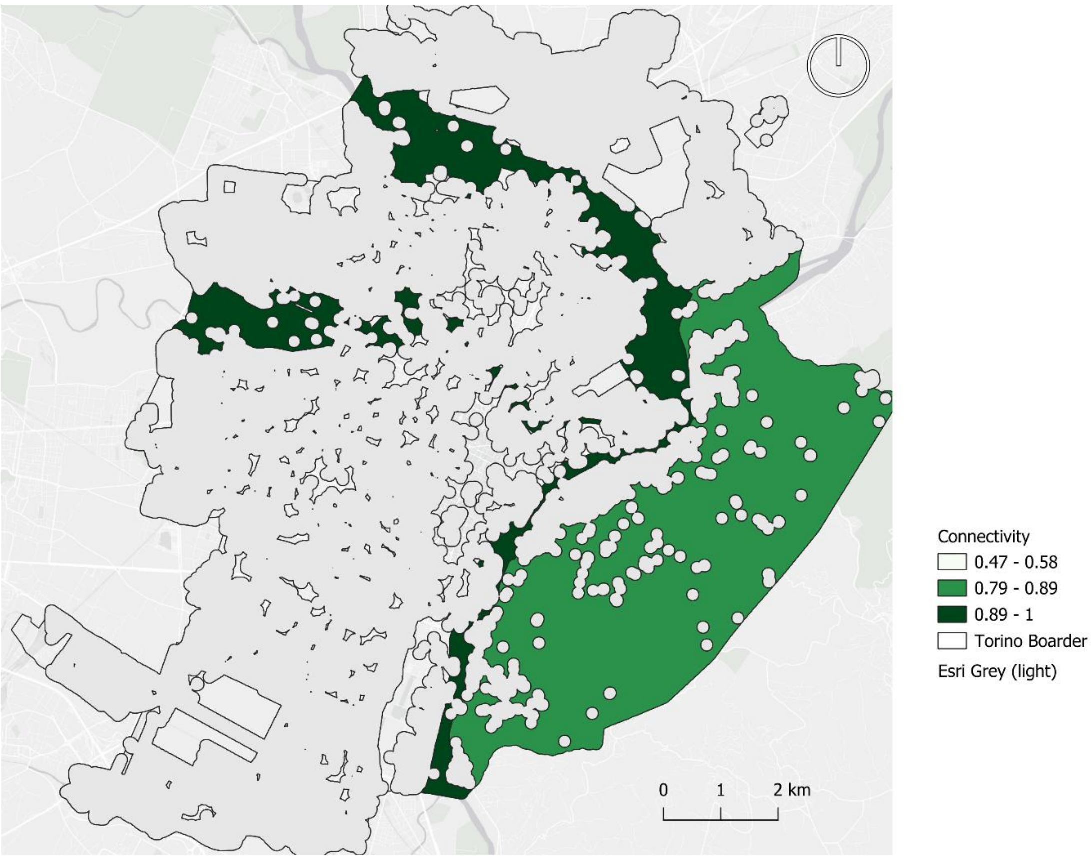

Figure 11 Connectivity Map

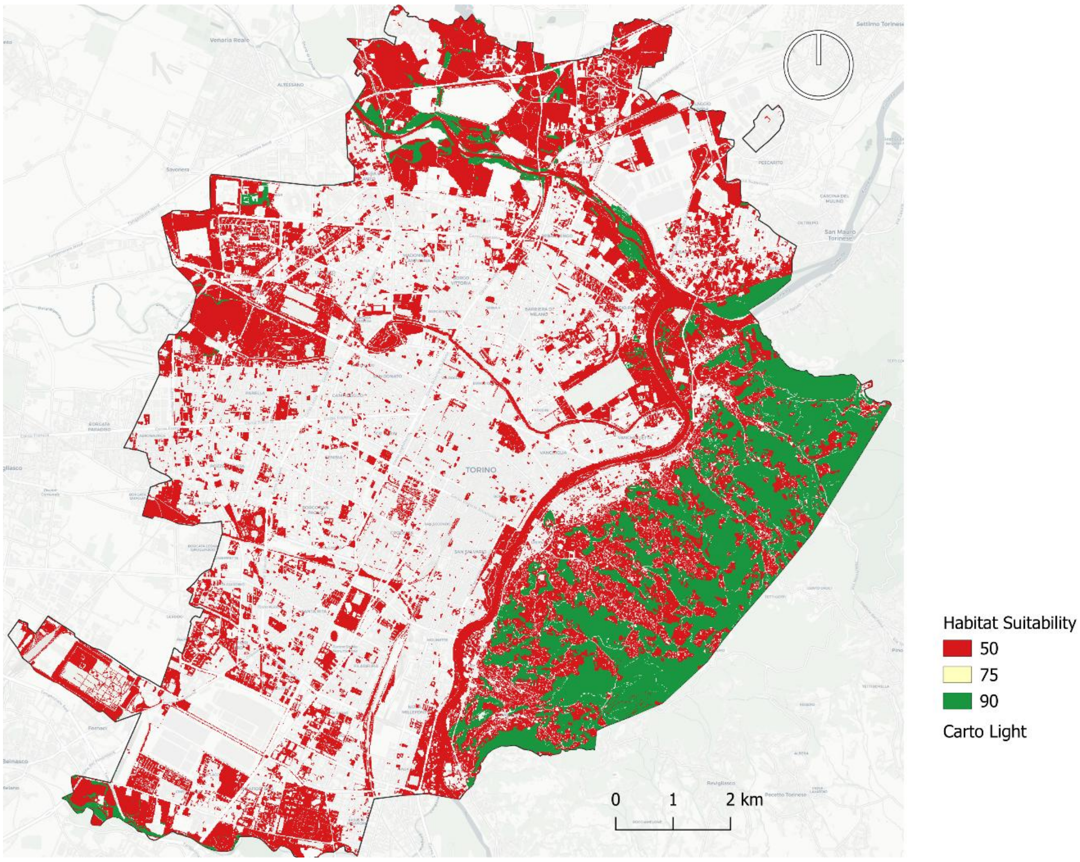

Figure 12 Habitat Suitability Map

1. **Connectivity Distribution**: The connectivity map shows a clear east-west gradient, with the Turin's east being significantly more connected (0.79-1.0) compared to the city's western and central areas (0.47-0.58). This pattern is parallel to the distribution of habitat suitability, as shown in the second map.

2. **Hill Zone Connectivity**: The eastern hill zone of Turin exhibits the highest connectivity values (0.89-1.0, dark green), forming a crucial ecological backbone for the city. This area functions as the primary biodiversity reservoir and provides essential habitat for numerous plant and animal species.

3. **River Corridor Function**: The Po River corridor functions as a critical north-south connectivity element, with connectivity values ranging from 0.79-0.89 (medium green). This riverine system serves as a vital movement pathway connecting otherwise isolated habitat patches.

4. **Urban Core Fragmentation**: The central and western portions of Turin display significantly lower connectivity values (0.47-0.58, white areas), reflecting the highly fragmented nature of green spaces in these densely urbanized zones. These areas are characterized by isolated habitat patches with limited functional connections.

5. **Habitat Suitability Correlation**: Habitat Suitability Correlation: Comparing the habitat suitability map indicates a very high correlation between connectivity and habitat quality. Regions of high suitability (90, dark green in second map) always possess higher values of connectivity, while regions of lower suitability (50, red) possess lower connectivity.

Compared to EU benchmarks derived from the Natura 2000 network, Turin's ecological connectivity is varied. The eastern hill region excels or meets EU benchmarks with ecological connectivity scores greater than 0.80, but the urban center is below the lowest urban connectivity of 0.65 implemented in the EU Biodiversity Strategy for 2030.

Chapter 6. Discussion

The environmental assessment of Nature-Based Solutions (NbS) in Turin reveals a complex and detailed urban environmental intervention. By a step-by-step analysis of five key environmental indicators, the present study provides valuable insights into the efficacy of NbS for urban environmental management.

Air Temperature Trends

The analysis shows a relative effectiveness of NbS in mitigating urban heat. Despite the implementation of green infrastructure, Turin registered a rising trend of warming between 2001-2023, and temperature anomalies during the summer were always higher than +1.5°C since 2018. The inference is that the current NbS have not been sufficiently capable of reversing the urban heat island effect. The green corridors and the eastern hill region are promising locations, but the central city remains vulnerable to rising temperatures.

This warming trend presents significant implications for urban resilience. Santamouris emphasized the vanurability of Mediterranean cities to heat island effects, and Turin data verifies this threat. The recurring positive anomalies, especially for the summer months, necessitate specific targeted NbS that can mitigate the impact of urban heat island.

Greenhouse Gas Emissions

The emissions profile proves the stark deficiencies in current NbS approaches. As methane accounts for over 95% of CO_2 equivalent emissions, traditional carbon sequestration measures fall short. The sharp variability of emissions between 2013 and 2019 proves that the current NbS have not established a stable trajectory of emissions reduction. This underscores the need for more differentiated, sector-based action.

Comparing these findings with the European Green Deal's climate targets, which aim for a 55% reduction in greenhouse gas emissions by 2030, Turin's emissions trajectory presents both challenges and opportunities.

Natural Disaster Risks

The spatial analysis discloses both the strengths and weaknesses in the application of NbS. Of the population, 45.20% are threatened by heat island effects and 8.93% by flood risk, positioning Turin also at risk compared to the European average. However, the concentration of risks in the urban area and along river corridors shows that present NbS are not equally effective across the urban region.

However, the spatial distribution of these risks is crucial. The concentration of heat island effects in the urban core and flood risks along river corridors demands location-specific NbS. This finding supports Raymond et al. Assertion that urban environmental interventions must be contextually tailored rather than uniformly applied.

Ecological Connectivity

The most insightful view is given by ecological connectivity analysis. The dramatic east-west connectivity gradient indicates extreme fragmentation of the urban ecosystem. Urban core connectivity values continue to be below the EU Biodiversity Strategy target value of 0.65, indicating that currently implemented NbS have not adequately addressed urban ecosystem integration.Compared to the EU Biodiversity Strategy's target of 0.65 minimum connectivity for urban areas, Turin's urban core falls short, highlighting a critical area for NbS intervention. The research demonstrates that ecological connectivity is not merely about green space quantity, but about strategic spatial configuration and habitat quality.

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Methodological Contributions and Limitations

The study's integrated assessment framework represents a significant methodological contribution to urban environmental research. By developing standardized definitions, calculation protocols, and benchmark integrations, the research provides a reproducible approach to NbS performance evaluation.

However, the research also revealed comprehensive methodological weaknesses. Most evident weakness was in the Rainwater and Graywater Capture and Reuse indicator, where poor data impaired sound interpretation. This gap is representative of the larger issue in Mediterranean urban environmental monitoring the lack of proper infrastructure for the monitoring of water management interventions.

The study design also indicated the limitations of traditional measurement approaches. By moving away from single-metric approaches, the study demonstrated the need for wide, integrated schemes to address the multifaceted nature of the urban environmental interventions.

Comparing Turin as a Mediterranean city to cities in Northern Europe and Northern America

USA shows warming with temperature anomalies reaching approximately +1.7°C in recent years, Europe displays more dramatic warming reaching +1.51°C by 2024, while Turin exhibits extreme monthly fluctuations with recent peaks up to +2.9°C.

On the other hand, comparing Turin to Sweden as a northern European country, while Sweden shows a steady, gradual decline in CO_2 emissions from approximately 55 Mt in 2000 to 32.454 Mt in 2022, Turin's emissions exhibit extreme volatility with a dramatic V-shaped pattern, plummeting from 125,000 tCO_2e in 2013 to just 12,000 tCO_2e in 2015 before surging back to 90,000 tCO_2e by 2019.

Turin's emissions are microscopic compared to nations: Turin peaked at 0.000125 Gt (2013), dropped to 0.000012 Gt (2015), then rose to 0.00009 Gt (2019), while during the same period China emitted between 10-11.5 Gt annually, the EU 3.1-3.5 Gt, and the US 5.1-5.5 Gt - making Turin's emissions roughly 100,000 times smaller than China's despite showing much more dramatic percentage changes.

Turin's flood risk affects approximately 8.93% of people, showing higher vulnerability than Sweden (4%), Norway (3%), the UK (1%), Denmark (18%) and Finland (15%), but significantly lower than Latvia's extreme case (24%) of population exposed to river flooding (Halecki & Młyński, 2025).

Turin's connectivity is relatively poor compared to North America (Belote et al., 2022), with only small isolated corridors (0.89-1.0) and a limited eastern green zone amid a highly fragmented urban matrix, whereas North America maintains vast, continuous connectivity networks across mountain ranges, forests, and natural landscapes even at regional scales, though Turin's river corridor resembles the channelized connectivity patterns seen in North America's landscape-level analyses.

Future Research and Policy Implications

This research underscores the necessity of context-specific NbS approaches in Mediterranean cities. Generic solutions such as improving data collection infrastructure and Improving data collection infrastructure are inadequate for addressing the unique environmental challenges presented by cities like Turin, with their distinctive climate, hydrology, and urban morphology.

Conclusion

Nature-Based Solutions (NbS) represent an innovative approach to addressing urban environmental challenges, particularly in the cities of the Mediterranean urban area like Turin, that are exposed to certain climatic and ecological pressures. The present research has performed an in-depth environmental analysis of NbS through a multi-indicator framework, which showed the opportunities and the complexities involved in implementing such emerging urban policies.

The study's key findings extend beyond mere performance measurement:

- NbS showed limited effectiveness in mitigating urban heat island effects, with temperature anomalies consistently positive since 2018
- Unique methane-dominated emissions profile highlighted the need for specialized NbS approaches
- Significant east-west gradient revealed urban ecosystem fragmentation
- NbS showed limited effectiveness in mitigating urban heat island effects, with 45.20% of the urban population exposed to heat island risks
- Localized flood risk affecting 8.93% of the population

- Generic NbS approaches are inadequate for Mediterranean urban environments
- Limited impact on urban heat island effects as a natural disaster risk
- Challenges in data collection and monitoring considering the limitation of lack of basic data

The research gives valuable insights into urban environmental management by illustrating the boundaries of generic NbS in Mediterranean cities. By highlighting the unique issues of Turin's urban ecosystem the research gives an advanced strategy to intervention. The GREEN-INC European Project methodology framework is an effective tool for urban planners, policy makers, and environmental scientists that focuses on the context-based, interdisciplinary nature that goes beyond traditional methods of urban environmental analysis.

The GREEN-INC European Project's approach in Turin demonstrates the potential of collaborative, interdisciplinary research in developing innovative urban environmental solutions. By bridging scientific research, policy implementation, and local context, we can create urban environments that are not just sustainable, but regenerative.

This research is not an endpoint, but a critical step such as comprehensive mediterranean urban NbS database, advanced monitoring infrastructure and targeted intervention strategies towards reimagining urban landscapes as dynamic, interconnected ecosystems that support both human and natural communities.

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