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Cost-Effectiveness of Nature-Based Solutions under Different Implementation Scenarios: A National Perspective for Italian Urban Areas

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Citation: Di Pirro, E.; Roebeling, P.; Sallustio, L.; Marchetti, M.; Lasserre, B. Cost-Effectiveness of Nature-Based Solutions under Different Implementation Scenarios: A National Perspective for Italian Urban Areas. *Land* **2023**, *12*, 603. https://doi.org/10.3390/land12030603

Academic Editor: Elizelle Juanee Cilliers

Received: 30 January 2023
Revised: 28 February 2023
Accepted: 1 March 2023
Published: 3 March 2023

Abstract: Worldwide, national governments and private organizations are increasingly investing in Nature-Based Solutions (NBS) to foster both human well-being and biodiversity while achieving climate and environmental targets. Yet, investments in NBS remain uncoordinated among planning levels, their co-benefits underestimated, and their effectiveness undermined. This study aims to provide a spatially explicit approach to optimize the budget allocation for NBS implementation across Italian urban areas while maximizing their effectiveness in terms of environmental health. We explored three different NBS implementation scenarios oriented to (i) maximize the Ecosystem Services supply of NBS (Scenario BP), (ii) minimize costs of NBS (Scenario LC), and (iii) maximize Ecosystem Services supply of NBS at the lowest cost (Scenario CP). Once selected, we prioritized their allocation through the territory following an environmental risk index for population, and we explored the relationship between costs and effectiveness for the three scenarios. The implementation of Scenario BP costs EUR 777 billion while showing 31 billion of effectiveness. Scenario LC costs 70% less than scenario BP (EUR 206 billion) while losing 70% of its effectiveness. Scenario CP costs 60% less than Scenario BP (EUR 301 billion), offering just 20% less effectiveness. Our results show that employing the risk index for NBS allocation would allow for reducing the surface of interventions by saving 67% of the budget in the three scenarios with a negligible loss in terms of return for human health. The here-proposed approach can guide the national funds' allocation system, improving its cost-effectiveness and equitableness.

Keywords: bio-based economy; nature-positive economy; large-scale; environmental policies; urban challenges; risk index; co-benefits

1. Introduction

Investing in nature is not only an ecological imperative, it is also a socio-economic one [1]. Nature provides essential services to human beings, simultaneously delivering several co-benefits [2]. Nature helps societies in the protection from natural hazards, i.e., landslides, floods, or extreme heat. The tragic natural disasters hitting the world in the last summers (e.g., heatwaves) [3,4] are stark reminders of how much this protection is crucial [5].

Natural capital stocks per capita have declined by nearly 40% between 1992 and 2014, and one million plant and animal species are facing extinction [6]. Consequently, half of the global GDP (about USD 44 trillion) is at immediate risk [1]. This is a severe threat to our present as well as future welfare, requiring a shift from an economy based on natural resources overexploitation and fossil fuels towards a regenerative bio-based and nature-positive economy [6–8]. A massive and rapid decarbonization (e.g., reaching climate neutrality by 2050) needs to be coupled with the restoration and sustainable management of natural carbon sinks and reservoirs [9].

Making investments with nature-positive outcomes can increase business opportunities to the scale of USD 10 trillion per year and generate, by 2030, about 395 million jobs [1]. Nature-Based Solutions (NBS) can be effective to lead this paradigm shift [10]. The European Commission defined NBS as "solutions inspired and supported by nature, designed to address societal challenges which are cost-effective, simultaneously provide environmental, social and economic benefits, and help build resilience" [11]. From investing in the conservation or restoration of degraded lands [12] to optimizing the performance of traditional infrastructures (e.g., roofs [13]), there is remarkable evidence proving that NBS play a critical role in meeting environmental and socio-economical needs [14,15]. Indeed, a large part of the NBS appeal is linked to their potential to simultaneously address multiple sustainable development goals and societal challenges [2,16,17], as well as generate job innovation [18,19]. The benefits provided by NBS are generally supplied over long time frames and multiple spatial scales, meaning that benefits accrue to society as a whole rather than solely to the single beneficiary or investor [1,20]. However, these multiscale benefits are still hardly captured in current economic models [21,22].

The European Commission invested and fostered research on NBS under the Horizon 2020 research and innovation program, aimed to improve knowledge regarding NBS [23,24]. Concurrently, a growing number of private businesses identified NBS as a strategic frame to meet the Paris climate goals, offsetting their greenhouse gas emissions [25]. In addition, the recovery strategies from the COVID-19 pandemic offered the chance to invest in bringing back nature to the core of our societies [26,27] and move out from a carbon-based economy (e.g., clean energy in EU) [6]. However, the opportunities to include NBS in the recovery strategy are seized with different budgetary efforts by countries [28]. Therefore, despite the strong economic case of national governments (e.g., [29]), the gap between the current and potential scale of investment in NBS urgently demands bridging [30]. Scaling NBS investments toward potential implies several challenges for national governments, including the predictability of benefits and costs and the need to maximize their effectiveness and equitableness [22].

Different economic evaluations have already been proposed in the literature to assess direct and indirect costs and benefits of the project or investment level [31–33]. The implementation costs for new NBS are generally associated with land acquisition, design, installation, maintenance/administration, employees' salaries, and opportunity costs associated with the loss of income that would have been obtained for alternative uses [34,35]. Obviously, all these costs can vary according to specific features, e.g., NBS lifecycle, location, etc. [33,36], with special regard to the transaction costs that are still hidden and variable, which hamper policy and planning [37]. Due to the different adopted techniques and methodologies, the evaluation and comparison of the benefits in monetary terms are also still tricky [12,38]. For this purpose, the cost–benefit analysis is usually employed to estimate the net present value over the project lifetime, valuing the stream of all benefits and net of the stream of all costs [39–41]. When social or environmental effects are impossible—or difficult—to monetize, the project performance can be evaluated with other criteria [42], such as cost-effectiveness, cost impact analysis, lifecycle cost analysis, and multicriteria decision analysis/making [21]. The main purpose of cost-effectiveness analysis is to identify the economically most efficient way to meet an objective, usually considering the cost of achieving one objective and the level of its achievement [39,43]. In the case of NBS implementation, cost-effectiveness studies can rely on environmental and social outcomes (effects) being quantified using a metric expressing these effects as a single number [43].

NBS cost-effectiveness is well investigated by scholars, helping to underpin investment decisions in both government and private sectors [22,23,30]. The literature includes, e.g., the development of frameworks for cost analysis through lifecycle costing [36,44], combining multiple outcomes in the effectiveness account [31,45], comparison between NBS and gray approaches [46], and analysis in contexts with limited space availability [47]. Yet, information regarding the cost-effectiveness of large-scale NBS implementation is still lacking. Especially, the possibility of supporting national governments in optimizing funds allocation through maximizing the return for people in terms of environmental health is almost unexplored. Indeed, previous studies often assess effectiveness as the Ecosystem Service(s) supply.

However, especially in urban contexts, the enhancement of Ecosystem Services supply is related to the amount of beneficiaries [38] and not only limited to their biophysical characteristics [48] (e.g., pollution mitigation). This is due to the fact that population density is considered as an explanatory factor [49] to assess how environmental benefits and/or burdens affect human health [50]. Furthermore, as the NBS provide co-benefits, the effectiveness could be higher if the interventions are planned to address multiple challenges simultaneously (e.g., removing pollutants and reducing flood hazards) [45,47]. Accordingly, this could also link NBS implementation and management to other sectors (e.g., linking financial streams for nature and health sector), opening the possibility to receive extra financial resources and fight planning silos [32], especially at the national scale. This approach could also help private investors to target specific areas and have confidence that their investments will help face actual challenges.

According to these gaps, this work aims to evaluate how to minimize the costs and maximize the effectiveness of different typologies of NBS in terms of (i) the number and intensity of environmental challenges to address and (ii) the degree of risk exposure for the population, under three different NBS implementation scenarios. Using Italian urban areas as a case study, we simulated the fine-scale (10 m resolution) NBS implementation in impervious and permeable non-forested land covers, according to a risk index for human health and well-being. We designed three different strategies of NBS selection, coupling their costs and their ability to address three environmental challenges threatening human health and well-being (i.e., air quality, climate adaptation and mitigation, and water management). A case study is provided to assess the potential scale of investments to reach the national environmental targets and improve human well-being through large-scale NBS implementation. The here-proposed approach can thus guide the national fund allocation system involving as many beneficiaries as possible while maximizing the return in terms of environmental health.

2. Materials and Methods

Our case study is represented by Italian urban areas where we explored the relationship between costs and effectiveness of three different scenarios of NBS implementation, following a spatially explicit approach. NBS effectiveness is expressed as their capacity to (i) face multiple environmental challenges and (ii) reduce the degree of risk to which the population is exposed. The three proposed scenarios represent three different strategies for selecting the NBS to be implemented to face environmental challenges, while the priority of intervention is common among the three scenarios. Specifically, we hypothesized the following three strategies for selecting NBS to be implemented: (i) maximizing NBS biophysical performance to meet environmental challenges (without any budget constraints), (ii) minimizing costs (neglecting the different NBS capacities to address environmental challenges), and (iii) maximizing NBS biophysical performance at the lowest cost (combining the strategies proposed in the two previous scenarios). Once NBS were selected for each scenario, we adopted the same priority of implementation on the territory according to an aggregate index of risk exposure for the population to three environmental challenges (air quality, climate adaptation and mitigation, and water management). Accordingly, we prioritized the implementation of NBS in the pixels showing the higher population exposed to a higher intensity of challenges (i.e., high values of risk index). Lastly, we compared the three scenarios, investigating the relationship between different costs and the related effectiveness.

2.1. Study Area and Input Data

Italy, like many other countries of the Mediterranean basin, is facing the adverse effects of climate change, such as flood events, drought periods, and heatwaves, combined with high exposure of the three most harmful air pollutants in the European Union [51–54]. The intensity of these environmental challenges strongly varies throughout the national territory, as well as the number of inhabitants they affect. Furthermore, the national territory is characterized by a highly scattered and fragmented urban mosaic [55]. Accordingly, Italy is experiencing issues related to soil sealing (e.g., Ecosystem Services and biodiversity loss and habitat fragmentation [56]), with sealed surfaces reaching one of the highest relative national coverages among EU countries [57,58]. To tackle these challenges, the Italian national government envisaged different urban sustainability strategies and policies (e.g., promoting sustainable mobility and tree-planting initiatives), allocating money to specific administrative domains and municipalities [28,59]. Pursuing the aim of this work, we focused our analysis on the Italian urban areas according to the CORINE Land Cover map 2018 (CLC) [60]. CLC uses a Minimum Mapping Unit (MMU) of 25 hectares (ha) for areal phenomena and a minimum width of 100 m for linear phenomena. Particularly, we selected all the land uses included in class 1 of CLC, namely "Artificial surfaces", to define the boundaries of the Italian urban areas. Within these boundaries, we explored different layers of information: (i) the environmental challenges and their spatial co-occurrence [61], (ii) the population's exposure to the challenges (i.e., risk index [62]), (iii) the NBS Performance Score to address different groups of challenges (i.e., capacity to provide Ecosystem Service [61]), and (iv) the land cover where different typologies of NBS can be implemented, i.e., impervious and permeable non-forested [63] (Figure 1).

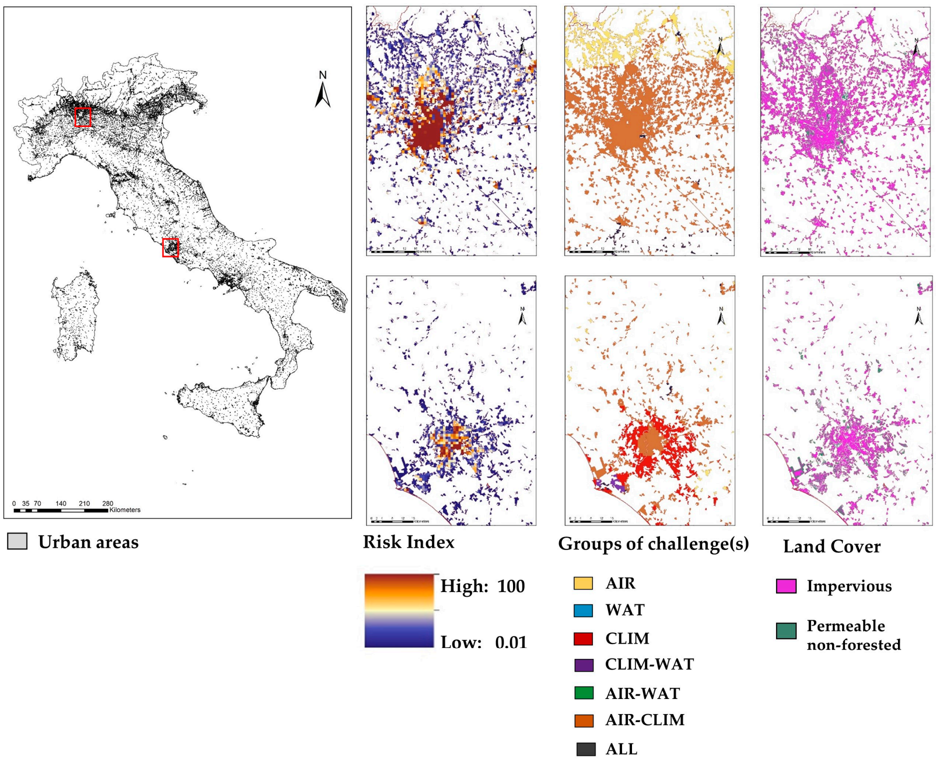

Figure 1. Datasets employed for the analysis within Italian urban areas, risk index (adapted from [62]), groups of challenge(s) (adapted from [61]), and land cover (adapted from [63]). The boundaries of Italian urban areas were defined according to Class "1- Artificial surfaces" of CORINE land cover.

From Di Pirro et al. [61], we derived the maps of three environmental challenges and their spatial co-occurrence. Specifically, the authors identified and mapped 7 groups of challenges: "AIR" group (i.e., air quality), "CLIM" group (i.e., climate adaptation and mitigation), "WAT" group (i.e., water management), "AIR-CLIM" group (i.e., air quality co-occurring with climate adaptation and mitigation), "AIR-WAT" group (i.e., air quality co-occurring water management), "CLIM-WAT" group (i.e., climate adaptation and mitigation co-occurring with water management), and "ALL" group (i.e., the three challenges simultaneously).

From Di Pirro et al. [62], we derived the aggregate risk index ranging from 0 to 100 that expresses the population exposure to these groups of environmental challenges with a spatial resolution of 1 km^2. The risk index was employed in this work to (i) guide the spatial allocation of the NBS for the three scenarios (i.e., priority of intervention) and (ii) estimate the effectiveness of interventions in each pixel.

From Di Pirro et al. [61], we derived the Performance Score (ranging from 0 to 1) of 24 NBS to address the different environmental challenge(s). Furthermore, for each of the 24 NBS, the authors provided information regarding the land cover where NBS can be implemented. The NBS that can be implemented in impervious land covers (I-NBS) are those fixed to buildings (i.e., extensive green roofs, green facades, green wall systems, intensive green roofs, planter green walls, semi-intensive green roofs, vegetated pergolas, and vertical mobile gardens), and along streets and parking lots, close to buildings and houses (i.e., pocket gardens/parks, private gardens, raingardens, swales, street trees, and vegetated grid paves). The NBS that can be implemented in permeable non-forested land covers (P-NBS) are community gardens, constructed wetlands, green corridors, heritage gardens, infiltration basins, large urban parks, urban forests, urban orchards, and (wet) retention ponds.

To refine the detection of impervious and permeable non-forested land, overcoming the MMU of CLC (i.e., 25 ha), we used the land cover map of ISPRA with a spatial resolution of 10 m [63]. Particularly, to identify the impervious surfaces within urban areas, we selected the class "abiotic artificial" (i.e., class 111), and to identify the permeable non-forested surfaces, we selected the class "herbaceous vegetation" (i.e., class 222). Forested areas were thus excluded from our analysis, as we did not consider the possibility to implement NBS in already forested areas.

According to the land covers, the spatial resolution of all the layers derived from the previous studies was changed to 10 m. Hence, we simulated the NBS implementation at a spatial scale of 100 m^2.

2.2. Assessing the Costs of Nature-Based Solutions

Investment and maintenance costs were assigned to 22 NBS out of the 24 identified by [61]. We could not find data regarding the implementation costs of "Planter green wall" and "Shelter for Biodiversity"; thus, they were excluded from our analysis. For each of the 22 NBS, we derived the investment costs (C_{Inv}; in EUR/m^2; see Appendix A) as an average of the investment costs reported in project reports from two H2020 projects and one LIFE project financed by the European Union [64–66]. Based on these same project reports, we derived that the annual maintenance costs ($C_{Main,t}$; in EUR/m^2/yr; see Appendix A) are, on average, about 2.5% of the investment costs. Although we are aware that an NBS can last over a long-time frame (e.g., 25 years for green roofs), and thus the investment costs could be averaged over those time frames, we decided to estimate the mean annual investment costs according to a policy cycle in the European Union (i.e., 7 years). Therefore, the Annual Costs (C_t) of implementation for each NBS (i) are given by:

$$C_{i,t} = \frac{C_{Inv,i}}{T} + C_{Main,i,t}$$

where T is the policy lifecycle. All costs are in Euro for the year 2019.

2.3. Scenario Building

Three alternative scenarios were designed to select the NBS to be implemented and relative budgets to be allocated in all Italian urban areas.

The first scenario aims to maximally address the environmental challenges by implementing the best-performing NBS for each of the seven groups of challenges, without any budget constraint. Therefore, for this Best Performance (BP) scenario, we selected, for each group of challenges, the I-NBS and P-NBS showing the highest Performance Score (i.e., Ecosystem Services supply) to address the specific challenges. In case two or more NBS showed the same Performance Score, the cheapest was selected.

The second scenario aims to minimize NBS costs (both investment and maintenance), neglecting the different NBS capacities to address the challenges. Hence, for this Least Cost (LC) scenario, the cheapest I-NBS and P-NBS were selected for each group of challenges.

The third scenario combines the first two scenarios to best address the different challenges at the least cost. Hence, for this Cost-Performance (CP) scenario, we selected, in each group of challenges, the I-NBS and P-NBS showing the lowest value resulting from the ratio between their costs and Performance Scores.

After the NBS were identified and selected according to (i) the scenario, (ii) the group of challenges, and (iii) the land cover (impervious and permeable non-forested), their allocation was simulated nationwide following a decreasing value of the risk index. Consequently, the higher is the risk index value, the higher the NBS implementation priority.

2.4. Calculating Costs and Effectiveness for Each Scenario

Applying the insights from previous studies (i.e., NBS Performance Score, groups of challenges to be addressed, and risk index and costs), we investigated the investment to implement NBS at a national scale, while exploring their return both for environment and society (effectiveness). For each of the three scenarios, we thus calculated the Total Annual Costs and Total Annual Performance that we obtain by implementing the selected NBS in Italian urban areas.

The Total Annual Costs (TC_t; in 2019 Euros) represent the annual investment and maintenance costs required to implement NBS in all available surfaces (impervious and permeable non-forested), dealing with at least one of the three challenges (i.e., risk index > 0). Hence, we calculated the Total Annual Costs (TC_t) as the product of the Annual Costs of the selected I-NBS and P-NBS for each scenario ($C_{t,i\,=\,I}$) and the suitable surfaces (S_i) over all pixels (p) in each group of challenges, as follows:

$$TC_t = \sum_{i,p} C_{t,i=I} \times S_{i.p}$$

where the minimum surface available is the single pixel (100 m^2).

The Total Annual Performance (TP_t) represents the biophysical performance provided by NBS to address all the challenges in the suitable surfaces, and it is calculated as the product of the Annual Performance Score per m^2 of the selected I-NBS and P-NBS for each scenario ($P_{t,i\,=\,I}$) and the suitable surfaces (S_i) over all pixels (p) in each group of challenges, as follows:

$$TP_t = \sum_{i,p} P_{t,i=I} \times S_{i.p}$$

where the minimum surface available is the single pixel (100 m^2). The value of the Annual Performance Score ($P_{t,i}$) ranges between 0 and 1 for all the NBS and, thus, the Total Annual Performance (TP_t) is always positive and greater than 1.

However, we did not limit our analysis to the NBS capacity to provide Ecosystem Services (i.e., Performance Score); rather, we included their potential effect on the population at risk.

The Total Annual Effectiveness (TE_t) is calculated as the product of the Annual Performance Score of the selected I-NBS and P-NBS for each scenario ($P_{t,i\,=\,I}$), the Annual Risk Index in each pixel ($R_{t,p}$), and the suitable surfaces (S_i) over all pixels (p) in each group of challenges, as follows:

$$TE_t = \sum_{i,p} P_{t,i=I} \times R_{t.p} \times S_{i.p}$$

where the minimum surface available is the single pixel (100 m^2). The value of the Annual Risk Index (R_t) ranges between 0.01 and 100, while the Annual Performance Score ($P_{t,i}$) in each pixel is always greater than 1. Hence, the Total Annual Effectiveness (TE_t) will be greater than the Total Annual Performance (TP_t) when the risk index is greater than 1. On the other hand, the Total Annual Performance will be greater than the Total Annual Effectiveness in all the pixels where the risk index drops below 1, as in those pixels, the Ecosystem Services supply by the NBS is high, while the number of beneficiaries at risk is low.

In other terms, while we can assume the Total Annual Performance as a measure of the potential Ecosystem Services supply (e.g., regardless of the beneficiaries of the intervention), the Total Annual Effectiveness, which includes the actual number of beneficiaries exposed to risk, represents a measure of the real benefits for people linked to the implementation of NBS.

We thus obtained, for the three scenarios (i.e., BP, LC, and CP), three different Total Annual Costs, Total Annual Performances, and Total Annual Effectivenesses. Considering the case of implementing NBS in all urban areas for the three scenarios, the value of the Total Annual Effectiveness is different only for the Total Annual Performance, as the Annual Risk Index stays the same.

Lastly, we calculated the Annual Cost-Effectiveness Ratio (CER_t; in 2019 Euros per unit) and its variation throughout the urban areas of the national territory and across scenarios. The Cost-Effectiveness Ratio determines the relation between the inputs in monetary terms and the outcomes in physical terms, and it is calculated as follows:

$$CER_t = TC_t / TE_t$$

Therefore, if we assume the same level of investment for the three scenarios, the lower the Cost-Effectiveness Ratio, the higher the return for society (i.e., Total Annual Effectiveness). Similarly, if we assume the same level of Total Annual Effectiveness for the three scenarios, the lower the Cost-Effectiveness Ratio, the lower the budget needed to achieve those benefits.

Finally, cost-effectiveness curves per scenario are derived by summing-up the single-pixel value effectiveness (Cumulative Effectiveness) and Annual Costs (Cumulative Costs), starting from those with the highest risk (i.e., 100) to those with the lowest risk (i.e., 0.01). Particularly, we explored the variation of the Cost-Effectiveness Ratio among scenarios above and below the risk index equal to 1.

3. Results

The results show that 12,694 km^2 out of 16,798 km^2 of Italian urban areas have a risk index higher than 0, overlaying with impervious and permeable non-forested land covers. Specifically, 8841 km^2 are imperviousness, while 3853 km^2 are permeable non-forested areas. The most recurrent group of challenges in urban areas is AIR-CLIM (47.1%), followed by AIR (27.4%), ALL (12.4%), CLIM (10.1), AIRWAT (1.6%), CLIMWAT (1.3%), and lastly, WAT (0.1%) (Figure 2).

3.1. Costs Assessment

Among the 22 considered NBS, 13 are I-NBS and 9 are P-NBS. The average cost of the I-NBS is 55 EUR/m^2/yr, ranging from the lowest cost of the raingardens (13.4 EUR/m^2/yr) to the highest cost of the vertical mobile gardens (142.7 EUR/m^2/yr). The average cost of P-NBS is 44.8 EUR/m^2/yr, ranging from the lowest cost of the urban orchards (22.7 EUR/m^2/yr) to the highest cost of constructed wetlands (125 EUR/m^2/yr). Please see Appendix A for extensive information regarding costs and performances of the 22 considered NBS.

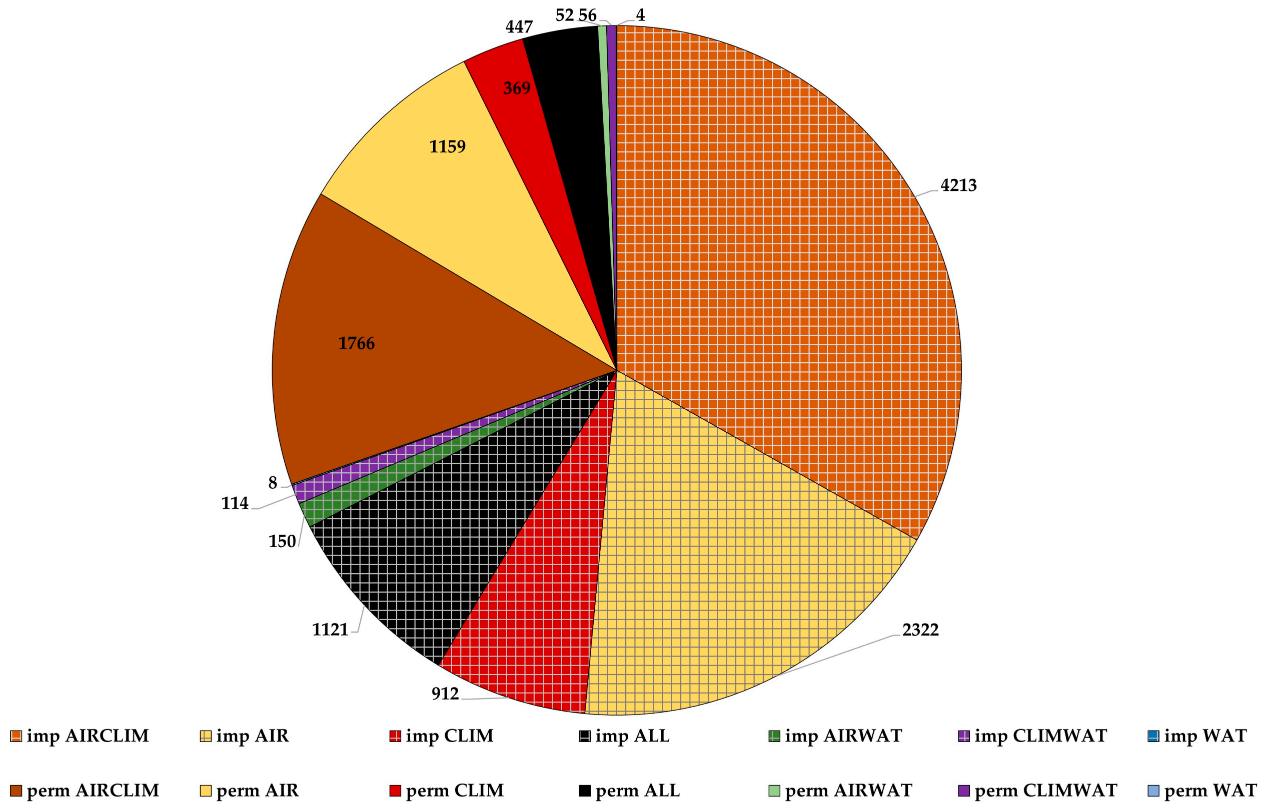

Figure 2. Absolute coverage (km^2) of groups of challenges and land covers (impervious and permeable non-forested) within Italian urban areas. The different colors represent the seven group of challenges (adapted from [61]). The different patterns, squared and full-color, represent impervious and permeable surfaces, respectively.

3.2. Nature-Based Solutions Selected for Each Scenario

According to the three strategies designed for the NBS selection in each scenario (Table 1), in the BP scenario, the selected I-NBS have Performance Scores ranging from 0.8 to 1 and costs ranging from 50.4 EUR/m^2/yr for private gardens to 78.9 EUR/m^2/yr for green facades. For the selected P-NBS in this scenario, the Performance Score is 1 in all the groups of challenges, and the costs range from 30.6 EUR/m^2/yr for the infiltration basins to 37.8 EUR/m^2/yr for the large urban parks. For the LC scenario, the selected I-NBS have Performance Scores ranging from 0.3 to 0.8 (i.e., raingardens) with a cost of 13.4 EUR/m^2/yr, while for P-NBS, the urban orchards were selected with a Performance Score ranging from 0.2 to 0.4 and a cost of 22.7 EUR/m^2/yr. For the CP scenario, the Performance Scores of the I-NBS range from 0.5 to 0.9, and the costs range from 13.4 EUR/m^2/yr for raingardens to 18.5 EUR/m^2/yr for extensive green roofs; for the P-NBS, the Performance Scores range from 0.9 to 1, and the costs range from 30.6 EUR/m^2/yr for the infiltration basins to 37.8 EUR/m^2/yr for the large urban parks.

3.3. Comparison among Scenarios

Firstly, we estimated the investment annually required to implement the NBS (both I-NBS and P-NBS) on the identified 12,694 km^2. Results show that, regarding the BP scenario, the estimated Total Annual Cost is about EUR 777 billion, with a Total Annual Effectiveness of 31 billion and a Total Annual Performance of about 12 billion. For the LC scenario, the estimated Total Annual Cost is about EUR 206 billion, with a Total Annual Effectiveness of 12 billion and a Total Annual Performance of about 5 billion. For the CP scenario, the Total Annual Cost is about EUR 301 billion, with a Total Annual Performance of 25 billion and Total Annual Performance of about 10 billion. Regarding the Cost-

Effectiveness Ratio, the BP scenario shows the highest value with 24.6, followed by LC and CP (16.3 and 11.9, respectively).

Table 1. Selected NBS for the three scenarios, Best Performance (BP), Least Cost (LC), and Cost per Performance (CP). The NBS are proposed according to the 7 group of challenges (i.e., AIR, CLIM, WAT, AIRCLIM, AIRWAT, CLIMWAT, and ALL) and the land cover (impervious and permeable non-forested). Particularly, the I-NBS are those implementable in impervious land covers, while the P-NBS those implementable in permeable land covers. For each NBS, the Performance Scores (PS per m^2) and cost (EUR/m^2/yr; in 2019 Euros) required for their implementation and maintenance are reported.

Scenarios	NBS, PS, Costs	AIR	CLIM	WAT	AIR-CLIM	AIR-WAT	CLIM-WAT	ALL
BP	I-NBS	Green facade	Private gardens	Semi-intensive green roof	Green façade	Intensive green roof	Intensive green roof	Private gardens
	PS per m^2	1	1	1	1	0.8	0.9	0.8
	Cost (EUR/m^2/yr)	78.9	50.4	52.0	78.9	52.0	52.0	50.4
	P-NBS	Large urban park	Large urban park	Infiltration basin	Large urban park	Large urban park	Large urban park	Large urban park
	PS per m^2	1	1	1	1	1	1	1
	Cost (EUR/m^2/yr)	37.8	37.8	30.6	37.8	37.8	37.8	37.8
LC	I-NBS	Raingardens	Raingardens	Raingardens	Raingardens	Raingardens	Raingardens	Raingardens
	PS per m^2	0.4	0.3	0.8	0.4	0.6	0.6	0.5
	Cost (EUR/m^2/yr)	13.4	13.4	13.4	13.4	13.4	13.4	13.4
	P-NBS	Urban orchards	Urban orchards	Urban orchards	Urban orchards	Urban orchards	Urban orchards	Urban orchards
	PS per m^2	0.3	0.2	0.5	0.3	0.4	0.3	0.3
	Cost (EUR/m^2/yr)	22.7	22.7	22.7	22.7	22.7	22.7	22.7
CP	I-NBS	Swales	Extensive green roof	Raingardens	Street trees	Swales	Raingardens	Raingardens
	PS per m^2	0.6	0.9	0.8	0.8	0.7	0.6	0.5
	Cost (EUR/m^2/yr)	15.1	18.5	13.4	21.0	15.1	13.4	13.4
	P-NBS	Large urban park	Large urban park	Infiltration basin	Large urban park	Infiltration basin	Infiltration basin	Infiltration basin
	PS per m^2	1	1	1	1	0.9	0.9	0.9
	Cost (EUR/m^2/yr)	37.8	37.8	30.6	37.8	30.6	30.6	30.6

Similarly, analyzing these indices and curves till the pixels corresponding to risk index equal to 1, we observe that, beyond this threshold, the tails of the curves of the three scenarios start to run almost parallel to the y-axis (i.e., Cumulative Costs) (Figure 3). Consequently, corresponding to this threshold, the analyzed indices are EUR 68 billion and 12 billion effectiveness in the LC scenario, EUR 98 billion and 24 billion effectiveness in the CP scenario, and EUR 270 billion and 30 billion effectiveness in the BP scenario.

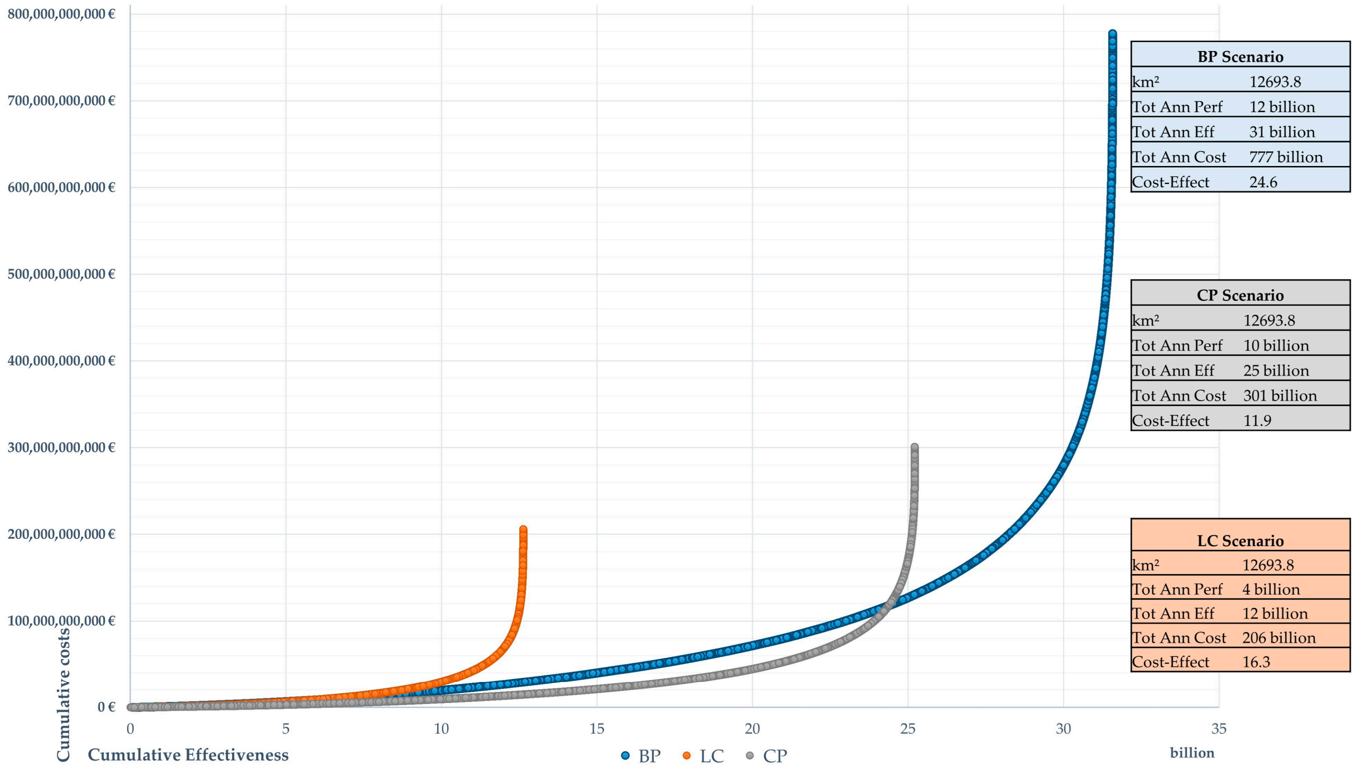

Figure 3. Trends of Cumulative Costs (*Y*-axis) as a function of Cumulative effectiveness (*X*-axis) for the three scenarios depicted: Best Performance (BP), Least Cost (LC), and Cost per Performance (CP). All the NBS, selected according to the scenarios, are allocated pixel by pixel following the decreasing values of the Risk Index. The three informative boxes, one for each scenario, show the surface covered by NBS implementation (km^2), Total Annual Performance, Total Annual Effectiveness, Total Annual Cost (2019 Euros), and Cost-Effectiveness Ratio.

4. Discussions

4.1. Characteristics of Urban Areas and Implication for Nature-Based Solutions Implementation

The characteristics of urban areas must be addressed in relation to the associated socio-economic challenges to ensure effective enhancements in urban Ecosystem Services provision by NBS planning and management [17,67]. Our analysis shows that 12,694 km^2 of urban areas in Italy are risky for the population's health: 70% in impervious surfaces and 30% in permeable non-forested surfaces (the forested surfaces were excluded from our analysis). Furthermore, 62% of these areas show multiple challenges simultaneously, particularly with the AIR-CLIM group (i.e., challenges of air quality and climate adaptation and mitigation occurring simultaneously), which occupies the greatest relative surface both on impervious and permeable non-forested land covers (Figure 2). These results are in line with the previous literature showing the relationship between sealed surfaces and the interaction of air pollutants and thermal discomfort [67–69]. From an urban planning perspective, these results offer the following insights: (i) the need to consider the multiple challenges to tackle as a key criterion to improve the NBS cost-effectiveness and (ii) NBS research and implementation need to strengthen their focus on impervious surfaces.

Currently, the financing commitments in urban areas are increasingly focused on tree-planting campaigns, mainly intended for climate adaptation and mitigation (e.g., 6.6 million trees in Italy [28] and 3 billion trees in Europe [70]), risking to trigger severe competition for land [71], a scarce and expensive resource especially in cities' core areas [72]. Our results show that impervious surfaces are the predominant land cover in Italian urban areas, around 70%, underlying the strategic role of I-NBS for increasing urban sustainability both on buildings and along the street (such as green roofs and vertical green technology [73], private gardens [17], and street trees [74,75]). Indeed, I-NBS, even if less-performing than P-NBS, are ideal to requalify often unemployed spaces [76] and, consequently, tone down conflicts around open spaces with fragmented ownership in densely urbanized areas [17,77]. However, due to intrinsic and structural characteristics of I-NBS (e.g., reduced amount of substrate in green roofs [78]), it is crucial to carefully consider their expensiveness and lower Ecosystem Services supply compared with P-NBS as the ratio between Cost/Performance Scores proposed in the CP scenario. If, on one hand, we considered a full-scale I-NBS implementation in all impervious surfaces regardless of their actual availability, on the other, we did not include the possibility of depaving actions. These measures are growing in the literature and in practice [64,79] as a valid alternative to re-establish the Ecosystem Services supply [80] undermined by soil sealing (e.g., carbon stock [81] and habitat degradation [82]). Moreover, these measures play a key role to reach the European goal of zero (net) land take. As the information regarding their costs is limited to specific case studies and not easily replicable in other contexts and scales, we did not include it in our analysis.

Despite impervious surfaces being the main land cover in urban areas, around 30% is covered by permeable non-forested surfaces. Recently, di Cristofaro et al. [83] underlined that this land cover decreased in Italian built-up areas during the last three decades, especially in densely populated areas. Their results support our findings and highlight the importance of maintaining and promoting these open areas through the implementation and management of new NBS, which can effectively address environmental challenges and restore degraded lands (e.g., brownfields [12,84,85]) at a lower average cost compared with I-NBS (Table 1). Furthermore, P-NBS can be employed in two other sectors with significant economic interests, biofuels production (e.g., growing perennial biomass crops [86]), and biomaterials constructions (e.g., building with timber, cork, and bamboo [87]). Both could substantially reduce the carbon footprint of our cities while creating durable carbon pools [8].

4.2. Variation in Costs and Effectiveness among Scenarios

According to our results, Scenario CP shows the best Cost-Effectiveness Ratio (11.9), followed by scenario LC (16.3), and lastly, Scenario BP (24.6).

Notwithstanding, the maximum Total Annual Effectiveness is found in the BP scenario (i.e., 31 billion), where the selected NBS show the maximum Total Annual Performance (i.e., the highest Ecosystem Services supply), involving all the population at risk in Italian urban areas. The maximum benefit (i.e., Total Annual Effectiveness) that can be expected by implementing NBS is crucial information for policymakers [88], as it allows to identify the BP scenario as the best option that should be adopted to pursue the main objective of addressing challenges and reducing the population at risk.

Reaching the maximum Total Annual Effectiveness also leads to the maximum investment, showing the highest Total Annual Cost among the three scenarios (i.e., EUR 777 billion), exceeding 61 EUR/m^2/yr, suggesting that the maximum return for the population could be reached but at the highest cost. On the other hand, selecting the cheapest NBS allows a mean investment of just 24 EUR/m^2/yr, with a Total Annual Cost of about 70% less than the BP scenario (EUR 206 billion), as well as losing 70% of its Total Annual Effectiveness. Although it is not surprising that the CP scenario is the most cost-effective, we quantitatively show that evaluating the ratio between cost and Ecosystem Services supply (i.e., cost/Performance Score), even in the NBS selection phase, can effectively help to save money, with a negligible decrease in terms of effectiveness. Indeed, the Total Annual Cost is 60% less than the BP scenario, while losing just 20% of Total Annual Effectiveness.

Therefore, the results obtained by scenario CP represent an optimal option for all the European Member States that need to effectively leverage investments in NBS provided by the Green Deal, developing strategies to generate gains for biodiversity, adaptation and mitigation, disaster risk reduction, and health [89].

We are aware that the results of all three scenarios show huge annual investments (EUR 777, EUR 206, and EUR 301 billion, respectively, for the BP, LC, and CP scenarios). This is due to the fact that we considered a full-scale implementation on all impervious and permeable non-forested land covers falling in Italian urban areas that do not necessarily correspond with the real space availability. Due to the large scale of this work, we did not consider archaeological constraints, limited space in city centers, nor social variables that should be included to support local-scale governance and NBS design [61].

However, these large investments might be considered more feasible if they do not limit NBS funding merely to the "environmental sphere" (e.g., environmental ministry and municipal forestry agency). Since NBS proved to be important to improving health [90,91], McDonald et al. [32] pointed out that the use of innovative finance and policy tools can enable public health funding to be linked to, e.g., tree-planting funding. Similarly to public health, funding for NBS could be linked to risk management and social policies [45], as well as the engineering sector and bio-based industry (as recently highlighted by the European Forest Institute [8,92,93]). Accordingly, the estimated Total Annual Costs for the three scenarios can represent a starting point to identify the investment gap to fill by (i) linking different levels of governance, (ii) streaming finance from different departments, and (iii) identifying and quantifying financial and other institutionalized incentives (e.g., PES [43]), with the final aim to fight the planning silos that often limit the correct management of resources and the definition of responsibilities among departments [22,27,32,94,95].

For this purpose, we adopted the descending order of the risk index to prioritize NBS implementation. Its employment confirmed how the effectiveness of the same intervention might be totally different in terms of human health improvement based on its location. This is particularly evident in the curves of Cumulative Effectiveness and Cumulative Costs, where we explored that the costs increase steadily along the curves, inversely to their effectiveness (Figure 3). Considering the effectiveness given by the product between the Performance Score and risk index values, the more the latter decreases, the more the effectiveness decreases. Indeed, the NBS implementation costs, as well as their potential Ecosystem Services supply, remain constant throughout the territory, while the return in terms of human health varies according to the amount of population exposed to a given level of environmental challenge (i.e., risk). Particularly, in the pixels where the risk index drops below 1, the Total Performance Score starts to be higher than the Total Effectiveness in all scenarios. Particularly, this threshold (i.e., risk index equals to 1) corresponds to EUR 68 billion and 12 billion effectiveness in scenario LC, to EUR 98 billion and 24 billion effectiveness in scenario CP, and to EUR 270 billion and 30 billion effectiveness in Scenario BP. The difference between the Total Annual Costs needed to cover the whole urban areas and this threshold (i.e., tails of the curves in Figure 3) highlights that EUR 138 billion, EUR 203 billion, and EUR 507 billion are additionally required to reach, respectively, the Total Annual Effectiveness of LC, CP, and BP (12 billion, 25 billion, and 31 billion, respectively). Thus, the tails of the curves represent the portions of territory where NBS are financially maintained, while potentially supplying Ecosystem Services, but their actual beneficiaries decline. Accordingly, in each scenario, investing about 33% of the respective Total Annual Costs needed to cover the whole urban areas would be enough to reach between 88% (BP scenario) and almost 100% (LC scenario) of the Total Annual Effectiveness. This evidence allowed us to identify the risk index equal to 1 as a helpful threshold to orient and optimize the budget allocation throughout the territory, maximizing the return in terms of benefits for the population. Therefore, the rationale "the higher the risk the higher the priority to implement NBS" would lead to improving the cost-effectiveness (i.e., maximizing the return for human beings), as well as the environmental justice (i.e., enhance well-being of most vulnerable groups [96]).

Our approach is also confirmed by the previous literature employing exposure indices in environmental justice to brief decisionmakers regarding the social inequity of cumulative hazards' exposure [97], to support and select urban planning alternatives reducing the risk for citizens [67], and to orient the allocation of the investment for disaster risk reduction [98]. Our findings also suggest that risk exposure to multiple challenges could be read as an Ecosystem Services demand from the population, representing a reliable parameter for urban planners to prioritize and locate multifunctional interventions. This approach is supported in the literature by other authors recognizing Ecosystem Services frameworks for their support in urban planning [99–102], to define priority areas for NBS implementation [103,104], and ensure their equitable distribution throughout the territory [17,105]. Yet, these frameworks are proposed at the municipal scale, conversely, we proposed a framework involving all urban areas in Italy (according to a land cover definition, i.e., CLC), improving the cartographic detail (10 m resolution). Our approach thus further allowed us to (i) detect the small patches of permeable spaces within urban areas, (ii) adopt a strategic vision of all urban areas and not consider municipalities as single and isolated units, and (iii) avoid the intrinsic limitation in employing administrative boundaries for Ecosystem Services assessment [82,106], NBS implementation (e.g., urban forests [107]), and environmental challenges mitigation [62].

5. Conclusions

In this work, we compared different NBS selection strategies and how their implementation in the Italian urban areas deals with two recurring issues for a national government: achieving environmental objectives (e.g., Italy has infringed EU law on air quality [54]) and saving money.

Our national-scale perspective gives decisionmakers and investors insights about the total investments required for large-scale implementations of NBS and to optimize their contribution toward achieving national objectives and international goals. This is in line with the need that recently emerged in the literature to upscale NBS [10,21,88], especially in national and European policy frameworks [108].

For a fine-scale application, our results show that relating information regarding Ecosystem Services and costs can be crucial to select the optimal set of NBS based on territorial conditions and threats (CP scenario). For a broader-scale application, our framework also proved that, contrary to NBS selection, their implementation throughout the territory should not be limed just to the potential Ecosystem Services supply but necessarily need the inclusion of their demand as well. Indeed, limiting the intervention surface to the portions of the territory with a risk index greater than 1 would allow saving 67% of the Total Annual Costs, with a negligible loss in terms of return for human health.

Even with optimizing the budget allocation, NBS implementation over all the risky areas would require significant investments, often a limiting factor for interventions. Thanks to their multifunctionality, we highlight that these large investments could be covered by co-financing actions following the needs of different stakeholders and policy areas (e.g., as similarly proposed in the "health in all policies" approach [109]).

In this work, we quantified effectiveness as a metric to improve citizens' environmental health. However, effectiveness could also synthesize other environmental and social outcomes (e.g., improve social cohesion, energy efficiency, etc.). We thus point out how the employment of an aggregated metric, able to quantify multiple outcomes, is a helpful approach to limit institutional fragmentation and, in turn, strengthen potential co-financing opportunities.

Moreover, we averaged the Total Costs for 7 years (an EU policy cycle), as annual calculations give policymakers insights into the impact of NBS implementation on their annual budget. However, we are aware that the short-term nature of decision making can hinder the longer-term planning and maintenance required to sustain NBS benefits, usually with a longer lifecycle. This is one of the main challenges for future financial and political systems, on which future research should be focused (e.g., transaction costs [30,37]). Based on the framework here-proposed, practitioners could make more informed choices for the provisioning of both large-scale and long-term ecosystem investments by promoting multilateral and multilevel partnerships. Our methodology can be potentially replicated across all Member States, as well as upscaled (e.g., EU) to ensure a more effective funds allocation and identification of new areas of research and innovation projects.

Author Contributions: Conceptualization E.D.P., P.R. and L.S.; methodology: E.D.P. and P.R.; software, formal analysis, and data curation, E.D.P.; investigation and validation E.D.P., P.R. and L.S.; writing—original draft preparation, E.D.P.; visualization, L.S. and B.L.; writing—review and editing: E.D.P., L.S., P.R., M.M. and B.L.; supervision, L.S., M.M. and B.L.; project administration and resources, M.M. and B.L.; funding acquisition, B.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work has received funding from the research project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4—Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of University and Research funded by the European Union—NextGenerationEU; Project code CN_00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, CUP H73C22000300001, Project title "National Biodiversity Future Center—NBFC".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Authors wish to thank the research project "Establishing Urban FORest based solutions In Changing Cities" (EUFORICC), cod 20173RRN2S, funded by the PRIN 2017 program of the Italian Ministry of University and Research (project coordinator: C. Calfapietra). Authors wish to also thank Mirko Di Febbraro for his suggestions about the methodological section. Finally, thanks are also due for financial support to CESAM (UIDB/50017/2020 and UIDP/50017/2020), to FCT/MCTES through national funds, and the co-funding by European funds when applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Nature Based Solutions	Performance Score (PS/m^2)							Inv Cost (EUR/m^2)	Ann Inv Costs (EUR/m^2)/7yr	Maint. Costs (EUR/m^2/yr) 2.5%	Costs (EUR/m^2/yr)
I-NBS	**AIR**	**CLIM**	**WAT**	**AIR-CLIM**	**AIR-WAT**	**CLIM-WAT**	**ALL**				
Street trees	0.8	0.9	0.4	0.8	0.6	0.7	0.7	125	17.9	3.1	21.0
Extensive green roof	0.5	0.9	0.6	0.7	0.5	0.7	0.7	110	15.7	2.8	18.5
Raingardens	0.4	0.3	0.8	0.4	0.6	0.6	0.5	80	11.4	2.0	13.4
Vegetated grid pave	0.2	0.5	0.8	0.3	0.5	0.6	0.5	115	16.4	2.9	19.3
Private gardens	0.5	1.0	0.8	0.8	0.6	0.9	0.8	300	42.9	7.5	50.4
Pocket garden/park	0.6	0.6	0.8	0.6	0.7	0.7	0.7	210	30.0	5.3	35.3
Semi-intensive green roof	0.7	0.8	1.0	0.8	0.8	0.9	0.8	310	44.3	7.8	52.0
Intensive green roof	0.7	0.9	0.8	0.8	0.8	0.9	0.8	310	44.3	7.8	52.0
Swales	0.6	0.2	0.9	0.4	0.7	0.5	0.6	90	12.9	2.3	15.1
Green faCade	1.0	1.0	0.2	1.0	0.6	0.6	0.7	470	67.1	11.8	78.9
Vegetated pergola	0.5	0.8	0.3	0.6	0.4	0.5	0.5	600	85.7	15.0	100.7
Green wall system	1.0	0.8	0.0	0.9	0.5	0.4	0.6	700	100.0	17.5	117.5
Vertical mobile garden	1.0	0.9	0.0	1.0	0.5	0.5	0.6	850	121.4	21.3	142.7
P-NBS											
(Wet) Retention Pond	0.8	0.6	1.0	0.7	0.9	0.8	0.8	193	27.5	4.8	32.3
Infiltration basin	0.8	0.8	1.0	0.8	0.9	0.9	0.9	183	26.1	4.6	30.6
Green Corridors	1.0	1.0	0.7	1.0	0.8	0.8	0.9	230	32.9	5.8	38.6
Large urban park	1.0	1.0	0.9	1.0	1.0	1.0	1.0	225	32.1	5.6	37.8
Community garden	0.3	0.5	0.8	0.4	0.6	0.7	0.6	160	22.9	4.0	26.9
Heritage garden	1.0	1.0	1.0	1.0	1.0	1.0	1.0	300	42.9	7.5	50.4
Urban forest	1.0	0.9	0.8	0.9	0.9	0.9	0.9	225	32.1	5.6	37.8
Urban orchards	0.3	0.2	0.5	0.3	0.4	0.3	0.3	135	19.3	3.4	22.7
Constructed wetlands	0.0	0.3	1.0	0.1	0.5	0.6	0.4	750	107.1	18.8	125.9

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