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Built Heritage Preservation and Climate Change Adaptation in Historic Cities: Facing Challenges Posed by Nature-Based Solutions

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Abstract

Historic centres are extremely complex parts of contemporary cities, particularly from morphological, architectural, and cultural points of view, where a significant proportion of the land area may be occupied by built heritage sites that require protection and conservation. These urban contexts are also characterised by scarce green and public open spaces endowment, a high proportion of private property, and high levels of natural risk exposure. From a climate change adaptation perspective, Nature-based Solutions (NbS) have emerged as measures to manage urban ecosystems to address environmental and societal challenges. To overcome the conflicting objectives of climate change adaptation and built heritage preservation, this study proposes a three-step methodology applied to the historic centre of Catania (Italy): (i) Land-Use/Landownership and Land Cover/Maintenance and Quality analyses; (ii) Land Transformability Assessment; (iii) Land Transformation Scenarios Assessment. According to this methodology, five Land Transformation Scenarios have been drawn up: (1) NbS full installation; (2) NbS installation with some limitations; (3) NbS installation after re-arrangement; (4) NbS installation strongly limited; (5) NbS installation not viable. This approach allowed us to identify the most feasible and suitable buildings and open spaces, while distinguishing public and private properties, to implement a more comprehensive integration of NbS and built heritage preservation in historic cities for mutual benefits.

Keywords: historic centres; climate change adaptation; natural risks mitigation; built heritage preservation; nature-based solutions

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1. Introduction

1.1. Nature-Based Solutions for Adapting to Climate Change

The severity and speed of climate change are posing a threat to contemporary cities, negatively impacting both human well-being and urban life [1,2]. Indeed, climate change has raised the average global temperature, as well as the frequency, duration, and intensity of heat- and rain-related events [1]. Consequently, human health and society are being negatively impacted by heat extremes, heat waves, and urban pluvial floods [3]. The risk-related effects of these natural events are dramatically increasing due to the high concentration of urban populations, with nearly 73% of Europeans living in cities today [4], and the low resilience of cities, which is frequently caused by specific urban fabrics, land-use patterns, and impervious surfaces [5].

The most evident consequences of these climate processes are urban heat islands. Described as a unique urban climate, they are made worse by an increasing number of days with extreme temperatures [6]. They are characterised by higher daytime and nighttime temperatures in built-up areas than in the surrounding natural environment [7]. Urban heat islands worsen heat stress on living organisms, change biodiversity and ecosystem functions [8], increase energy consumption for summer building cooling [9], and promote photochemical smog production and particle matter accumulation due to poor horizontal air dispersion and subsidence [10]. Ongoing urbanisation and the loss of urban green spaces have also increased the risk of pluvial floods in the context of climate change [11], raising doubts about the effectiveness of conventional management techniques. When rainfall intensity locally exceeds soil infiltration and the sewage system's conveyance capacity, urban pluvial floods occur [12]. Due to their small temporal scale, which makes their prediction difficult [13], as well as the substantial harm they can inflict on people and property [14], they pose a significant challenge to the entire world [15].

Because urban ecosystems are complex, managing urban heat islands and flooding requires interdisciplinary research as well as comprehensive urban planning policies and practices [16]. Therefore, flexible and multipurpose solutions are needed to solve these issues [17]. Out of all of them, Nature-based Solutions (NbS) is an approach that employs integrated solutions to lower urban heat islands and runoff, while also gaining other benefits [18]. The goal of NbS is to promote sustainable urbanisation, a top priority, by providing engineered green solutions inspired by or supported by nature [19]. NbS encompasses a broad range of practices, including permeable surfaces, infiltration strips, rain gardens, street trees, urban gardens, green roofs and facades, and more [20]. If properly planned and executed, NbS could facilitate climate-resilient solutions (either adaptation or mitigation), promote sustainable urbanisation, restore degraded natural ecosystems, improve natural risk management, and offer several social advantages [21]. Social cohesion, health, carbon sequestration, biodiversity, noise reduction, urban heat island reduction, sustainable water management, urban agriculture facilitation, and air quality are among the ten main advantages that NbS offer cities [22].

Therefore, adding NbS is a useful mitigation strategy to lessen urban heat islands, especially during hot summers like those that are typical of a Mediterranean climate [23]. The amount of water that is brought into conventional and existing drainage and sewer systems can be reduced by using NbS to control stormwater and manage flooding in terms of retention, infiltration, and runoff. In addition, NbS reduces respiratory illnesses [24] and enhances biodiversity, amenity, and water and air quality [25]. By incorporating vegetation into the built environment, either by placing greenery directly on buildings or by using engineering techniques to manage the drainage of streets and other open spaces, cities can incorporate NbS [26].

1.2. Conflicts Between Nature-Based Solutions and Built Heritage Preservation

Despite its growing development in many cities, it is still unclear whether and how NbS can be utilised in urban fabrics that hold cultural, architectural, and archaeological significance. This is especially true for historic cities, where sites recognised as cultural assets typically occupy a sizable section of the area. The main reason why NbS implementation in these urban environments is still limited is because of the numerous policies and programmes that provide various obstacles to the protection of cultural assets [27]. The intricacy of historic cities inevitably necessitates a deeper comprehension of the opportunities and difficulties associated with the distribution and application of NbS in these urban settings.

However, as a preeminent global authority on cultural heritage, UNESCO admits that the NbS concept may present chances for more effective and sustainable methods of cultural heritage protection. The obvious acknowledgement of cultural heritage as a crucial facilitator of achieving the Sustainable Development Goals has served to further solidify this perspective. Opportunities to integrate constructed heritage preservation with NbS delivery in urban areas are rarely acknowledged, despite their significance and efficacy [28]. Prior research on the heritage preservation of historic centres has mostly been on revalorisation, renewal and rebuilding, and cultural perception, whilst natural disaster mitigation, including heat waves and pluvial floods, has received less attention [29]. Babí Almenar et al. [30] noted that relatively few studies have examined the preservation of cultural heritage in conjunction with NbS inclusion when evaluating the relationships among NbS, environmental services, and urban issues. Furthermore, the very few studies on NbS integration in historic cities [27,28,31] have restricted their focus to site-specific NbS implementation measures and local design solutions. As a result, these studies exposed a general shortage of research on how these urban fabrics might be effectively transformed while accounting for the socioeconomic complexity brought on by landownership assets and actual conflicts with land uses.

A more integrated approach to cultural heritage preservation is required in order to explore viable ways to deal with the difficulties of both heatwaves and heavy precipitations. According to this viewpoint, an NbS approach should address the characteristics of historic centres and incorporate heritage protection into the process of mitigating and adapting to natural risks, which would help to address current and upcoming difficulties [32]. Greening building envelopes and rooftops, walls, abandoned structures, bridges, and archaeological sites that are protected and classified for cultural heritage purposes are essentially ways in which NbS can be incorporated into historic urban fabrics. In this instance, maintaining and improving these elements' historical, architectural, aesthetic, and collective heritage values is the fundamental goal [33]. The natural mechanisms of greenery should essentially be understood and used as the foundation for creating more balanced and evidence-based policy decisions in order to better integrate NbS into constructed heritage [34]. Indeed, nature in urban areas is generally regarded as a threat to cultural heritage because of the part that microbes, plants, and small mammals play in causing (i) biodegradation, which is defined as direct physical harm; (ii) the loss of associated cultural values; and (iii) impediments and complications in managing and conserving practices. In particular, bio-deterioration needs to consider how climate change and natural field succession affect the relationships between urban vegetation and heritage building materials [35,36].

Nonetheless, there is mounting evidence that certain plants, algae, and lichen-rich biofilms may actually slow down the deterioration of building materials rather than speeding it up [34,37–39]. This happens as a result of the direct aggregation of those bioprotecting organisms as well as the development of shielding colonised surfaces that provide protection against decomposition agents such as pollution, rain, and UV light [40,41]. Additionally, masonry wall tops, abandoned or damaged buildings, and archaeological sites have gradually come to be seen as being effectively protected by soft capping [42]. In order to minimise weathering processes and decrease rainfall intake, vegetation is used to reinforce the tops of exposed masonry structures [38]. Furthermore, addressing the long-term, spontaneous greenery colonisation of architectural heritage may yield new bio-cultural heritage forms via the natural field succession mechanism [43]. Furthermore, sustainable urban drainage systems may offer practical ways to control the interplay between water and constructed heritage [44]. In fact, there may be ways to replicate and improve the bio-receptivity of historic and archaeological sites using conventional building materials and construction techniques [45].

Therefore, built heritage in historic cities should be viewed as an active urban element that should be included in strategies and policies for mitigating and adapting to the consequences of climate change, in addition to being protected. Therefore, it is important to develop a comprehensive greening approach based on NbS implementation and heritage preservation by taking into account and improving existing heritage values and preservation needs, while also improving the built environment's quality, aesthetics, and accessibility. However, these urban settings, which are marked by high densities and a general shortage of open spaces, present significant obstacles to NbS design decisions. This is especially true given the primary challenge of locating enough suitable locations and meeting the necessary technical and spatial requirements for their implementation.

From this perspective, the study proposes a novel Land Transformability Assessment methodology for exploring the aptitude of historic centres to host NbS through assessing the transformability of urban fabrics when referring to the land-use and landownership assets of property, and land cover and maintenance-quality levels of buildings and open spaces. By combining these features, five distinct NbS integration scenarios are drawn up in order to better understand which historic city elements are suitable for transformation at varying degrees of technological, financial, and social viability. This would allow the pursuit of climate change adaptation while preserving cultural heritage in old and dense towns in the framework of urban transformation projects. To explore these scenarios, the historic centre of Catania (Italy) is chosen for its UNESCO's architectural, cultural, archaeological, morphological, and landscape natural heritage features, which imply both obstacles to be overcome and excellent chances to be explored for implementing NbS.

2. Materials and Methods

2.1. Study Area

A representative portion of the historic centre of Catania, a municipality on Sicily's east coast has been chosen as the study area. The city has a municipal land area of approximately 182.8 km^2 and a population of 301,104 inhabitants, according to data from the 2021 Census. The case study covers an area of 994,812 m^2 and it is characterised by a dense and complex historical urban fabric. The municipality's location and the urban area under investigation are illustrated in Figure 1.

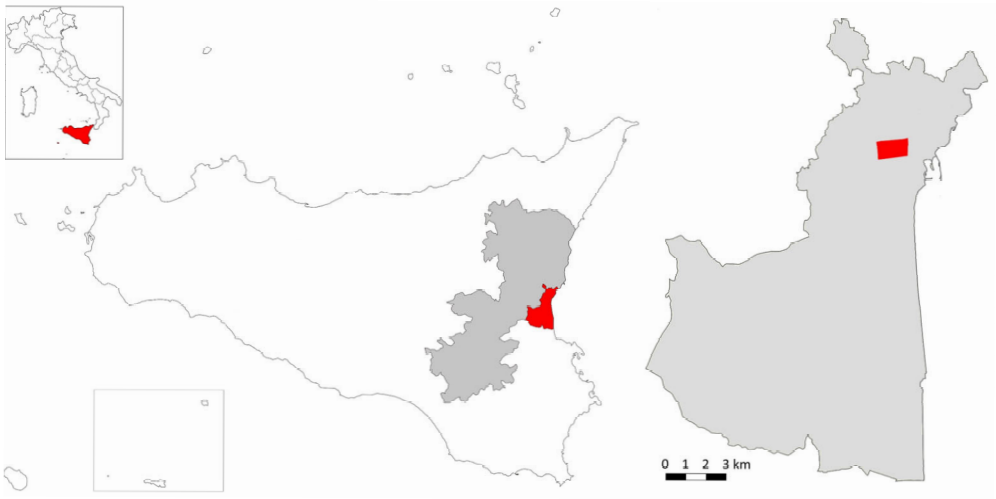


Figure 1. Top left: the position of Sicily (in red) in relation to Italy (in white); **Middle**: the municipality of Catania (in red) as positioned in relation to the Catania province (in gray) and Sicily (in white); **Right**: the case study area (in red) within the municipality of Catania (in gray) (source: authors).

Catania is one of the late baroque towns in South-Eastern Sicily that are listed as UNESCO World Heritage. Following the 1693 earthquake, Catania was rebuilt on its original location. Consequently, its historic centre is made of huge important late 18th-century buildings and monumental compounds dating back to the period of the city's post-earthquake reconstruction (Figure 2). This historic town also has a wealth of Roman archaeological remains and 16th-century fortress walls from the Spanish colonial era. Eleven bastions and seven entrance gates make up the 16th-century walls, which were severely damaged by the terrible lava flow from the volcano Etna in 1669 and innumerable seismic events over the ages. Nonetheless, the city walls' outline may still be seen today at a few locations across the historic core. The massive 1669 lava flow, which was the last to directly impact the town of Catania, is another feature that defines the site's orography and morphology. A portion of the north-west walls from the 16th century were demolished by the lava, creating holes that let the flow elevate the ground level by roughly 12 m close to a sizable monastic compound before continuing southwards towards the sea. The lava flow from 1669 is still visible today, revealing significant crags with outstanding scenic and iconic importance.



Figure 2. Catania's UNESCO sites: (**a**) Exterior façade of the Benedictine Monastery of "San Nicolò"; (**b**) The Eastern Cloister inside the Benedictine Monastery of "San Nicolò"; (**c**) Church of "San Nicolò"; (**d**) Via dei Crociferi; (**e**) The Ancient Greek/Roman-era Theatre; (**f**) Archaeological remains in Piazza Dante. (Source: authors).

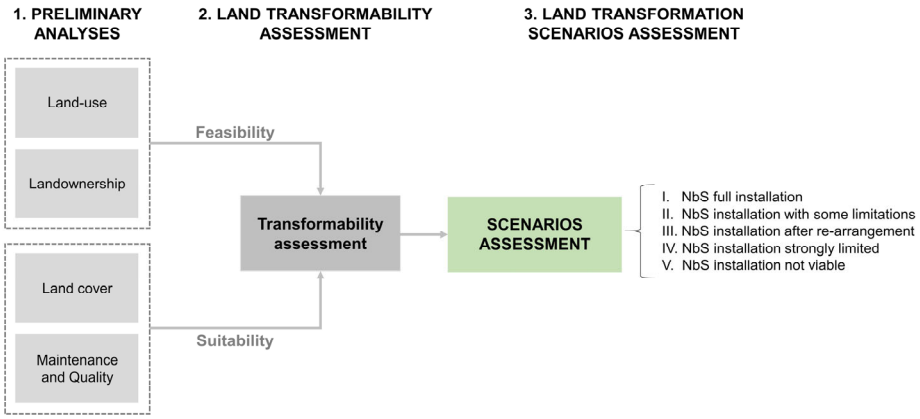
2.2. Method Framework

With the aim of exploring the aptitude of the historic centre to be adapted and transformed for hosting NbS, the proposed method was developed through three different phases as follows:

1. Four preliminary analyses were run: Land-Use Analysis for drawing an overall picture of the land pattern; Landownership Analysis for identifying the current situation in terms of property assets; Land Cover Analysis for investigating the bio-physical features of buildings and open spaces; and Maintenance and Quality Analysis for exploring their conditions of use/maintenance levels and historic/cultural/architectural quality.
2. Through selecting the two transformability criteria of feasibility and suitability, respectively, based on the results of Land-Use/Landownership Analyses and Land Cover/Maintenance and Quality Analyses, a Land Transformability Assessment was developed, and three levels of transformability have been identified (max, med and min).
3. Combining all possible pairs of feasibility and suitability levels, a Land Transformation Scenarios Assessment was then carried out, and five different scenarios of NbS integration within the urban fabric were drawn up: NbS full installation, NbS installation with some limitations, NbS installation after re-arrangement, NbS installation strongly limited, and NbS installation not viable.

All these phases were performed using ArcMap 10 ESRI software, where each patch was manually drawn by visual interpretation of satellite images (Google Earth, 2025) and the ATA1213 topographic map and related orthophotos provided by the Regional Planning Authority of Sicily (Italy).

The proposed method framework is graphically represented in the following flowchart (Scheme 1):



Scheme 1. Flowchart of the method framework.

2.2.1. Preliminary Analyses: Land-Use, Landownership, Land Cover, and Maintenance and Quality

The first phase of the proposed method was aimed at running the following four distinct analyses:

- Land-Use Analysis was based on a topographic map (1:2000) provided by the municipal authority of Catania. Eleven land-use categories were identified: residential, trading, manufacturing/industrial, neighbourhood services, municipal services, archaeological sites, ruins, seminatural, public open spaces, parking areas, and roads.
- Landownership Analysis was aimed at characterising each land-use patch according to the landownership asset. In order to distinguish between private and public patches, a visual interpretation of satellite images, topographic maps, and orthophotos was delivered, and land-use patches were subdivided into two categories: public and private.

- Land Cover Analysis was conducted through a visual inspection of satellite images (Google Earth, 2025), which allowed the detection of different bio-physical features of land-use patches. Nine land cover categories were identified within the study area: trees, trees on impervious surfaces, herbaceous vegetation, buildings with pitched roofs, buildings with flat roofs, impervious surfaces, ruins with vegetation, archaeological remains, and roads.
- Maintenance and Quality Analysis was developed to identify and map the land state/conditions of use. It was conducted on land cover patches in order to identify the level of maintenance and the historic/cultural/architectural values of buildings and state/conditions of use of open spaces. Accordingly, the following categories were identified: ruined buildings, monumental buildings and abandoned/underused buildings/open spaces, and buildings with regular levels of maintenance. The latter category includes all patches—both buildings and their courtyards as well as open spaces—that do not have any particular historic, cultural, or architectural value and are in a good state of maintenance.

2.2.2. Land Transformability Assessment

As a second phase of the proposed method, a Land Transformability Assessment was developed to evaluate the feasibility and suitability of each land patch of the historic centre to be adapted and/or transformed for hosting new potential NbS. In this study, transformability was set up into three possible levels (max, med, min) and assessed according to the two following criteria, respectively, based on the concept of feasibility through the Land-Use/Landownership scores, and suitability through the Land Cover/Maintenance and Quality scores:

- Feasibility Criterion—Land-Use/Landownership: Transformability is understood as the economic and social feasibility of effectively undertaking NbS integration into buildings and open spaces. When dealing with public land-owned patches (buildings and/or open spaces), the feasibility level is set at "max" because administrators and policymakers may only act in the public interest by taking advantage of complete land availability, institutional ease, and regulatory procedure flexibility for executing urban interventions. Moreover, it is assumed that there is always public consensus when carrying out urban transformations of the public realm. When considering public patches characterised by restricted land uses (municipal services such as hospitals, military barracks, police, and fire stations subjected to sectorial regulatory restrictions), the feasibility level is reduced to "med" because health, hygiene, safety, and security requirements have to be met and therefore might partially affect the NbS installation. Transformability in terms of feasibility is "min" when involving strictly private land-owned patches (i.e., residential land uses) because the property asset is highly fragmented into several homes and landlords and there is no clear interest and economic convenience for them to intervene with NbS. Feasibility can be upgraded to "med" when involving private buildings/open spaces for public uses (trading, manufacturing/industrial, business, cultural, leisure, sport). This could be the case for mall centres, sports facilities, and cinemas where private landowners may have an interest in investing in NbS to enhance their business value.
- Suitability Criterion—Land Cover/Maintenance and Quality: Transformability is understood as the suitability to physically and technically accommodate NbS into buildings and open spaces. The "max" suitability level is assigned to land patches characterised (from the land cover side) by buildings with flat roofs (where it is viable to install green roofs and green walls), impervious surfaces, roads, and bare soils that allow tree planting and greenery; and (from the Maintenance and Qual-

ity side) patches that are characterised by a regular level of maintenance and historic/cultural/architectural quality (other buildings and open spaces in Maintenance and Quality Analysis). Transformability in terms of suitability is "med" only for archaeological remains and monumental buildings, where the introduction of NbS might be more complex due to local protection rules for the preservation of the cultural heritage. The "Min" level of suitability occurs for patches such as ruins with vegetation, ruined buildings, and abandoned/underused buildings and open spaces where, due to very bad maintenance conditions and absence of current uses, there is no option to intervene but to demolish or implement complex urban policies.

The conceptual model of the Transformability Assessment is presented in Scheme 2.

Transformability Assessment		
Levels	Criteria	
	Feasibility (Land-Use and Landownership)	**Suitability** (Land Cover and Maintenance and Quality)
max	Public (municipal and neighbourhood services, public open spaces, parking areas, roads)	Buildings with flat roofs, impervious surfaces, roads, bare soils, and buildings and open spaces with regular levels of maintenance and quality (other buildings and open spaces)
med	Private for public uses (trading, manufacturing/industrial, cultural, business) and public with restricted land uses (municipal services such as hospitals, military barracks)	Archaeological remains and monumental buildings with flat roofs
min	Private (residential)	Ruins with vegetation and ruined buildings, abandoned/underused buildings and open spaces

Scheme 2. Transformability Assessment conceptual model (transformability levels shown in greyscale). Source: authors.

According to the aims of the proposed Transferability model, the land cover patches already equipped with greenery (trees, trees on impervious surfaces, herbaceous vegetation) and/or not allowing for the addition of new greenery (buildings with pitched roofs) were excluded in advance from the assessment.

2.2.3. Land Transformation Scenarios Assessment

The final third phase of the proposed methodology was to explore the relationship between the different combinations of transformability levels, as defined in the previous phase, and the consequent Land Transformation Scenarios that can be drawn up for introducing NbS in historic urban fabrics. Following the Transformability Assessment criteria, a couple of feasibility–suitability values (selected among the max, med, and min scores) are assigned to each land patch according to the Land-Use/landownership and the Land Cover/Maintenance and Quality criteria. In order to take into account all the possible pairs that can be formed by choosing two scores from three (max, med, min), including repetitions and different orders, a total of nine pairs have been found. These nine pairs of feasibility–suitability values are associated with five Land Transformation Scenarios (which are characterised by different land patches where NbS can be installed at different feasibility and suitability levels) according to the following:

I. NbS full installation: NbS can be integrated into public ordinary buildings and open spaces with no limitations due to public landownership assets (there is always public consensus when carrying out the urban transformation of public realms) and/or maintenance levels/cultural heritage features. This scenario includes buildings with flat roofs (among the municipal and neighbourhood services), impervious surfaces (parking areas, public open spaces), roads, bare soils, and buildings and open spaces with regular levels of maintenance and quality (other buildings and open spaces in Maintenance and Quality analysis). The scenario is associated with land patches with a "max" level of transformability (feasibility = max and suitability = max), both in terms of Land-Use/Landownership and Land Cover/Maintenance and Quality scores.

II. NbS installation with some limitations: NbS can be installed on public/private cultural heritage buildings and sites where the main limitations refer to the protection of artistic/architectural components and decorative elements of the buildings (mainly concentrated on the envelopes). For cultural sites/archaeological remains, the main opportunities can be found on the ground and paved areas. This scenario also includes public facilities with restricted land uses (municipal services such as hospitals, military barracks, police, and fire stations), where health, hygiene, safety and security norms and regulations can limit NbS installation. Reversely, on private buildings/open spaces for public uses (trading, manufacturing/industrial, business, cultural, leisure, sport), private landowners might be encouraged to intervene with NbS because they could find interest and economic convenience to improve their business. The scenario includes all patches characterised by the feasibility–suitability pairs "med-max", "max-med", or "med-med".

III. NbS installation after re-arrangement: In order to install NbS, public or private for public use buildings and open spaces need to be partially adapted/transformed due to their underused/abandoned conditions and/or very low maintenance levels. The re-arrangement of buildings could include the demolition of both public/private ruined, abandoned, or underused buildings or ruins with vegetation to install new NbS. This last option could be taken into consideration because this scenario only includes regular buildings with no artistic/architectural/historic components and decorative elements to be protected. This scenario involves all patches associated with the "feasibility = max and suitability = min" and "feasibility = med and suitability = min" pairs.

IV. NbS installation strongly limited: Due to private residential uses, even if characterised by buildings with flat roofs, impervious surfaces, roads, bare soils, and buildings and open spaces with regular levels of maintenance and quality, the

introduction and development of NbS is strongly affected by unclear interest and doubtful convenience for private landowners to intervene with NbS. This scenario includes "min-max" and "min-med" pairs of feasibility–suitability levels.

V. NbS installation not viable: Installation of NbS is not viable due to the under-use/abandonment and/or very low maintenance levels of private buildings and open spaces. These conditions further complicate and burden private landowners in intervening to introduce NbS on their properties. This scenario refers only to land patches with "feasibility = min and suitability = min", according to Land-Use/Landownership and Land Cover/Maintenance and Quality scores.

Scheme 3 reports the logical framework of the Land Transformation Scenarios Assessment (in gray-scale, the feasibility-suitability levels; in green-scale, the five Land Transformation Scenarios).

Land Transformation Scenarios Assessment		
Feasibility (Land-Use and Land-ownership)	**Suitability** (Land Cover and Maintenance and Quality)	**Scenarios**
max	max	**NbS full installation** on public ordinary buildings and open spaces with no limitations due to public landownership assets and/or maintenance levels/cultural heritage features
med	max	**NbS installation with some limitations** on public/private cultural heritage buildings and sites, or on land patches with restricted public land uses, or mixed landownership assets (private for public uses)
max	med	
med	med	
max	min	**NbS installation after re-arrangement** of public or private for public use buildings and open spaces due to under-use/abandonment and/or very low maintenance levels
med	min	
min	max	**NbS installation strongly limited** due to private residential uses

Scheme 3. *Cont*.

min	med	
min	min	**NbS installation not viable** due to under-use/abandonment and/or very low maintenance levels of private buildings and open spaces

Scheme 3. Land Transformation Scenarios Assessment logical framework. Source: authors.

3. Results

3.1. Land-Use and Landownership Analyses

Land uses are mapped in Figure 3 and summarised in Table 1. It can be seen how the case study area is made of a very high-density urban fabric mainly characterised by residential blocks (in red). Indeed, the prevailing land use is residential, accounting for 48.9%, followed by roads at 21.7%, municipal services at 15.8%, and neighbourhood services at 7.2%. Municipal and neighbourhood services (in light and dark blue) are mainly located in the southeast part of the area, where high schools, university departments, municipal offices, civic libraries, and small museums are accommodated in both historic and modern buildings. However, it can be seen that built-up areas cover the majority of the land (72.1%), whereas open spaces sum up to only 27.2%. Thus, a general lack of public open spaces resulted, with only 1% represented by a few public squares evenly spread throughout the case study area.

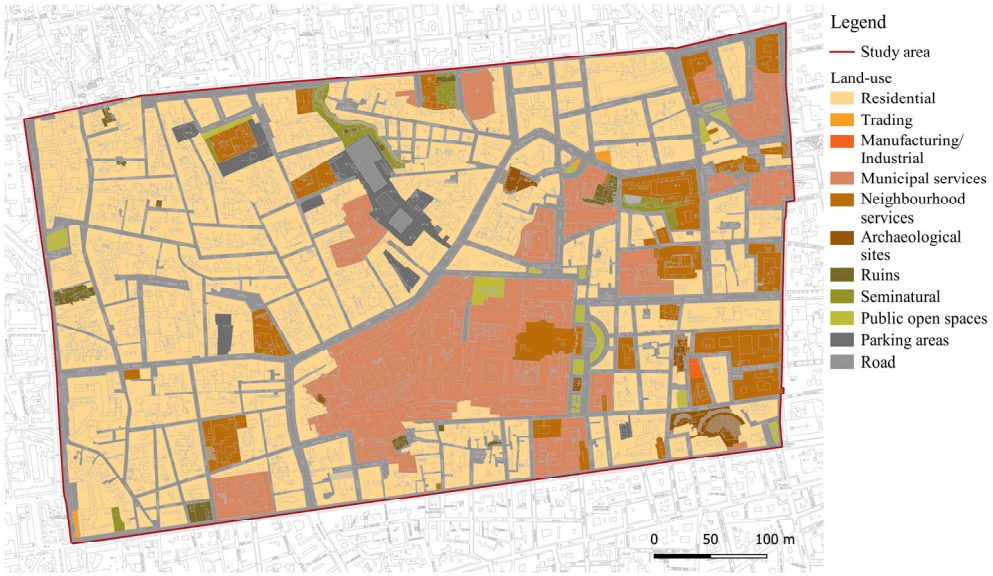


Figure 3. Land-use map of the case study area. Source: authors.

Table 1. Distribution of land-use categories over the case study area.

Land-Use Category	Area (m^2)	% of the Case Study Area
Residential	486,567	48.9
Trading	1067	0.1
Manufacturing/Industrial	706	0.1
Neighbourhood services	71,500	7.2
Municipal services	157,418	15.8

Table 1. *Cont.*

Land-Use Category	Area (m^2)	% of the Case Study Area
Archaeological sites	9563	1.0
Ruins	7399	0.7
Seminatural	10,675	1.1
Public open spaces	9614	1.0
Parking areas	25,296	2.5
Roads	215,801	21.7

Landownership Analysis results (mapped in Figure 4 and summarised in Table 2) show a fairly balanced distribution between public (48.4%) and private land (51.6%). An interesting portion of public buildings/open spaces is composed of facilities with restricted uses (7.3%), mainly represented by municipal services such as hospitals, military barracks, police stations, and fire stations, which are subject to sectorial regulatory restrictions in terms of health, hygiene, and/or safety/security issues. A very tiny percentage of the urban fabric (0.4%) is characterised by private buildings/open spaces intended for public access/use, such as mall centres, cinemas, and sports facilities.

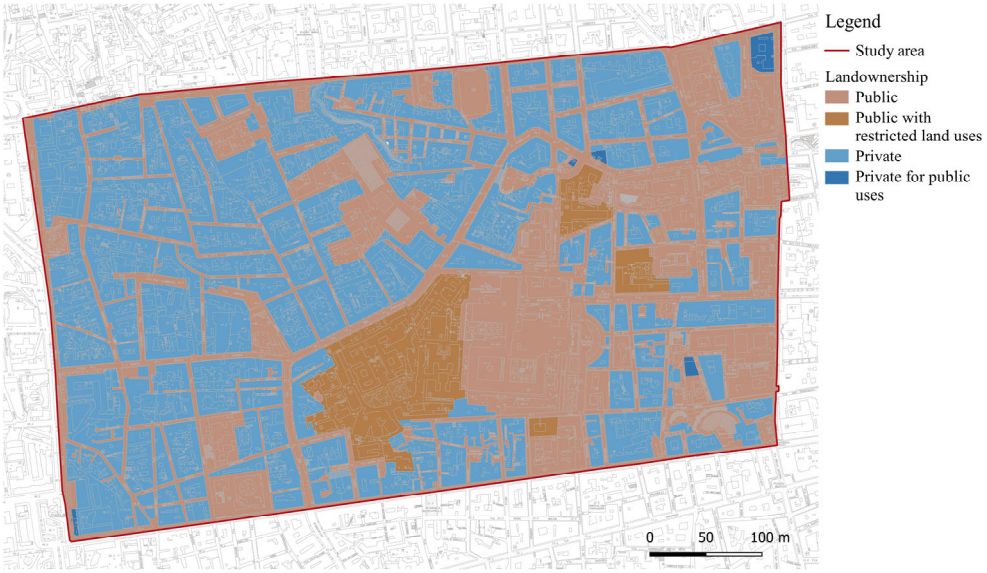


Figure 4. Landownership map of the case study area. Source: authors.

Table 2. Distribution of landownership categories over the case study area.

Landownership Category	Area (m^2)	% of the Case Study Area
Public	408,744	41.1
Public with restricted land uses	72,458	7.3
Private	509,595	51.2
Private for public uses	4425	0.4

3.2. Land Cover and Maintenance and Quality Analyses

Land Cover Analysis results are mapped in Figure 5 and summarised in Table 3. According to the identified land-use categories, soil is predominantly covered by buildings with both pitched and flat roofs (47.6%), followed by roads at 21.5%, and impervious surfaces at 20.3%, resulting in an impressive 89.4% of impervious soil over the total area. Very few permeable open spaces were detected, and they were often characterised by

small building inner courtyards. These limited permeable soils were represented by trees (4.8%) and herbaceous vegetation (2.7%), mainly found within abandoned open spaces and archaeological remains (0.9%). Excluding trees planted on impervious surfaces (1.5%) and ruins with vegetation (0.7%), the resulting permeable surface sums up to 8.4% of the total area.



Figure 5. Land cover map of the case study area. Source: authors.

Table 3. Distribution of land cover categories over the case study area.

Land Cover Category	Area (m^2)	% of the Case Study Area
Trees	48,145	4.8
Shrubs	0	0
Trees on impervious surface	14,615	1.5
Herbaceous vegetation	27,419	2.7
Bare soil	0	0
Buildings with pitched roofs	381,256	38.1
Buildings with flat roofs	95,601	9.5
Impervious surfaces	203,029	20.3
Ruins with vegetation	6760	0.7
Archaeological remains	9343	0.9
Roads	215,801	21.5

The results of Maintenance and Quality Analysis are mapped in Figure 6 and summarised in Table 4. The Maintenance and Quality Analysis identified monumental buildings (11.8%) characterised by high levels of architectural and historic values; ruined buildings that have been damaged and lost their original architectural features (1.4%); and abandoned or underused buildings and open spaces (3.6%), mainly consisting of hospital compounds often contiguous to smaller derelict residential buildings blocks. This includes some residential fabrics where small building units were built along the pre-existing road network, composed of narrow, winding, irregular streets and poor, cramped public spaces that have marked the urban landscape and inhabitants' living conditions for centuries. However, the majority of the case study area is still occupied by a remarkable 83.2% of regular residential building blocks.



Figure 6. Maintenance and Quality map of the case study area. Source: authors.

Table 4. Distribution of Maintenance and Quality categories over the case study area.

Maintenance and Quality Category	Area (m^2)	% of the Case Study Area
Monumental buildings	118,251	11.8
Abandoned or underused buildings and open spaces	36,311	3.6
Ruined buildings	13,540	1.4
Buildings with regular levels of maintenance and quality	830,620	83.2

3.3. Land Transformability and Land Transformation Scenarios Assessment

Among the nine potential combinations of max, med, and min values as prospected by the Transformation Scenarios Assessment, seven different pairs were found, which corresponded to three public and four private scenarios.

The NbS full installation scenario (Figure 7) covered 50.71% of the available land area to be transformed for NbS and 28.45% of the total study area, representing the most extensive public transformation scenario in the case study (Table 5).

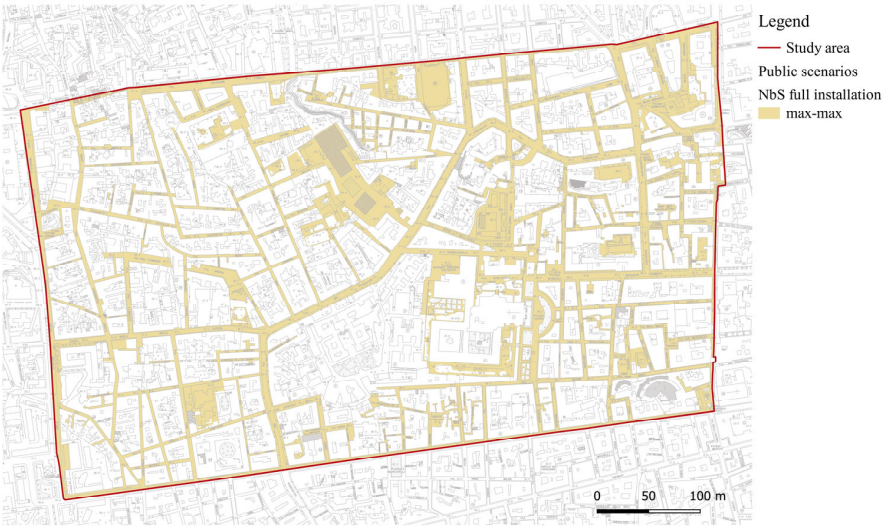


Figure 7. Public NbS full installation scenario (feasibility–suitability levels = max–max). Source: authors.

Table 5. Results of public and private scenarios.

	Scenario	Feasibility-Suitability Levels	Area (m^2)	% of the Available Land Area	% over the Case Study Area
public	NbS full installation	max–max	283,170	50.71	28.45
	NbS installation with some limitations	med–max	31,506	10.93	6.13
		max–med	22,737		
		med–med	6804		
	NbS installation after re-arrangement	max–min	4016	4.72	2.65
		med–min	22,346		
	Total		370,579	66.36	37.24
private	NbS installation with some limitations	med–max	3558	0.64	0.36
		med–med	0		
	NbS installation after re-arrangement	med–min	97	0.02	0.01
	NbS installation strongly limited	min–max	158,948	28.80	16.16
		min–med	1864		
	NbS installation not viable	min–min	23,377	4.19	2.35
	Total		187,844	33.64	18.88

The NbS installation with some limitations scenario covered 10.93% of the available land area to be transformed for NbS and 6.13% of the total study area (Table 5). It included public cultural heritage buildings and sites or land patches with restricted public land uses (Figure 8).



Figure 8. Public NbS installation with some limitations scenario (feasibility–suitability levels = med–max, max–med, med–med). Source: authors.

The third public scenario was NbS installation after re-arrangement (Figure 9), which covered 4.72% of the available land area to be transformed for NbS and 2.65% of the total study area (Table 5).

In total, the three public scenarios (Figure 10) covered 66.36% of the available land area to be transformed for NbS and 37.24% of the total study area (Table 5).

From the private side, the NbS installation with some limitations scenario (Figure 11) covered only 0.64% (four land patches) of the available land area to be transformed for NbS and 0.36% of the total study area (Table 5).



Figure 9. Public NbS installation after re-arrangement scenario (feasibility–suitability levels = max–min, med–min). Source: authors.



Figure 10. The three public scenarios: NbS full installation (feasibility–suitability levels = max–max), NbS installation with some limitations (feasibility–suitability levels = med–max, max–med, med–med), NbS installation after re-arrangement (feasibility–suitability levels = max–min, med–min). Source: authors.

In the NbS installation after re-arrangement scenario (Figure 12), only one combination occurred (feasibility-suitability = med-max), which covered 0.02% (only one land patch) of the available land area to be transformed for NbS and 0.01% of the total study area (Table 5), representing the least extensive private transformation scenario in the case study.

The NbS installation strongly limited scenario included all private residential uses (Figure 13). Two combinations of feasibility and suitability levels occurred in this scenario (min–max, min–med), which overall, covered 28.80% of the available land area to be transformed for NbS and 16.16% of the total study area (Table 5), representing the most extensive private transformation scenario in the case study.

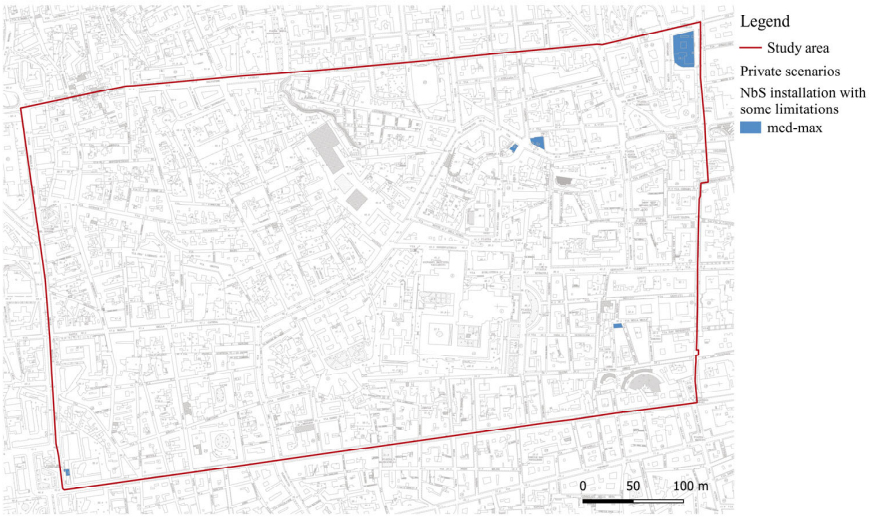


Figure 11. Private NbS installation with some limitations scenario (feasibility–suitability levels = med–max). Source: authors.



Figure 12. Private NbS installation after re-arrangement scenario (feasibility–suitability levels = med–min). Source: authors.



Figure 13. Private NbS installation strongly limited scenario (feasibility–suitability levels = min–max, min–med). Source: authors.

The NbS installation not viable scenario (Figure 14) covered 4.19% of the available land area to be transformed for NbS and 2.35% of the total study area (Table 5).

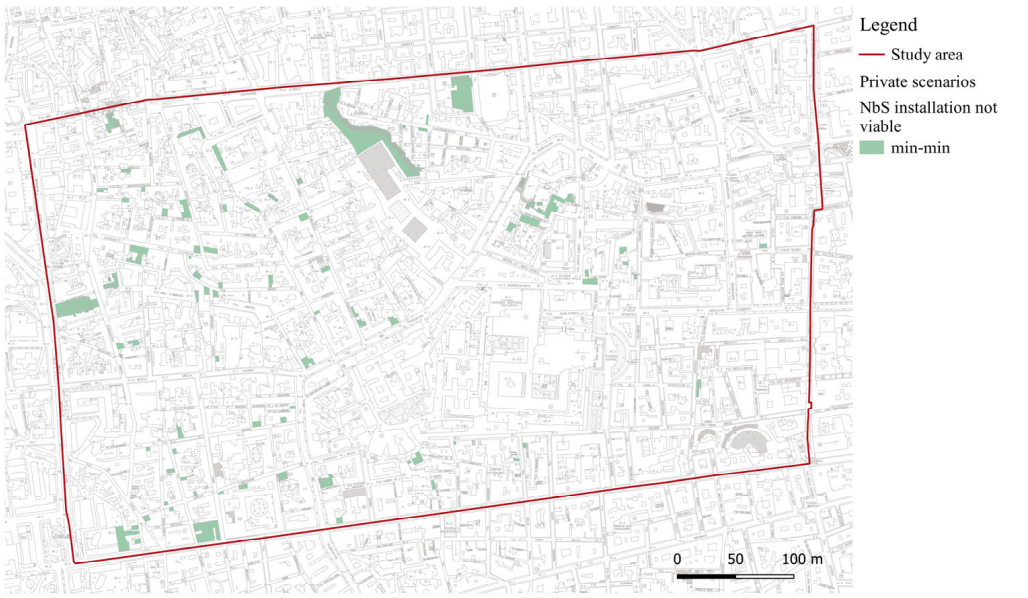


Figure 14. Private NbS installation not viable scenario (feasibility–suitability levels = min–min). Source: authors.

In total, the four private scenarios (Figure 15) summed up 33.64% of the available land area to be transformed for NbS and 18.88% of the total study area (Table 5).



Figure 15. The four private scenarios: NbS installation with some limitations scenario (feasibility–suitability levels = med–max), NbS installation after re-arrangement scenario (feasibility–suitability levels = med–min), NbS installation strongly limited scenario (feasibility–suitability levels = min–max, min–med), NbS installation not viable scenario (feasibility–suitability levels = min–min). Source: authors.

The final results of both public and private scenarios are summarised in Figure 16 and Table 5.

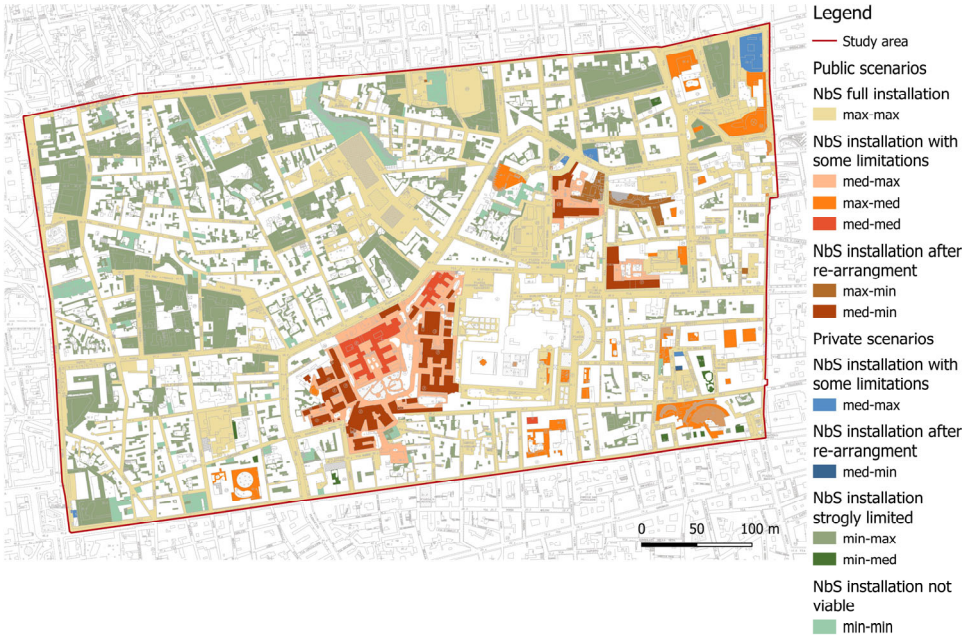


Figure 16. Public and private scenarios. Source: authors.

4. Discussion

4.1. Comments on Results

Integrating the objectives of adaptation to climate change risks and those of built heritage preservation should start from the recognition of the multiple identity values of historic centres, as well as the effective availability of land for introducing new NbS. To this aim, the study finally provided five Land Transformation Scenarios that showed different options for allocating NbS according to different levels of feasibility and suitability for actual implementation.

NbS full installation was considered the most feasible scenario because it involved only publicly owned buildings and open spaces such as buildings with flat roofs, impervious surfaces, roads, bare soils, and buildings and open spaces with regular levels of maintenance and quality. These land patches were also considered the most suitable urban components for hosting NbS and represented a surprising 50.71% of the available land (but only 28.45% over the case study area).

On the opposite side, two other scenarios focused on privately owned land, which represented the two most challenging options to be delivered. Indeed, NbS installation strongly limited scenario, despite providing a large availability of land (28.80%) for installing NbS, was described as the most unlikely to be undertaken. The NbS installation not viable scenario, involving those land patches characterised by under-use/abandonment and/or very low maintenance levels of private buildings and open spaces, was considered even null. This is because the residential buildings and related courts/backyards show a highly fragmented property asset, and, moreover, individual private landowners may lack the interest or economic incentive to implement NbS.

In between public and private, two further intermediate scenarios were proposed. Although providing a limited proportion of land (10.93%), the NbS installation with some limitations was the core scenario, focusing on the aptitude of public historic/cultural/architectural valued buildings and archaeological remains to host, even if limitedly, NbS which would result compatible with heritage preservation. This scenario also highlighted that public facilities with restricted land uses showed potential for limited NbS installation due to health, hygiene, safety, and security norms and regulations. Furthermore, the NbS installation with some limitations scenario included a very tiny 0.64% of

private buildings/open spaces for public uses, which appeared as slightly feasible for NbS development because landowners might be encouraged to intervene to value their own business. Similarly, the NbS installation after re-arrangement scenario showed that the under-use/abandonment and/or very low maintenance level buildings and open spaces could be targeted as feasible both for public and private for public use, the latter as an opportunity to add value to the property. From the side of suitability, this scenario even envisaged the demolition of public/private ruined, abandoned, or underused buildings to make room for new NbS, which could contribute up to 4.74% of the total available area for NbS.

Even if the results of the proposed methodology finally showed a considerable two-thirds of public-owned land (66.34%) suitable to fully accommodate NbS, some adjustments to this figure are necessary. Firstly, this percentage drops to 37.24% if the entire study area is considered. Indeed, the methodology was based on the preventive exclusion of land patches that were already equipped with greenery and/or did not allow the definite addition of new greenery (i.e., buildings with pitched roofs). However, one of the most relevant contributions to the public components was provided by roads and courts/backyards of public buildings, which are not totally available to accommodate NbS. Following the results of a local study carried out in a relevant part of the historic centre of Catania [46], it could be estimated that only 20% of road surfaces and 40% of courts/backyards could be finally available for transformation according to the NbS approach. Indeed, the former circumstance would minimise difficulties in managing the vehicular traffic flow and the related local circulation plan due to the shrinking in road width, while the latter would guarantee the usability of public courts/backyards, which already have specific land uses that may not be compatible with NbS. Excluding this number of open spaces would imply a significant drop in the public land proportion from 37.24% to 26.10%. Moreover, it is necessary to highlight that 11.34% of those public patches were represented by public built heritage, which constituted a very sensitive portion of the urban fabric, and by ruined or abandoned/underused buildings to be re-arranged and/or demolished. The exclusion of these two other components of the urban fabric would lead to a final public land of 14.71%. On the other side, privately owned patches covered an important one-third (33.64%) of suitable land area, which should be reviewed as (100 − 14.71)% = 85.29% of land potentially available to accommodate new NbS but severely limited in terms of real transformation feasibility. In quantitative terms, this new proportion of private buildings and open spaces would represent the majority of the transformable land and an effective opportunity to compensate for the limitations coming from the public building stock. In particular, this alternative availability of room for NbS introduction could lead to a reduction in pressure on the public cultural heritage, avoiding the need to include NbS on protected buildings and sites at any cost.

4.2. Incentives-Based Policies to Support NbS Integration in Private Property

When planning to introduce NbS within urban fabrics, the identification of land tenure is crucial for assessing the actual feasibility of any transformation [47]. When operating in a public context, less negotiation with stakeholders is needed due to an implicit consensus at the political level upon the implementation of specific strategies, whilst action involving privately owned land must be undertaken primarily according to market-based conveniences [48]. Indeed, despite their high level of suitability to host NbS, these urban components face considerable resistance to being transformed due to the relevant limitations posed by the extreme private property fragmentation and the very weak economic conveniences for private landowners to undertake such solutions. These two conditions would block any effective possibility of carrying out transformations aimed

at the introduction of NbS, particularly in the NbS installation strongly limited scenario and the NbS installation not viable scenario. On the other hand, it is arguable that the very reduced contribution of cultural heritage land parcels (as envisaged in the *Nbs installation with some limitations scenario*) would result in the insignificant mitigation of heatwaves and urban pluvial floods risks, while possibly incurring significant economic and social costs due to the potential alteration of cultural heritage. Thus, fostering the inclusion of NbS in private historic urban fabrics is crucial for aspiring to balance adaptation measures through NbS and built heritage preservation. More specifically, the NbS installation strongly limited scenario would allow for an evenly spread NbS within the residential stock, whilst the re-arrangement and demolition options (as delineated in the NbS installation not viable scenario) would provide new supplementary room for NbS in the framework of wider spatial transformations. Therefore, pushing towards the development of these two private-based scenarios, the pressure on the NbS installation with some limitations scenario (which focuses on the installation of NbS on culture heritage buildings and open spaces) could be eased to favour more sensitive and careful protection of cultural heritage.

In order to overcome the effective unwillingness of private landowners to deliver NbS in their own property, due to the additional costs to be faced, a large number of incentives-based policies have been developed and implemented in recent decades [49]. One of the soundest incentive tools is represented by preferential tax treatments, which include tax incentives such as tax rebates, tax credits, and tax allowances for properties with green roofs or other NbS [50]. The most widely used strategies include lowering or eliminating planning fees in return for incorporating NbS into development projects [51]; providing discounts for the presence of stormwater source controls like green roofs [52]; lowering permit or building–construction-related fees for developers incorporating NbS like green roofs [53]; and providing stormwater fee rebates based on the percentage of impervious area or the presence of nature-based stormwater management measures (on buildings or the ground) on the property [54]. The provision of direct or indirect subsidies and grants typifies other forms of incentives-based approaches targeting existing and new buildings [55]. Direct subsidies and grant programmes are implemented to promote the installation of green roofs or other nature-based stormwater management measures, nature-based watershed restoration activities, and tree planting on private property [56]. Grant payments may be allocated to property owners who safeguard and manage their areas to maintain ecosystem services—commonly known as payments for ecosystem services schemes [57]. As indirect subsidies, an interesting solution is represented by the reduction of interest rates for loans sought to finance new construction/renovation projects for developers/owners installing green roofs or other greenery [58]. Finally, fast-tracking, expedited, or agile processes for approving projects and licensing building permits, also aimed at renovating existing residential units, can be used as a non-financial incentive to stimulate NbS integration and open space provision in urban transformation for incorporating urban greenery features in buildings and open spaces.

It is worth noting that the viability of these incentive-based policies can be seriously affected by the context-specific features of cities where those recommendations would be applied. When discussing the Catania case study, it is important to emphasise that the municipality has traditionally lacked both financial and human resources, which are necessary not only for addressing climate change responses but also for implementing public transformation projects. Promoting the integration of NbS through lowering or eliminating planning fees or permit building–construction-related fees and/or providing discounts/fee rebates would imply giving up the basic financial incomes that are needed for managing the fundamental urban policies. In such a context, instead of these unaffordable measures for the local administration, fast-tracking, expedited, or agile processes for

approving projects and licensing building permits could be more viable, as well as grant payments and the reduction of interest rates for loans, which should be provided by the national government.

4.3. Limitations and Further Research Insights

Although the proposed methodology provided an innovative conceptual framework to support decision-makers when dealing with NbS and cultural heritage, it presents some limitations. The case study focuses on a portion of around 1 km^2 of the historic centre of Catania, which is characterised by site-specific features in terms of artistic, architectural, construction, and functional values that may differ from other contexts in the world, in Europe, and even in Italy. Thus, the geographic location could affect the results of this methodology, basically because the criteria for selecting land patches potentially suitable for hosting NbS may not be adequate for every type of historic urban fabric. This would imply, for example, the need to replace categories such as buildings with flat or pitched roofs, impervious surfaces, archaeological sites, bare soils, and roads with others that are more appropriate to the specific local context. Another important limitation of the methodology lies in the lack of investigation on building envelopes. Indeed, the Land Transformability Assessment and the Land Transformation Scenarios Assessment were carried out only taking into account the horizontal urban surfaces (building roofs and open spaces). As a result, building facades were excluded from the calculation, despite providing effective options to install adaptable NbS. This is the case with green walls, living walls, green coats and curtains, pergolas, and hanging gardens, which could be installed on both blind and open envelopes [59,60].

In order to overcome all these methodological limitations, more differentiated case studies could be compared and analysed through a random sampling approach for selecting a larger number of sample cells to study. This would definitely provide more robust and statistically sound results. Moreover, a supplementary assessment should be developed for estimating the envelope surfaces corresponding to each building roof, thereby expanding the availability of space to introduce NbS within the historic urban fabric. Finally, extending the study to the investigation and selection of the most adjustable NbS for built heritage represents a future step in this research. This could be the way to implement a more effective and far-reaching planning tool for identifying proper and site-specific strategies to balance NbS implementation with built heritage preservation.

The development of such a methodology does not require a significant amount of work to gather and process data. However, local decision-makers should work closely together with urban planners to build datasets, define goals, and explore scenarios within the context of an accurate local spatial plan. Attaining this methodology as a standard urban planning procedure would make it convenient in the long run from both a financial and human resources point of view.

5. Conclusions

Historic centres are emerging on the contemporary urban scene, showing their fragilities mainly due to the challenges posed by the effects of climate change, such as urban heat islands and pluvial floods. Therefore, regenerating historic centres through strategies for climate change adaptation, urban risk mitigation, and built heritage preservation represents a challenge as ambitious as it is necessary—one that can guarantee higher levels of quality, safety, and livability.

Despite their importance and effectiveness, the integration of both built heritage preservation and the implementation of NbS in cities remains controversial, with natural conflicts emerging between these two apparently opposing practices. On one hand, preservation

policies and programmes impose several constraints on cultural heritage sites; on the other hand, the inclusion of nature in the city is widely considered to have significant impacts on built heritage, mainly due to biodeterioration, loss of cultural values, and challenges in management and protection. In order to overcome the conflicting objectives of climate change adaptation and mitigation versus built heritage conservation, this study explored challenges and opportunities for integrating NbS and built heritage preservation in historic cities for mutual benefits. This was carried out by searching the most feasible and suitable buildings and open spaces, distinguishing between public and private properties to implement a more comprehensive and effective NbS. To this aim, five scenarios explored the effective feasibility and suitability of land for introducing new NbS into the historic centre of Catania, which was characterised by a severe lack of public open spaces and a mix of public and private land tenure. Notwithstanding the fact that results showed a considerable amount of publicly owned land (more than 66%) suitable to fully accommodate NbS, the final 85% of the total land that could be effectively used for new NbS was made up of private buildings and open spaces. This share represents a good opportunity to lessen the strain on public cultural heritage by avoiding the need to install NbS on protected buildings and sites at all costs [28]. The study also showed that adopting NbS in such contexts could become viable by encouraging private landowners to intervene on their own properties, by means of tailored incentive-based policies. This would foster a wider implementation and a more equitable distribution of NbS, while easing the pressure on public culture heritage [61,62]. In particular, delivering fast-tracking and agile processes for licensing building permits, as well as providing grant payments and reduction of interest rates on loans, would be financially viable procedures for local governments with limited funding to encourage private parties to step in.

Swinging between preservation and innovation, this work pursues to fill the current literature gap on the topic of integrating built heritage preservation with the implementation of NbS in historic cities. It proposes a novel methodology based on the concepts of suitability and feasibility for NbS accommodation in specific public and private buildings and spaces. In doing so, it provides an innovative perspective for activating a new life cycle of historic centres— one compatible with the history and cultural values of these settlements—while redefining their role in a more livable, valuable, and safer contemporary city.

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