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Nature-Based Solutions Planning for Urban Microclimate Improvement and Health: An Integrated Ecological and Economic Approach

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Abstract: Nature-based Solutions (NbSs) play a pivotal role in mitigating the impact of microclimates on human well-being. The effectiveness of NbSs is contingent upon the synergy between natural capital, defined by the ecological structure and functions of the ecosystem, and human-derived capital, encompassing the economic investments required for implementation. This study introduces a decision-making framework designed to evaluate the impact of NbSs and advocate for optimal solutions for human health at the local scale, amalgamating ecological and economic assessments. Physiological Equivalent Temperature (PET) was chosen as a key urban parameter to assess the efficacy of NbSs in mitigating urban microclimates and enhancing human health. The PET analysis was conducted using ENVI-met 5.0.3 software across diverse urban scenarios in Gallipoli city, Italy. Integrated with a cost–benefit analysis of NbSs considering various investment scenarios, the study aimed to identify the most effective solution. Results indicated positive effects of NbSs in open spaces and around building blocks where the PET levels remained below 30 °C. Conversely, scenarios without NbSs exhibited PETs exceeding 40 °C, with peaks of 50 °C, posing potential risks to human health. Considering the social and economic benefits associated with PET mitigation, the cost–benefit analysis suggests that implementing NbSs using a mix of young and mature plants in the initial phase is advantageous compared to using only young plants. Thus, in establishing NbSs, it is crucial to consider not only the quantity of vegetation but also the strategic timing of implementation. In conclusion, our work offers an innovative framework that combines ecological and economic perspectives, providing valuable insights for decision-makers in urban planning and promoting the practical application of NbSs for enhanced human well-being.

Keywords: ecosystem services; nature-based solutions; ecological urban planning; cost–benefit analysis; physiological equivalent temperature; social benefits

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1. Introduction

Urban areas, marked by the Urban Heat Island (UHI) effect, face pressing environmental challenges requiring innovative solutions. Urban expansion and industrialization amplify the UHI effect by transforming natural or agricultural land into dense networks of structures [1–3]. Glasgow, with its industrial legacy, exemplifies these challenges, experiencing a year-round UHI of over 3 °C. Similar challenges are observed globally in cities like Tokyo, each grappling with unique UHI dynamics [4].

The multifaceted impact of the Urban Heat Island (UHI) effect includes increased heat-absorbing surfaces, heightened anthropogenic heat production, altered air circulation patterns, and diminished evapotranspiration [5–8]. Research suggests that even a modest increase in Green Infrastructure could potentially eliminate the UHI effect. Additionally, elevated temperatures in urban areas increase pollution levels, affecting air quality [9–12] and human health. Impermeable surfaces further worsen these challenges by reducing water infiltration capacity and increasing flood risk [1,13]. This interplay highlights the need for comprehensive research to support resilient urban planning. In this context, natural capital—encompassing vegetation, green spaces, and ecosystems—is critical. Nature-based Solutions (NbSs) provide a holistic framework for mitigating microclimatic impacts on human well-being [14]. Their effectiveness depends on the integration of natural and human-derived capital [15]. Incorporating NbSs into urban planning enhances urban resilience and fosters sustainability [16,17]. The lack of vegetation intensifies UHI effects, increasing thermal stress and its associated health risks. Addressing urban heat, especially in the context of climate change and more frequent heat waves, underscores the importance of prioritizing microclimate mitigation in urban planning [18,19].

In the context of global warming, urban forests represent a crucial NbS for enhancing environmental and human well-being in cities. They play a significant role in microclimate regulation and UHI reduction by providing shade, cooling the surrounding area through evapotranspiration, and lowering the demand for air conditioning. This cooling effect is particularly valuable in increasingly hot urban environments [16,20,21]. To ensure sustainability, urban forests must be integrated into urban planning frameworks as a key component of climate action, land-use planning, and public health strategies. Their valuation should comprehensively consider social, economic, and environmental dimensions [21,22]. The Physiological Equivalent Temperature (PET) serves as a useful index for assessing the effects of NbSs' impacts [23,24]. The PET comfort index evaluates the human heat balance with the environment, considering meteorological and thermo-physiological parameters. The assessment of PET for NbS planning needs to consider vegetation structure, human preferences, and human-derived capital, balancing cost investments with human benefits [15,25].

The effectiveness of NbSs is heavily influenced by the quality of their implementation, particularly regarding the ecological structures and functions that define the intended natural capital. The costs associated with NbSs represent a substantial investment in human-derived capital, encompassing financial resources and other components necessary for their implementation, rather than focusing solely on ecological aspects [14,15]. Human-derived capital plays a crucial role in determining the feasibility and success of NbS projects, as it establishes the conditions under which these solutions can be effectively applied and sustained. Understanding the role of human-derived capital in enhancing natural capital is crucial for urban decision-making, as it helps determine the optimal balance between natural capital and technological alternatives that influence investment cost [16]. This manuscript establishes a novel decision-making framework for NbS planning, assessing microclimate ecosystem services' impact on human health while incorporating cost–benefit analyses. The proposed framework adopts a systems approach to sustainable urban development, integrating natural and human-derived capital to inform decisions that promote long-term resilience and well-being in cities.

2. Materials and Methods

2.1. Study Area

The study area is a peri-urban region characterized by agroecosystems, consisting of arable land interspersed with sprawling residential areas. These residential zones are in line with the urban development plan outlined by the municipality of Gallipoli for new residential expansion (Figure 1). Gallipoli is a medium-sized town located on the western coast of the Salentine Peninsula, in the southern part of the Apulia Region. As of 2023, the town has a population of approximately 20,000 residents (https://demo.istat.it/

app/?i=RIC&l=it, accessed on 1 December 2023). Gallipoli is a key center in the region, known for its unique cultural heritage and coastal charm. The cityscape features traditional Mediterranean architecture, with two- to three-story buildings and winding narrow streets. The city's location is of particular interest for urban microclimate research because it is situated in the Mediterranean region, which has been recognized as a climate change "hot spot". This designation signifies that the impact of global warming, which showed an increasing trend over time, especially during the summer months, was recognized for the Mediterranean region, along with documented changes in precipitation patterns over the 20th-century [26]. According to the Köppen–Geiger climate classification, which is widely used to categorize global climates, Gallipoli falls into the Warm Mediterranean Climate 'Csa' class. This classification indicates a temperate–hot climate, with the average temperature of the coldest month ranging between 6 °C and 10 °C, the annual average temperature ranging between 14.5 °C and 17 °C, and having four months with an average temperature exceeding 20 °C. The unique climatic and geographical features of Gallipoli contribute to its distinctive atmosphere and make it a noteworthy area for further exploration and study.

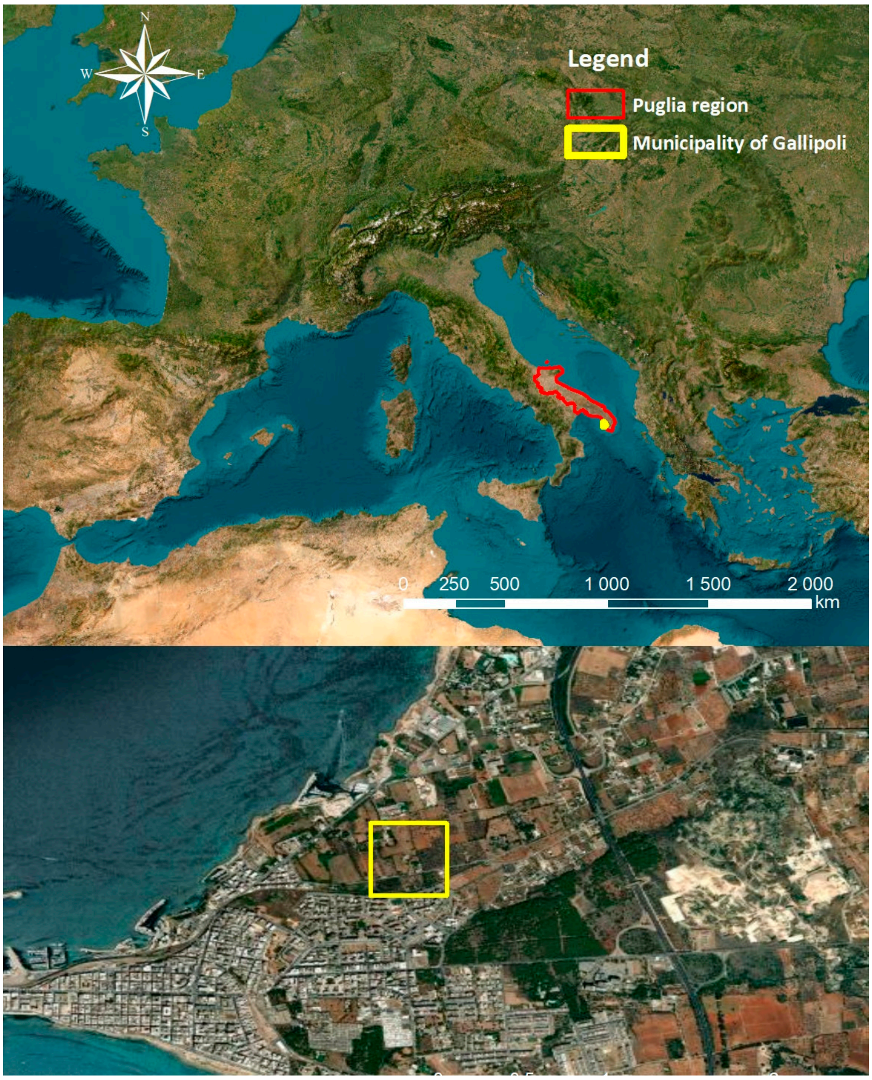


Figure 1. Study area of interest in Gallipoli municipality (base map from Google Earth).

2.2. Applied Decision-Making Framework

The decision-making framework evaluates the efficacy of ecosystem structure and function, defining the planned natural capital in NbSs, to achieve a favorable impact on priority ecosystem services. This entails comprehending how these natural elements contribute to lowering air temperature and PET in the urban setting through ENVI-met simulations across diverse scenarios [24,27]. Variations in the structure and function of natural capital, aimed at enhancing ecosystem service flows, significantly influence the investment costs associated with implementing NbSs. Therefore, different combinations of natural and human capital can result in different levels of ecosystem service flows and hence different human and economic benefits. For this reason, a cost–benefit analysis was conducted to appraise the direct social benefits of the different scenarios of the proposed NbSs. Various potential investment costs for its implementation were considered, aiding in selecting the optimal realization solution (Figure 2).

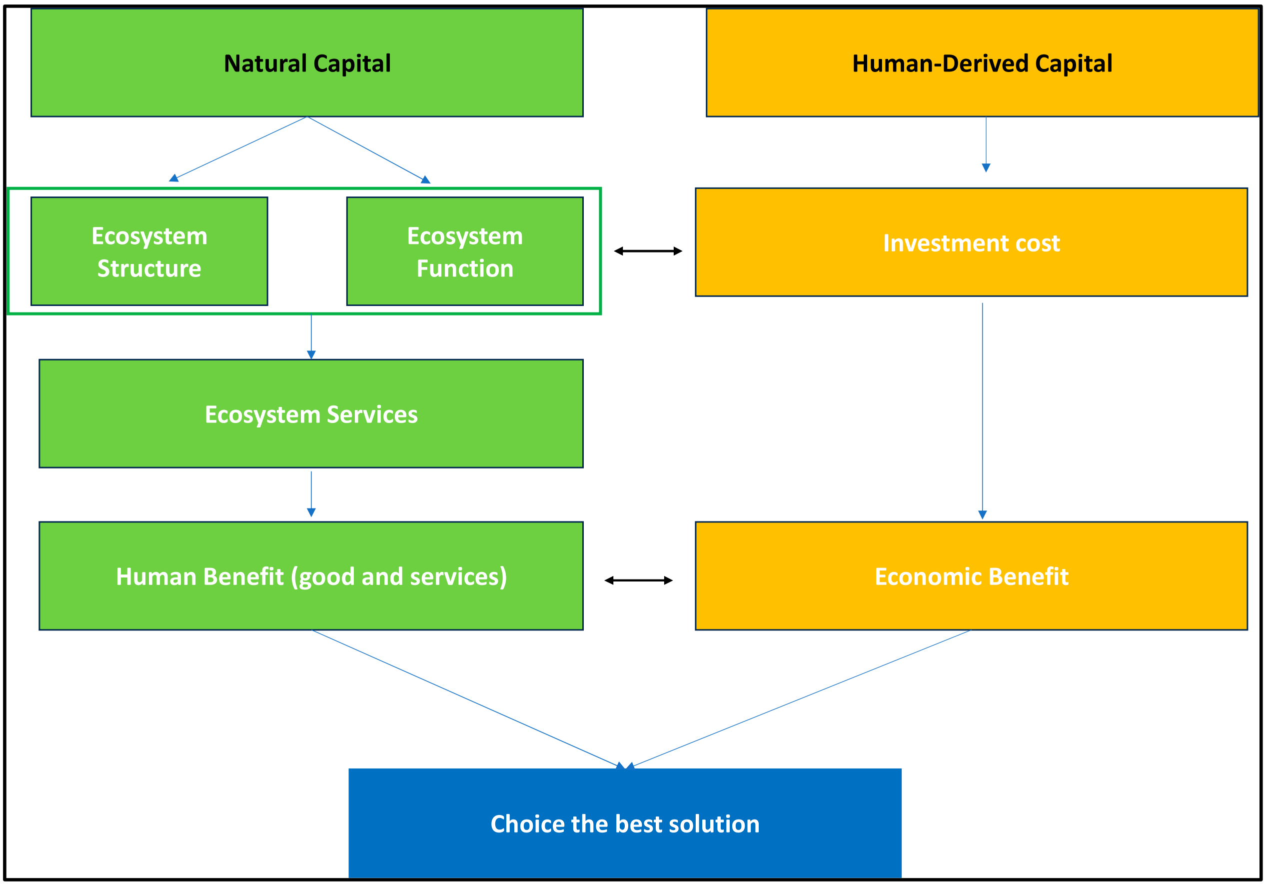


Figure 2. Framework applied to support decision-making processes.

2.2.1. ENVI-Met Analysis and Data Input

The PET serves as a crucial metric for assessing individuals' thermal comfort in outdoor settings [28–33]. The PET scale (Table 1) provides a classification of thermal comfort based on temperature, with the ranges listed below [28]. In the context of this study, a PET below 40 °C is considered acceptable for human health, as higher values may lead to increased thermal stress and health risks.

Temperature and PET simulations were conducted for different urban scenarios (Figure 3):

- First scenario (*Scenario zero*): This represents the current state scenario. It is characterized by the original land cover of the study area before urbanization, characterized mainly by arable land with a few buildings, including old rural structures mixed with new houses.
- Second scenario (*Intermedium scenario*): This represents the urban planned scenario without NbSs. It is characterized by the planned urbanization processes, featuring potential buildings, parking areas, roads, and arable land. Notably, no vegetation,

such as a green park, is included in this scenario. This setup allows for a comparison of urbanization effects on temperature and PET with both Scenario zero and the third scenario, which anticipates the implementation of NbS.

- Third scenario (*NbS scenario*): *This represents* the urban planned scenario with the planned urban forest NbS. It shares the same land cover attributes as the second scenario in terms of buildings, roads, and parking areas. However, it introduces the establishment of an urban forest as an NbS in place of arable land. The urban forest is strategically designed to address microclimate issues in the urban garden, along walkways, and around buildings, thereby enhancing thermal comfort.

Table 1. Ranges of Physiologically Equivalent Temperature (PET in °C) for different grades of thermal perception and physiological stress [28].

PET (°C)	Thermal Perception	Grade of Physiological Stress
<4	Very cold	Extreme cold stress
4–8	Cold	Strong cold stress
8–13	Cool	Moderate cold stress
13–18	Slightly cool	Slight cold stress
18–23	Comfortable	No thermal stress
23–29	Slightly warm	Slight heat stress
29–35	Warm	Moderate heat stress
35–41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

A thorough examination of microclimate and PET was conducted using ENVI-met software, a powerful tool for predicting intricate interactions between plants and atmospheric conditions in complex urban settings [24,27]. This software incorporates a 3D vegetation model that adapts to different biophysical structures in green spaces. As a result, it proves invaluable in assessing dynamic interactions between various types of vegetation and the surrounding environment, including built-up areas [16,28,29,34,35]. The suitability of ENVI-met for microclimate simulations in the Salento area has been validated through several local studies, exemplified by Gatto et al. [36]. Table 2 details the parameters utilized to configure the model for simulation.

Table 2. Initial and boundary conditions used in ENVI-met simulations.

Parameter	Definition	Value
Simulation time	Start date	31 July 2021
	Start of simulation (h)	00:00
	Total simulation time	19 h (5 h spin-up + 11 h)
Computational domain and grid	Grid cells (x, y, z)	170 × 170 × 25
	$\delta x \times \delta y \times \delta z$	2 m × 2 m × 2 m (equidistant: 5 cells close to the ground)
	Nesting grids	7
	Boundary conditions	Cyclic

Figure 3. Urban scenarios analyzed: (**A**) *Scenario zero*, (**B**) *Intermedium scenario*, and (**C**) *NbS scenario*.

The meteorological data incorporated into the model included air temperature, relative humidity, wind speed, wind direction, and precipitation. This information was sourced from the ARPA (Agenzia Regionale per la Prevenzione e la Protezione Ambientale)—Puglia station, measured at a height of 10 m above ground [37]. Specifically, values were selected from 1 July 2023 to 31 August 2023. The average values for each meteorological variable were calculated at every half-hour interval to establish the daily average profile, as shown in Figure 4.

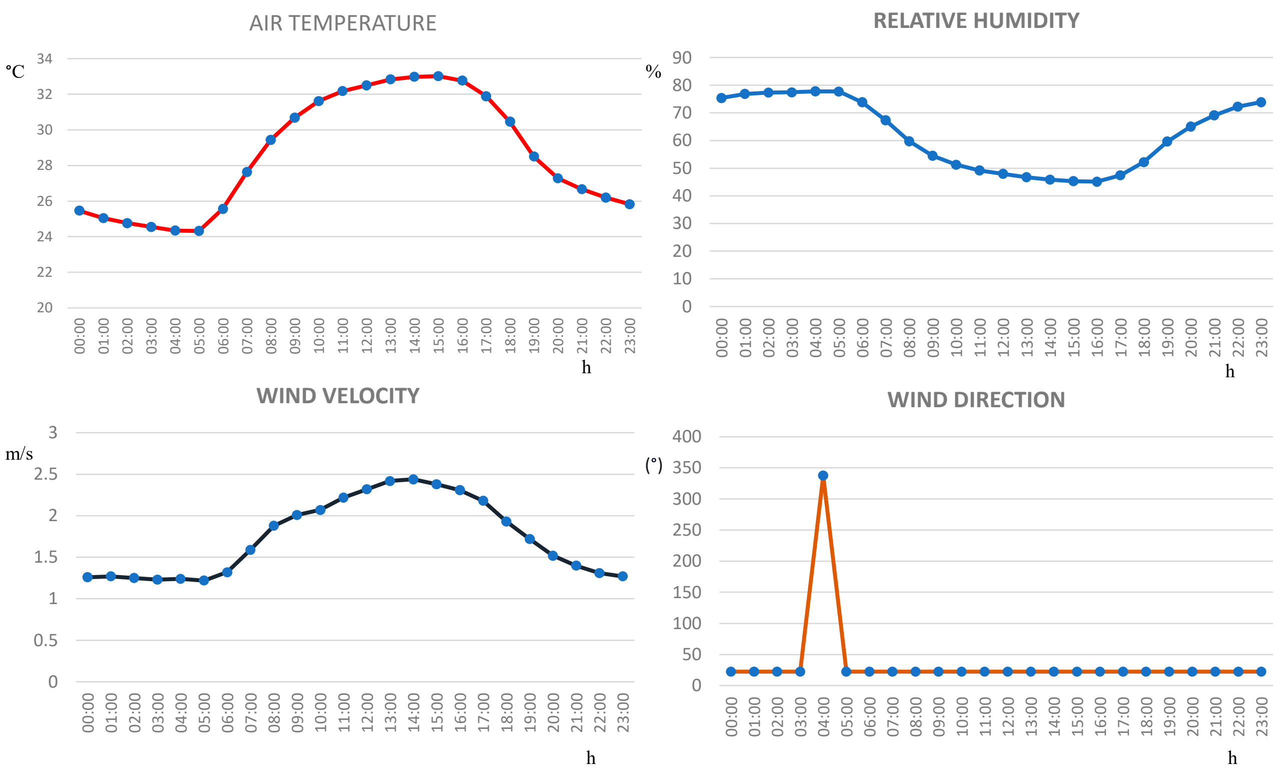


Figure 4. Daily profiles of meteorological parameters (Air Temperature, Relative Humidity, Wind Velocity and Wind Direction) employed as input in ENVI-met simulations.

2.2.2. Cost–Benefit Analysis

We conducted an analysis to assess the optimal method of implementing the NbS, focusing on planned social benefits through a cost–benefit analysis (CBA) centered on microclimate ecosystem services.

CBA is a systematic process employed to evaluate the potential social benefits and costs associated with a project, program, or policy [38–40]. It serves as a structured framework supporting decision-makers in assessing the effectiveness and desirability of various project options by quantifying and comparing their costs and benefits [38,39]. In this study, cost–benefit analysis (CBA) was used to evaluate the cost-effectiveness of three different implementation types for the same planned urban forest NbS. Given that urban forests provide a wide range of ecosystem services, the analysis focused on their impact on climate change mitigation and thermal comfort, as measured by the PET index, highlighting the direct human benefits derived from these services. These were defined as priority ecosystem services, while the energy saved from building cooling was considered an indirect benefit.

Three different implementation modalities of the urban forest were considered:

- In the first implementation modality of the NbS (Type A), the urban forest is planned to be established with plants 6–7 m in height, capable of developing into a mature forest in a short time. This type of urban forest is expected to support microclimate regulation and improve human health within a few years across the entire study area.
- In the second implementation modality of the NbS (Type B), the urban forest is planned to be established with plants 6–7 m in height, which require more time to grow and develop into a mature forest (approximately 20 years). As a result, this urban forest will not be able to support microclimate regulation or improve human health within the first few years.
- In the third implementation modality of the NbS (Type C), the urban forest combines elements of the first two modalities. It uses 6–7 m trees for 3/4 of the total tree population to mitigate microclimate effects around buildings, while incorporating

younger trees in the park area. This urban forest will be able to support microclimate regulation and improve human health within a few years, but only in the immediate vicinity of the buildings.

By assessing three different types of implementation costs, we calculated the Net Present Value (NPV) and benefit–cost ratio (BCR) for each. Specifically, the NPV represents the difference between the total Present Value of Future Benefits (PVFB) and the Present Value of Future Costs (PVFC) for each alternative considered [38,39]:

$$\text{NPV} = \sum \text{PVFB} - \sum \text{PVFC}$$

BCR represents the ratio between the total Present Value of Future Benefits (PVFB) and the total Present Value of Future Costs (PVFC), providing an indication of the feasibility and convenience of implementing a project [33,35,36].

$$BCR = \frac{\sum \text{PVFB}}{\sum \text{PVFC}}$$

The Present Value of Future Benefits (PVFB) is a method of assessing the benefits expected from a project or investment in today's terms and comparing them with its costs. Calculating the PVFB helps decision-makers understand whether the benefits justify the initial and ongoing costs of the project. The Present Value of Future Costs (PVFC), on the other hand, is the present value of the costs that will be incurred on the project over time, adjusted for the time value of money. The PVFB and PVFC were calculated using the Actualized Coefficient (AC), which is discount factor for restating future amounts to current values. Their values were calculated according to the following equations [38,40,41]:

$$\text{Present Value of Future Benefits} = \sum_{i=0}^{n} benefits * \text{AC}$$

$$\text{Present Value of Future Costs} = \sum_{i=0}^{n} Cost * \text{AC}$$

where AC = $\frac{1}{(1+r)^n}$, where r is discounting rate capital, representing the cost of money or capital, which was considered equal to 5% in relation to actual capital cost, and n represent years of analysis. In this study, n was considered for tree growth time windows of 5 years, 10 years, and 20 years [40].

The total cost comprises both initial costs (capital expenditures) and ongoing operational costs. In this instance, the total cost was estimated by considering the practices necessary to realize the urban forest, as detailed in Table 3. Therefore, an estimated calculation metric was made for the realization of the urban forest, considering the plants and materials needed for its realization. For each type of implementation considered, the price difference of the vegetation was determined by the size of the plants planned in the initial phase. Prices for each item were extrapolated from the price list commonly used for public projects in the Apulian region and informed by market analysis. Operational costs were omitted as they are likely to be similar across the three scenarios and, therefore, do not significantly impact the analysis. Similarly, the analysis systematically identifies and quantifies all benefits, both direct and indirect, arising from each alternative. In this study, the benefits considered for each scenario remain consistent, although the time required to achieve them varies. This accounts for the varying durations associated with growing urban forests using different practices (types A, B, and C). Primarily, the structural aspects of the plants change for each scenario, while the type remains consistent throughout the planting actions.

Table 3. Types of interventions considered for cost estimation of NBS in the cost–benefit analysis, aligned with the Puglia regional price list [42].

Code Price	Type of Intervention
OF 01.11	Tillage of the soil to a depth of no less than 60 cm on agricultural land
OF 01.03	Clearing of scrub and herbaceous vegetation on unwooded land, carried out by hand or using mechanical equipment (back-brush cutters), including collection, transport, and destruction of the resulting material
OF 01.24	Hole opening with a mechanical tool
OF 01.27	Planting of resinous and broad-leaved plants, including backfilling and compaction of the soil adjacent to the roots of the plants, and any other work necessary to ensure that the work is carried out in a workmanlike manner (excluding the delivery of the plant)
OF 01.32	Providing wooden stakes on site, including loading/unloading, transport and any other costs
OF 01.34	Supply and installation of a protective net cylinder for seedlings (tree shelter) to protect the seedling from ungulates
OF 01.30	Supply of broadleaf seedlings
Not available	Supply of adult broadleaf seedlings
OF 01.21	Localized mulching with discs or squares of biodegradable lignocellulosic material, minimum size 40 × 40 cm, including delivery, installation, and anchoring with stakes
OF 03.05	Crop care
OF 03.07	Emergency irrigation, including water supply at any distance and in any quantity, distribution of water by any means and in any way for each operation and seedling (20 L) (for the first three years after planting)

3. Results

3.1. ENVI-Met Analysis

The analysis of air temperature reveals a lower average in the urban scenario with the NbS (*NbS scenario*), as opposed to the higher average temperature observed in the urban scenario without the NbS (*Intermedium scenario*) and the current state scenario (*Scenario zero*) (Figure 5). Urbanization can have a detrimental effect on air temperature, resulting in elevated values compared to the area's natural state. However, this adverse impact can be mitigated through the implementation of NbSs, particularly those that incorporate forested elements. In this case study, NbSs play a crucial role in reducing the effects of urbanization, leading to a notable decrease in the average air temperature by approximately 3 °C during the hottest period of the day, specifically from 12:00 to 16:00. The analysis of variance revealed significant differences (Table 4), indicating that NbSs, especially those with forested components, contribute substantially to cooling effects and help counteract the temperature rise associated with urban development.

The maximum average air temperature was consistently recorded across all urban scenarios at 14:00, and Figure 6 illustrates the spatial distribution of air temperature between the *NbS scenario* and *Intermedium scenario* (the urban scenario without NbS). Specifically, it is noticeable that the air temperature around the residential building area can be reduced to below 30 °C thanks to the NbS, in comparison to the urban scenarios without the NbS. Mainly, the air temperature in the residential area can be reduced by more than 5 °C.

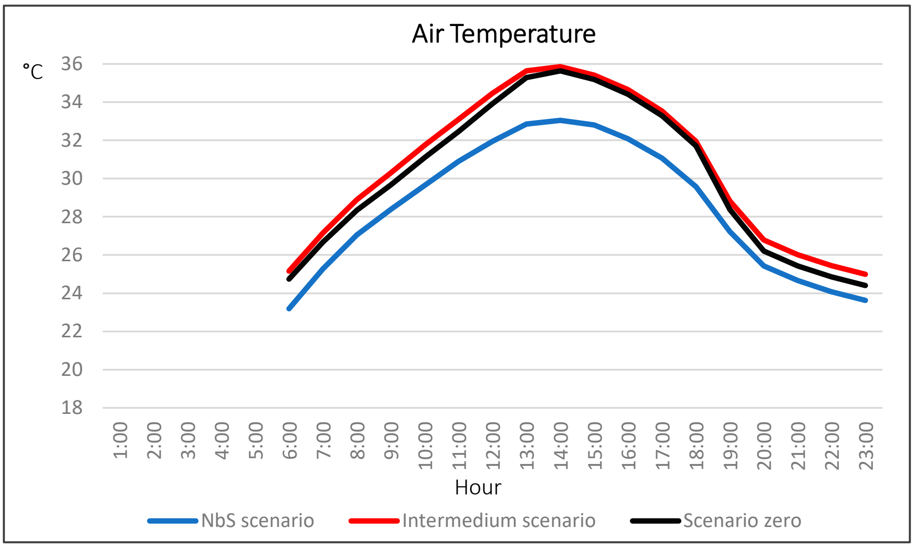


Figure 5. Daily profiles of air temperature obtained from ENVI-met simulations. The value represents the average air temperature of the study area.

Table 4. Analysis of variance between daily profiles of air temperature: (A) *NbS scenario* vs. *Intermedium scenario* and (B) *Intermedium scenario* vs. *Scenario zero*.

(A)																		
NbS scenario* vs. *Intermedium scenario																		
h	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
F Test	16.5	13.8	15.2	24.6	9.7	75.8	17.8	24.8	42.4	51.6	60.9	15.6	9.1	7.8	15.9	82.0	72.9	9.6
N	29,476																	
p Value	$p < 0.01$																	
(B)																		
Intermedium scenario* vs. *Scenario zero																		
h	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
F Test	37.1	78.6	23.3	40.0	15.7	50.6	10.7	16.1	28.2	33.6	35.5	32.3	29.3	23.5	66.3	11.4	170.0	66.6
N	29,476																	
p Value	$p < 0.01$																	

The positive impact of NbSs on the urban microclimate can have significant benefits for human health. The results of the PET analysis demonstrate the favorable influence of NbSs on enhancing livability in urban areas. This is reflected in the reduction in the spatially averaged (over the study area) PET value throughout the day when compared to an urban scenario without vegetation. The most notable change occurs at 17:00, where a difference of 11 °C in PET is observed. It is important to note that, in the urban setting with NbS, the highest spatially averaged PET value occurs at 13:00, reaching an average of 41.5 °C (Figure 7). However, during other times of the day, the spatially averaged PET values remain below 40 °C, which is considered a critical threshold for human health. In contrast, in the *Intermedium scenario*, spatially averaged PET values exceed 40 °C from 10:00 to 17:00, with the maximum recorded value reaching 50.6 °C. The analysis of variance showed significant differences (Table 5).

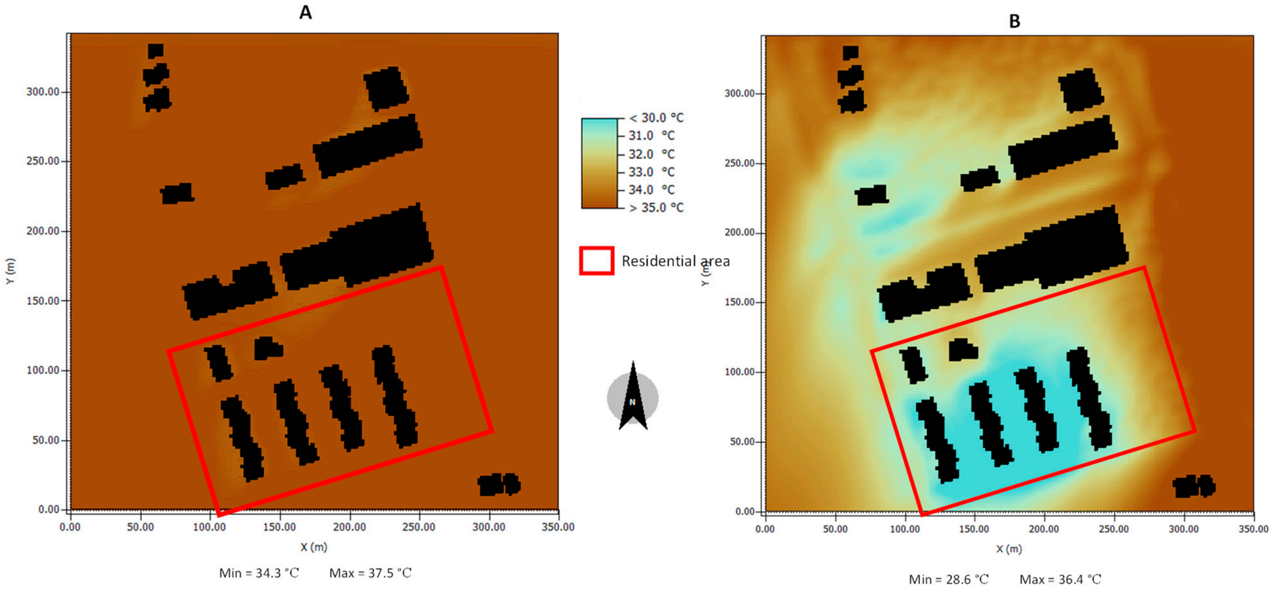


Figure 6. Spatial distribution of air temperature at z = 1.4 m at 14:00: (**A**) *Intermedium scenario* (urban scenario without NbS) and (**B**) *NbS scenario* (urban scenario with NbS).

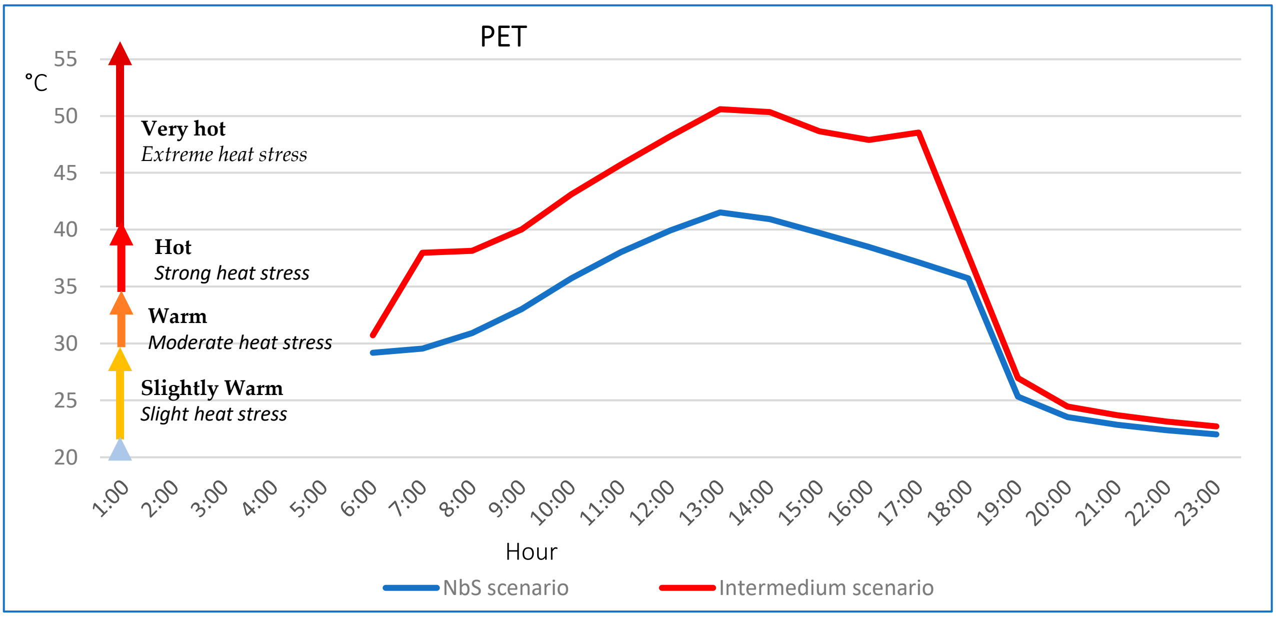
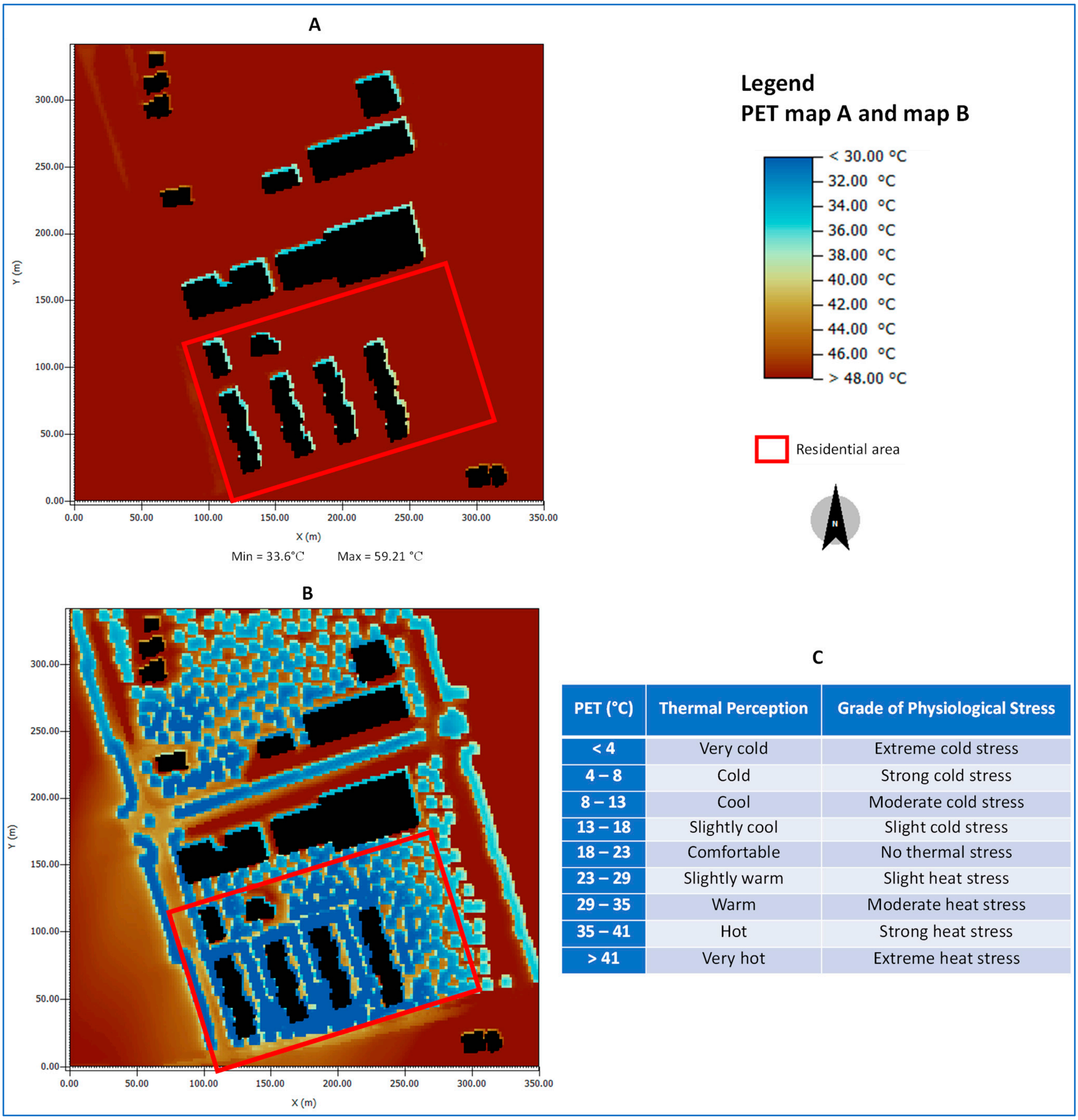


Figure 7. Daily profiles of spatially averaged PET values obtained from ENVI-met simulations, with indication of the thermal perception (bold) and the degree of physiological stress (italic) reported in Table 1.

Table 5. Analysis of variance between daily profiles of PET: *NBS scenario* (urban scenario with NbS) vs. *Intermedium scenario* (urban scenario without NbS).

NbS scenario **vs.** *Intermedium scenario*																		
h	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
F Test	1.8	1.4	0.7	1.3	1.4	1.4	1.4	1.2	1.3	1.5	1.8	1.7	1.6	1.8	2.1	1.8	1.6	1.7
N	29,476																	
p Value	$p < 0.01$																	

Figure 8 illustrates the spatial distribution of PET between the *NbS scenario* (the urban scenario with NbS) and the *Intermedium scenario* (the urban scenario without NbS). Specifically, it is noticeable that the PET around the residential building area can be reduced to below 30 °C thanks to the NbS, in comparison to the *Intermedium scenario*, which recorded values above 48 °C.



PET (°C)	Thermal Perception	Grade of Physiological Stress
< 4	Very cold	Extreme cold stress
4 – 8	Cold	Strong cold stress
8 – 13	Cool	Moderate cold stress
13 – 18	Slightly cool	Slight cold stress
18 – 23	Comfortable	No thermal stress
23 – 29	Slightly warm	Slight heat stress
29 – 35	Warm	Moderate heat stress
35 – 41	Hot	Strong heat stress
> 41	Very hot	Extreme heat stress

Figure 8. Spatial distribution of PET at z = 1.4 m at 13:00: (**A**) *Intermedium scenario* (urban scenario without NbS) and (**B**) *NbS scenario* (urban scenario with NbS). (**C**) Thermal Perception and Grade of Physiological Stress concerning the PET value (see Section 2.2.1).

NbSs can help reduce PET across the entire urban area, with varying impacts depending on the relationship between the urbanized zones and vegetation improvements (Figure 9). The most significant reduction in PET is observed in the residential areas. This decrease can positively influence the livability of these spaces, including outdoor areas like balconies, and potentially affect indoor environments as well. Importantly, this reduction is linked to the lowered air temperature resulting from the attenuation of solar irradiance throughout the day, as well as the wind intensity generated by the vegetation surrounding the buildings.

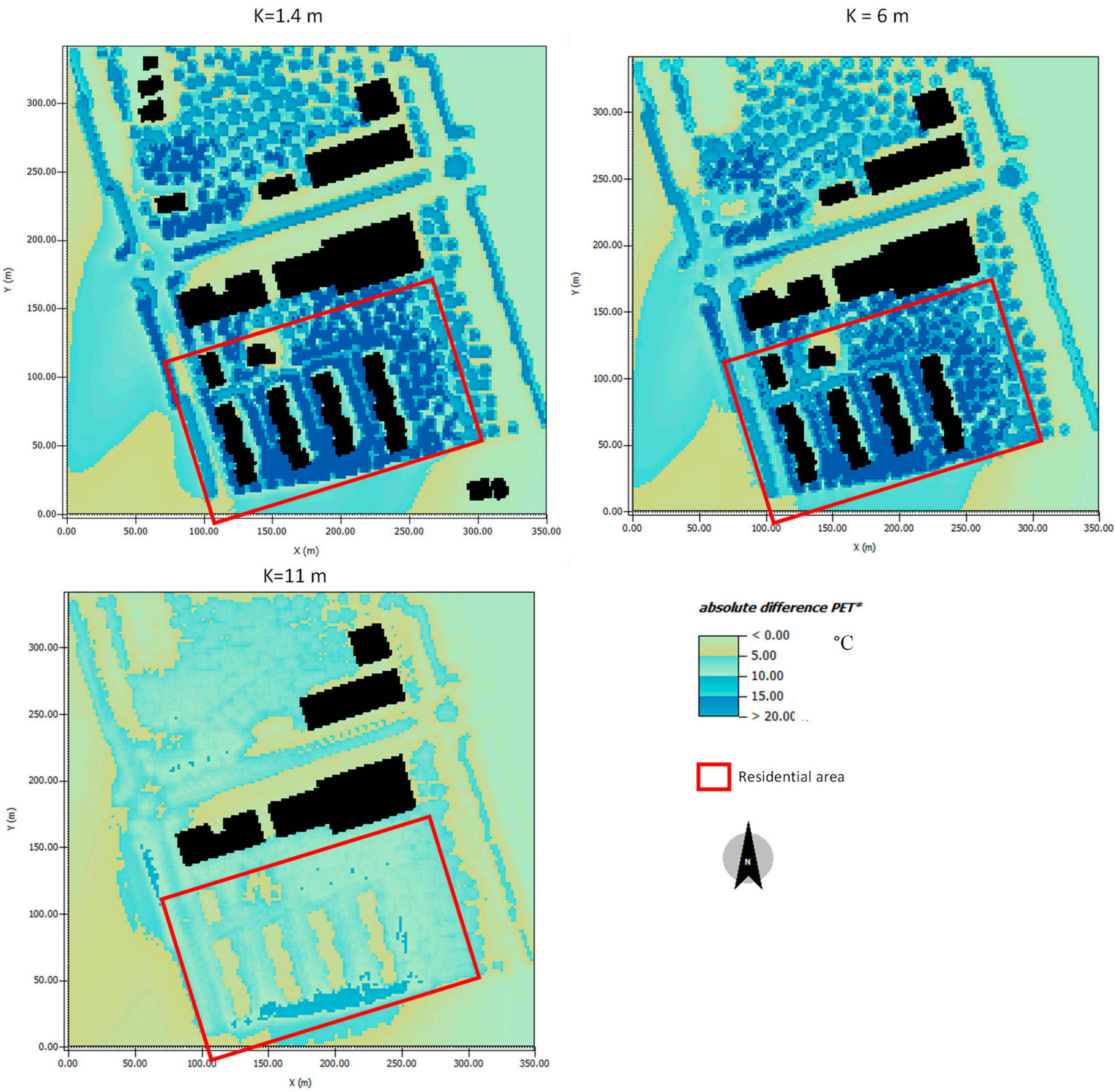


Figure 9. The difference in PET between the *NbS scenario* (urban scenario with NbS) and the *Intermedium scenario* (urban scenario without NbS) at 13:00 analyzed at different heights (z = 1.4 m, 5 m, 11 m).

These findings emphasize the effectiveness of NbSs at mitigating extreme temperatures and enhancing overall conditions in urban areas, especially during peak heat hours. Notably, the decrease in PET around the four residential buildings can contribute to a reduction in the human perception of heat and thermal stress.

This reduction in PET is crucial, as it not only improves comfort but also has a positive impact on human health by reducing heat-related risks. Additionally, by moderating outdoor temperatures, NbS can help lower energy consumption for cooling, potentially reducing the need for air conditioning. This dual benefit—improving public health and reducing energy consumption—emphasizes the importance of integrating NbSs into urban planning strategies, particularly in densely populated and heat-prone areas.

3.2. Cost–Benefit Analysis Results

Considering the characteristics of the study area, the priority ecosystem service considered when establishing the NbS is microclimate regulation to mitigate the human body's sensitivity to high temperatures, thereby reducing thermal discomfort in hot conditions, as measured by the PET. It can have a significant impact on human health when the PET exceeds 40 °C, leading to issues such as dehydration, cardiovascular problems, increased respiratory difficulties, and hyperthermia, which can escalate to heatstroke, potentially fatal if not promptly treated [14]. Furthermore, extended exposure to extreme temperatures can result in psychological effects, including heightened irritability and a reduced quality of sleep [14,43–47]. Therefore, the direct social and economic benefits that could be generated by an urban forest through microclimate regulation include the reduction in hospital costs for treating individuals affected by high PET and a decrease in building cooling expenses to lower air temperature and PET in the building. Specifically, trees in the residential area can reduce air temperature and direct solar radiation on the building during the hottest times. In this study, it was estimated that the total annual benefits could amount to EUR 67,500 for the forest capable of lowering the temperature and PET (Table 6).

Table 6. Estimation of economic benefits provided by NbSs. Benefit 1 is based on the daily public costs saved by hospitals in caring for single individuals in Italy [48]. Benefit 2 is estimated by considering the energy saved due to reduced cooling needs for buildings as a result of lower air temperatures and PET.

1	Benefit	**Hospital admission/day (EUR)**	**N days**	**N People**	**Total**
		500	3	9	13,500
2	Benefit	**Energy saved/day/study area (EUR)**	**N Days**		**Total**
		1200	45		54,000
				Total (1 + 2)	67,500

The practical framework for analyzing the impact of NbSs on social capital omust consider various scenarios in terms of the financial capital required to implement them and their capacity to provide ecosystem services [14,15]. Even when starting with the same planned NbS, different social and environmental impacts can be expected due to variations in the initial practices used for implementation. These differences may necessitate varying capital investments and yield diverse benefits over time.

In this study, investment cost scenarios for the realization of an urban forest have been examined (Figure 10):

- In the first NbS implementation type of (A), the investment cost for its realization was estimated at EUR 456,655. The ability of the forest to serve as a mature ecosystem for the provision of ecosystem services could begin five years after its establishment. Here, social benefits can be accounted for at 50% in the first five years and 100% thereafter.
- In the second NbS implementation type (B), the investment cost for its realization was estimated at EUR 50,029, and it may take up to 15 years before the forest generates direct benefits. Its full potential as an ecosystem for providing services will be reached 20 years after its establishment. Here, social benefits can be accounted for at 50% from 15 to 19 years and 100% from 20 years.
- In the third NbS implementation type (C), investment cost for its realization was estimated EUR 299,529. In this case, social benefits can be accounted for at 50% from 0 to 5 years, at 90% from 5 to 10 years, and then at 100%.

Year	AC	Type A) PVFC = 456 655 €				Type B) PVFC = 50 029 €				Type C) PVFC= 299 529€			
		Value Benefit	**PVFB**	**NPV**	**BCR**	Value Benefit	**PVFB**	**NPV**	**BCR**	**Value Benefit**	**PVFB**	**NPV**	**BCR**
0	0.00	0 €								0 €			
1	1.05	45,000 €								32,143 €			
2	1.10	42,857 €	220,434 €	-236,221 €	0.48		0	0	0	30,612 €	167,275 €	-132,254 €	0.56
3	1.16	40,816 €								29,155 €			
4	1.22	38,873 €								27,766 €			
5	1.28	52,888 €								47,599 €			
6	1.34	50,370 €								45,333 €			
7	1.41	47,971 €								43,174 €			
8	1.48	45,687 €	449,412 €	-7243	0.98		0	0	0	41,118 €	377,499 €	77,969 €	1.26
9	1.55	43,511 €								39,160 €			
10	1.63	41,439 €								41,439 €			
11	1.71	39,466 €								39,466 €			
12	1.80	37,587 €								37,587 €			
13	1.89	35,797 €								35,797 €			
14	1.98	34,092 €								34,092 €			
15	2.08	32,469 €	769,394 €	312,739 €	1.68	16,234 €	99,240 €	49,211 €	1.98	32,469 €	699,177 €	399,648 €	2.33
16	2.18	30,923 €				15,461 €				30,923 €			
17	2.29	29,450 €				14,725 €				29,450 €			
18	2.41	28,048 €				14,024 €				28,048 €			
19	2.53	26,712 €				13,356 €				26,712 €			
20	2.65	25,440 €				25,440 €				27,136 €			

Figure 10. The cost–benefit analysis carried out for three scenarios: (**A**) urban forest with mature trees; (**B**) urban forest with young trees, (**C**) urban forest with a mix of mature trees in residential areas and young trees elsewhere.

The CBA indicates that the first scenario is less advantageous than the other two, primarily in terms of their benefit–cost ratios (BCRs). While the first scenario may grant more benefits within the initial 5- and 10-year timeframes, these benefits are insufficient to offset the investment costs. The second scenario is unable to produce benefits before 15 years, as it takes time for the trees to reach the required height to reduce microclimate temperature by 3 °C and bring the PET below 40 °C in the residential area. In contrast, the third scenario is more advantageous compared to the other two because it can generate significant benefits within the first 5 years, effectively covering the initial investment costs. Therefore, it can be considered the most suitable solution, as it combines the natural capital required to provide priority ecosystem services with human-derived capital, considering implementation costs and direct social benefits over time.

The analysis was tested with different discount rates (r) to assess their potential influence on the results. The rates varied from 0.03 to 0.05 and 0.07, yet no significant differences in the main outcomes were observed. Specifically, the benefit–cost ratio (BCR) values consistently favor scenario C across all discount rates tested. For example, at a 7% discount rate, the BCR values at 20 years are A = 1.42, B = 1.42, and C = 1.94. At a 3% discount rate, the corresponding values are A = 2.03, B = 2.79, and C = 2.85. Additionally, the estimation of energy savings for cooling the building is considered a critical factor. Even when reducing the daily values to EUR 400 (daily economic value of the energy saved in cooling the buildings planned to be built in the area studied) for the total area, scenario C consistently demonstrates higher BCR values compared to the other two scenarios. At 20 years, the BCR values are A = 0.79, B = 0.93, and C = 1.09. Therefore, the results exhibit independence from the discount rate, indicating robustness in the findings.

4. Conclusions

NbSs provide a comprehensive framework for addressing the challenges of urbanization, including land use and land cover changes, while promoting sustainable urban development. This work shows the value of integrating ecological and economic perspectives to evaluate and implement NbSs that can mitigate urban microclimates and improve public health. Our findings demonstrate that urban forests, as a type of NbS, effectively reduce average temperatures by approximately 3 °C in peri-urban areas and lower the PET around residential buildings to below 40 °C, a critical threshold for human health [7,8]. These outcomes are particularly relevant in the context of global warming and urban heat islands, where high temperatures pose significant risks to population well-being. The results emphasize the dual benefits of NbS: enhancing thermal comfort and reducing energy consumption for building cooling.

The methodology developed here is not limited to local applications but offers potential for broader use, particularly in the Strategic Environmental Assessment (SEA) process. SEA, a mandatory practice across EU countries, evaluates the environmental impacts of urban plans and programs, making it an ideal framework to apply our approach. By assessing different urban scenarios, this study provides a replicable model for integrating environmental, social and economic considerations into urban planning decisions [49]. While the methodology focuses on comparative rather than absolute evaluations, this approach enables planners to understand the relative effectiveness of NbSs in specific contexts.

The integration of ecological and economic factors represents a key strength of this study, offering a holistic perspective on the planning and implementation of NbSs. However, we are aware that the accuracy of the results depends on the capacity of the models to simulate air temperature and PET in urban settings with specific vegetation configurations. Future research should prioritize improving model accuracy and testing the methodology across different urban contexts to enhance its applicability and reliability.

Additionally, this study reveals the importance of considering the temporal dynamics of NbS implementation. For example, urban forests that incorporate mature and younger trees can provide long-term benefits. This highlights the necessity of strategic timing and resource allocation when implementing NbSs to optimize their effectiveness.

From a policy perspective, this study underlines the need to focus not only on the quantity and type of NbSs but also on their real-world effectiveness in delivering ecosystem services. Urban policies should integrate the following:

- Natural capital, representing the ecological structures and functions of NbSs, which are essential for ensuring the provision of ecosystem services aligned with priority objectives [15,16];
- Human-derived capital, reflecting the economic investments and operational efforts required for NbS implementation. This integration ensures that NbSs are socially, economically, and environmentally sustainable [15].

This study also highlights the importance of considering cost-effectiveness in NbS planning. The results of the cost–benefit analysis reveal that implementation strategies combining mature and younger trees offer the highest BCRs. Policymakers must therefore develop strategies that balance ecological impacts with financial feasibility to maximize long-term benefits.

In conclusion, this research highlights the critical role of NbSs in addressing urban challenges associated with global warming. The key insights include the following:

- The necessity of defining priority ecosystem services, such as microclimate regulation, to guide NbS implementation [14,16];
- The importance of aligning natural and human-derived capital to ensure effective NbS delivery [15,16];
- The value of a comparative evaluation framework that enables urban planners to assess the relative benefits of different NbS scenarios.

By focusing on the real-world implementation and long-term sustainability of NbSs, this work offers actionable insights for policymakers and urban planners trying to create more resilient and livable cities.

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References

1. Emmanuel, R.; Krüger, E.L. Urban Heat Island Intensity in Sydney, Australia. *Procedia Environ. Sci.* **2012**, *14*, 85–96.
2. Yadav, N.; Rajendra, K.; Awasthi, A.; Singh, C.; Bhushan, B. Systematic exploration of heat wave impact on mortality and urban heat island: A review from 2000 to 2022. *Urban Clim.* **2023**, *51*, 101622. [CrossRef]
3. Rajagopal, P.; Priya, R.S.; Senthil, R. A review of recent developments in the impact of environmental measures on urban heat island. *Sustain. Cities Soc.* **2023**, *88*, 104279. [CrossRef]
4. Emmanuel, R.; Krüger, E. Urban Heat Islands and its impact on climate change resilience in a shrinking city: The case of Glasgow, UK. *Build. Environ.* **2012**, *53*, 137–149. [CrossRef]
5. You, M.; Huang, J.; Guan, C.H. Are New Towns Prone to Urban Heat Island Effect? Implications for Planning Form and Function. *Sustain. Cities Soc.* **2023**, *99*, 104939. [CrossRef]
6. He, B.; Zhao, Z.; Shen, L.; Wang, H.; Li, L. An approach to examining performances of cool/hot sources in mitigating/enhancing land surface temperature under different temperature backgrounds based on Landsat 8 image. *Sustain. Cities Soc.* **2019**, *44*, 416–427. [CrossRef]
7. Qi, J.; Ding, L.; Lim, S. A Decision-Making Framework to Support Urban Heat Mitigation by Local Governments. *Resour. Conserv. Recycl.* **2022**, *184*, 106420. [CrossRef]
8. Emmanuel, R.; Loconsole, A. Green infrastructure as an adaptation approach to tackle urban overheating in the Glasgow Clyde Valley Region. *Landsc. Urban Plan.* **2015**, *138*, 71–86. [CrossRef]
9. Wang, Y.; Guo, Z.; Han, J. The relationship between urban heat island and air pollutants and their influencing factors in the Yangtze River Delta, China. *Ecol. Indic.* **2021**, *129*, 107976. [CrossRef]
10. Swamy, G.S.N.V.K.S.N.; Nagendra, S.M.; Sch, U. Impact of urban heat island on meteorology and air quality at microenvironments. *J. Air Waste Manag. Assoc.* **2020**, *70*, 876–891. [CrossRef]
11. Ernst, M.; Le Mentec, S.; Louvrier, M.; Loubet, B.; Personne, E.; Stella, P. Impact of urban greening on microclimate and air quality in the urban canopy layer: Identification of knowledge gaps and challenges. *Front. Environ. Sci.* **2022**, *10*, 924742. [CrossRef]
12. Chaudhary, M.T. Urban Air Pollution, Urban Heat Island and Human Health: A Review of the Literature. *Sustainability* **2022**, *14*, 9234. [CrossRef]
13. Somers, K.A.; Bernhardt, E.S.; McGlynn, B.L.; Urban, D.L. Downstream dissipation of storm flow heat pulses: A case study and its landscape-level implications. *J. Am. Water Resour. Assoc.* **2016**, *52*, 281–297. [CrossRef]
14. Semeraro, T.; Gatto, E.; De Bellis, L.; Luvisi, A.; Emmanuel, R.; Buccolieri, R. A decision-making framework for promoting the optimum design and planning of Nature-based Solutions at the local scale. *Urban For. Urban Green.* **2023**, *84*, 127945. [CrossRef]
15. Tan, P.Y.; Zhang, J.; Masoudi, M.; Alemu, J.B.; Edwards, P.J.; Grêt-Regamey, A.; Richards, D.R.; Saunders, J.; Song, X.P.; Wong, L.W. A conceptual framework to untangle the concept of urban ecosystem services. *Landsc. Urban Plan.* **2020**, *200*, 103837. [CrossRef] [PubMed]
16. Semeraro, T.; Scarano, A.; Pandey, R. Ecosystem Services Analysis and Design through Nature-Based Solutions in Urban Planning at a Neighbourhood Scale. *Urban Sci.* **2022**, *6*, 23. [CrossRef]
17. Semeraro, T.; Radicchio, B.; Medagli, P.; Arzeni, S.; Turco, A.; Geneletti, D. Integration of Ecosystem Services in Strategic Environmental Assessment of a Peri-Urban Development Plan. *Sustainability* **2021**, *13*, 122. [CrossRef]
18. Akbari, H.; Kolokotsa, D. Three decades of urban heat islands and mitigation technologies research. *Energy Build.* **2016**, *133*, 834–842. [CrossRef]
19. Wong, N.H.; Tan, C.L.; Kolokotsa, D.D.; Takebayashi, H. Greenery as a mitigation and adaptation strategy to urban heat. *Nat. Rev. Earth Environ.* **2021**, *2*, 166–181. [CrossRef]
20. Semeraro, T.; Scarano, A.; Buccolieri, R.; Santino, A.; Eeva, A. Planning of Urban Green Spaces: An Ecological Perspective on Human Benefits. *Land* **2021**, *10*, 105. [CrossRef]

21. Zhao, J.; Davies, C.; Veal, C.; Xu, C.; Zhang, X.; Yu, F. Review on the Application of Nature-Based Solutions in Urban Forest Planning and Sustainable Management. *Forests* **2024**, *15*, 727. [CrossRef]
22. Battisti, L.; Giacco, G.; Moraca, M.; Pettenati, G.; Dansero, E.; Larcher, F. Spatializing Urban Forests as Nature-based Solutions: A methodological proposal. *Cities* **2024**, *144*, 104629. [CrossRef]
23. Zhang, S.; Zhang, X.; Niu, D.; Fang, Z.; Chang, H.; Lin, Z. Physiological equivalent temperature-based and universal thermal climate index-based adaptive-rational outdoor thermal comfort models. *Build. Environ.* **2023**, *228*, 109900. [CrossRef]
24. Höppe, P. The physiological equivalent temperature—A universal index for the biometeorological assessment of the thermal environment. *Int. J. Biometeorol.* **1999**, *43*, 71–75. [CrossRef] [PubMed]
25. Jones, L.; Norton, L.; Austin, Z.; Browne, A.L.; Donovan, D.; Emmett, B.A.; Grabowski, Z.J.; Howard, D.C.; Jones, J.P.G.; Kenter, J.O.; et al. Stocks and flows of natural and human-derived capital in ecosystem services. *Land Use Policy* **2016**, *52*, 151–162. [CrossRef]
26. Lionello, P.; Abrantes, F.; Congedi, L.; Dulac, F.; Gacic, M.; Gomis, D.; Goodess, C.; Hoff, H.; Kutiel, H.; Luterbacher, J.; et al. Introduction: Mediterranean climate: Background information. In *The Climate of the Mediterranean Region: From the Past to the Future*; Lionello, P., Ed.; Elsevier: Amsterdam, The Netherlands, 2012.
27. Bruse, M.; Fleer, H. Simulating surface–plant–air interactions insideurban environments with a three dimensional numerical model. *Environ. Softw.* **1998**, *13*, 373–384. [CrossRef]
28. Matzarakis, A.; Mayer, H.; Iziomon, M. Applications of a universal thermal index: Physiological equivalent temperature. *Int. J. Biometeorol.* **1999**, *43*, 76–84. [CrossRef]
29. Binarti, F.; Koerniawan, M.D.; Triyadi, S.; Matzarakis, A. The predicted effectiveness of thermal condition mitigation strategies for a climate-resilient archaeological park. *Sustain. Cities Soc.* **2022**, *76*, 103457. [CrossRef]
30. Binarti, F.; Triyadi, S.; Koerniawan, M.D.; Pranowo, P.; Matzarakis, A. Climate characteristics and the adaptation level to formulate mitigation strategies for a climate-resilient archaeological park. *Urban Clim.* **2021**, *36*, 100811. [CrossRef]
31. Cai, Y.; Li, C.; Ye, L.; Xiao, L.; Gao, X.; Mo, L.; Du, H.; Zhou, Y.; Zhou, G. Effect of the roadside tree canopy structure and the surrounding on the daytime urban air temperature in summer. *Agric. For. Meteorol.* **2022**, *316*, 108850. [CrossRef]
32. Manavvi, S.; Rajasekar, E. Evaluating outdoor thermal comfort in urban open spaces in a humid subtropical climate: Chandigarh, India. *Build. Environ.* **2022**, *209*, 108659.
33. Paramita, B.; Kusuma, H.E.; Matzarakis, A. Urban performance based on biometeorology index in high-density, hot, and humid cities. *Sustain. Cities Soc.* **2022**, *80*, 103767. [CrossRef]
34. Roth, M.; Lim, V.H. Evaluation of canopy-layer air and mean radiant temperature simulations by a microclimate model over a tropical residential neighbourhood. *Build. Environ.* **2017**, *112*, 177–189. [CrossRef]
35. Tsoka, S.; Tsikaloudaki, A.; Theodosiou, T. Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications–a review. *Sustain. Cities Soc.* **2018**, *43*, 55–76. [CrossRef]
36. Gatto, E.; Buccolieri, R.; Aarrevaara, E.; Ippolito, F.; Emmanuel, R.; Perronace, L.; Santiago, J.L. Impact of urban vegetation on outdoor thermal comfort: Comparison between a Mediterranean City (Lecce, Italy) and a Northern European City (Lahti, Finland). *Forests* **2020**, *11*, 228. [CrossRef]
37. Agenzia Regionale per la Prevenzione e la Protezione Ambientale. 2023. Available online: https://www.arpa.puglia.it/ (accessed on 1 December 2023).
38. Raihan, A.; Said, M.N.M. Cost–Benefit Analysis of Climate Change Mitigation Measures in the Forestry Sector of Peninsular Malaysia. *Earth Syst. Environ.* **2022**, *6*, 405–419. [CrossRef]
39. Biancardo, S.A.; Gesualdi, M.; Savastano, D.; Intignano, M.; Henke, I.; Pagliara, F. An innovative framework for integrating Cost-Benefit Analysis (CBA) within Building Information Modeling (BIM). *Socio-Econ. Plan. Sci.* **2023**, *85*, 101495. [CrossRef]
40. European Commission. *Guide to Cost-Benefit Analysis of Investment Projects. Economic Appraisal Tool for Cohesion Policy 2014–2020*; European Commission: Brussels, Belgium, 2014; ISBN 978-92-79-34796-2.
41. Roberts, R.J.; Naimy, V. Strategic Adoption of Genetically Modified Crops in L ebanon: A Comprehensive Cost–Benefit Analysis and Implementation Framework. *Sustainability* **2024**, *16*, 8350. [CrossRef]
42. Regione Puglia. Prezzario Regionale Puglia 2023. Dipartimento Bilancio, Affari Generali e Infrastrutture, Sezione Opere Pubbliche e Infrastrutture. 2023. Available online: https://regione.puglia.it/ (accessed on 1 December 2023).
43. Nastos, P.T.; Matzarakis, A. The effect of air temperature and human thermal indices on mortality in Athens, Greece. *Theor. Appl. Climatol.* **2012**, *108*, 591–599. [CrossRef]
44. Sharafkhani, R.; Khanjani, N.; Bakhtiari, B.; Jahani, Y.; Tabrizi, J.S. Physiological equivalent temperature index and mortality in Tabriz (The northwest of Iran). *J. Therm. Biol.* **2018**, *71*, 195–201. [CrossRef]
45. Dastoorpoor, M.; Khodadadi, N.; Masoumi, K.; Khanjani, N.; Idani, E.; Borsi, S.H.; Goudarzi, G.; Raji, H.; Sharafkhani, R. Physiological equivalent temperature (PET) and nonaccidental, cardiovascular and respiratory disease mortality in Ahvaz, Iran. *Environ. Geochem. Health* **2021**, *44*, 2767–2782. [CrossRef] [PubMed]
46. National Institute of Environmental Health Sciences. Temperature-Related Death and Illness. 2023. Available online: https://www.niehs.nih.gov/research/programs/climatechange/health_impacts/heat (accessed on 16 December 2023).
47. World Health Organization. Heat and Health. 2023. Available online: https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health (accessed on 13 December 2023).

48. Il Sole 24 Ore Journal. l Sole 24 Ore Ministero Della Salute. 2020. Available online: https://www.ilsole24ore.com/art/dal-check-up-ricovero-quanto-costa-curarsi-senza-sistema-sanitario-nazionale-AFrRBWQ?refresh_ce=1 (accessed on 1 November 2023).
49. EU. Strategic Environmental Assessment. 2024. Available online: https://environment.ec.europa.eu/law-and-governance/environmental-assessments/strategic-environmental-assessment_en (accessed on 30 November 2024).