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A Uniform Framework for Climate Change Adaptation of Critical Infrastructure Using Nature-Based Solutions

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Abstract

With climate change expected to intensify hazards across Europe, empowering communities and strengthening local adaptation is urgent. The challenge is bolstering the resilience of critical infrastructure (CI), which faces substantial risks. Transitioning from predominantly "grey" infrastructure to integrated "green-grey" solutions provides an effective way to safeguard societal and infrastructural assets against hazards and environmental degradation. Although several frameworks developed by international networks and regional authorities exist, they often fail to fully address the nuanced challenges of CI climate proofing, disaster risk reduction, and biodiversity protection. In response to these limitations and to address key societal challenges, the work here introduces an innovative, integrative blueprint framework. This framework synthesises existing approaches to CI climate adaptation, systematically strengthening resilience with nature-based solutions (NBS). The framework is partially applied and validated through the Public-Private-Civil Partnership (PPCP®) approach, and operationalised in two climatically distinct but heatwave-prone regions: Egaleo (Greece) and Helsinki (Finland). These Labs have promoted more inclusive policymaking by supporting collaboration among key stakeholders, encouraging knowledge sharing and co-designing strategies to advance NBS implementation for heatwave mitigation. The approach facilitated the design of interconnected activities and simplified technical details. Adapting methods to local needs, such as site visits and participatory mapping, has led to concrete outcomes. The prefeasibility analysis outcomes and the targeted NBS-based strategies identified from these areas ensure that solutions are culturally relevant, technically feasible, and collectively owned, incorporating local knowledge and fostering long-term sustainability.

Keywords: climate change adaptation; critical infrastructure; nature-based solutions; public-private-civil society partnership; resilience

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Academic Editors: Alfred Strauss, Rosemarie Stangl, Johannes Hübl and Mosbeh R. Kaloop

Received: 11 December 2025
Revised: 30 January 2026
Accepted: 4 February 2026
Published: 13 February 2026

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1. Introduction

According to the European Climate Risk Assessment (EUCRA) report [1], climate change is associated with more frequent and intense extreme weather events, such as

heatwaves, droughts, heavy rains, and cold extremes. These are expected to increase the risks to Europe's built environment, infrastructure, and critical services, including energy, water, transport, and communication. Infrastructures operate within a dynamic, rapidly changing operational environment and risk landscape that involves complex, compounded natural hazards, often worsened by climate change, hybrid threats, man-made threats, pandemics, and industrial accidents. Climate-related hazards may affect the lifespan and efficiency of critical infrastructures (CIs) or even lead to their destruction. According to [2], CI "refers to the systems, facilities and assets that are vital for the functioning of society and the economy. These infrastructures are considered essential because their disruption would affect public safety, security, health, and economic stability. Critical infrastructure includes both physical and virtual components that are interconnected and interdependent." Data from the UN-DRR report [3] indicated that more than 1500 EU and Central Asian assets were affected by disasters each year, leading to persistent failures or total damage to CI. According to the World Bank [4], low- and middle-income countries incur annual infrastructure disruption costs from US$391 billion to US$647 billion. Other estimates of economic losses from infrastructures and buildings range from US$732 billion to US$845 billion annually, with two-thirds attributed to climate change-induced extreme events according to the Coalition for Disaster Resilient Infrastructure (CDRI) [5]. Meanwhile, the Global Commission on Adaptation [6] has stated that investing x€ in climate risk-reduction initiatives could prevent 4x€ in future losses.

The Mediterranean region is predominantly vulnerable to the effects of warming, especially prolonged and more intense heatwaves, increased drought in an already dry climate, and the rising risk of coastal flooding [7]. Significant risks are associated with the most sensitive CI components in the Mediterranean region, particularly those involved in energy production, transmission, and demand, as well as in transportation, marine, and water management sectors. These risks could weaken efforts toward the green transition, affect regional climate resilience, and therefore create an urgent need for adaptation [8].

Infrastructures, networks, operators, public entities, and citizens are becoming more interconnected, requiring systemic transformative changes and new ways of thinking to implement climate change adaptation (CCA) and enhance their resilience and robustness [9]. As climate-proof CI becomes essential, this should equally focus on (a) maintaining "normal/daily" uninterruptible service delivery, including managing time, usage, and obsolescence to withstand environmental impacts, such as the slow onset effects of climate change, and (b) mitigating "extreme/abnormal" pressures, like climate extremes. Indeed, local governments are beginning to tackle the challenge of local adaptation and are often supported and encouraged by external assistance, such as that offered by international networks and initiatives [10,11] or regional-level authorities [12,13].

To increase local CCA efforts and foster resilient, carbon-neutral European societies and community empowerment [14], more transformative adaptation solutions must be implemented in CI; these are the backbone systems that can ensure the sustainable delivery of services such as water, telecommunications, and transportation, as well as help safeguard food and energy security.

A viable way forward is to systematise CI resilience through nature-based solutions (NBS) as innovative, cost-effective opportunities for sustainability and resilience [15,16]. According to IUCN [17], NBS are defined as "actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits." NBS are regarded as a comprehensive framework for ecosystem-based approaches to tackle major societal challenges [18,19]. NBS can significantly contribute to reducing greenhouse gas emissions, boosting carbon sequestration, and lessening vulnerability to climate

change [20,21]. Therefore, NBS can play a crucial role in mitigating and adapting to climate change. Additionally, they can be incorporated into the built environment and infrastructures, helping to protect CI from climate change-related hazards and environmental damage [22]. Therefore, NBS can be strategically used to safeguard CI assets and services against various hazards and the short- to long-term impacts of climate change. It is well-established that NBS can provide multiple external benefits, such as generating income for local communities that rely on these resources for their health and well-being. From investing in the restoration of degraded lands and shorelines to optimising the performance of traditional infrastructure, extensive evidence demonstrates that nature plays a vital role in meeting societal needs [23]. In general, NBS are based on the understanding that healthy, comprehensive ecosystems provide a broad spectrum of benefits vital to resilient, sustainable infrastructure and improved urban liveability [24].

Efforts to develop principles, standards, or guidelines for global ecosystem management initiatives under NBS are ongoing and significant. Within the EU research area, a number of projects have studied climate-resilient infrastructures with differences from the present context. Examples include RAIN (GA608166), INTACT (GA608166), RESIN (GA653522), RISKADAPT (GA101093939), and MIRACA (GA101093854), which focused on the resilience of interconnected critical infrastructures to climate change and weather extremes using decision support systems and modelling tools without specific attention to NBS and their real-world implementation. NBS4INFRA (GA101121210) aimed to demonstrate future-proofing and secure infrastructure through real-world applications of nature-based solutions without addressing the challenges of the Mediterranean climate. The study by [25] highlighted that currently China's NBS practices emphasise integrating productivity gains and embedding solutions into policy frameworks. Public engagement with NBS has remained low, so localised community-driven projects were recommended to increase participation. The work by [26] similarly proposed that China should develop a unified policy and practical system to link stakeholders, encourage sustainable financing, and empower vulnerable groups to mainstream NBS nationwide. Furthermore, ref. [27] noted that given rising concerns about water security and climate change in North America, there is a growing need for complex, multi-stakeholder collaborations and better integration of NBS into water infrastructure through updated policies and practices.

By combining the "green" elements of nature-based solutions with "grey" engineering, communities can maximise the benefits of both approaches while minimising individual constraints. Through design or thought-adaptive transformation, the integration of NBS into grey infrastructures—also known as "green-grey" infrastructures—serves as a hybrid solution that benefits both infrastructure and society by, among other things, cooling urban areas and reducing the impact of climate-induced disasters [28]. For NBS to become mainstream, several obstacles must be addressed, such as (i) the lack of space for interventions, particularly in urban areas; (ii) the relatively longer time it takes NBS for their efficacy to be demonstrated compared to grey infrastructures; (iii) cost-effectiveness compared to engineered solutions; (iv) resilience to climate change; (vi) performance variability; and (vii) the often complex ownership conditions. An additional challenge could be the inherent uncertainty surrounding land use, soil, climate, and hydrologic conditions. Other challenges related to governance and financial decisions may hinder systematic funding, stakeholder support for NBS implementation at scale, and awareness of the value of NBS among authorities [29].

Although several CCA initiatives exploiting NBS are ongoing at all levels, there is an inconsistent understanding in the true urgency of their implementation; recent extensive destructions in the Mediterranean serve as a stark reminder [30,31]. There is a planning gap that fails to consider real local needs and align with the vulnerable environment. External

pressures, such as tourism, migration, and local circularity, are often overlooked in CI planning, and grey CI remains the standard.

This paper presents part of the work under the EU-funded Med-IREN (Mediterranean Critical Infrastructure Resilience Engineering with Nature-Based Solutions) project, which aims to demonstrate how to climate-proof the Mediterranean CI using NBS across vital sectors, such as energy, transportation, information and communication technology (ICT), water, and social services. These sectors are involved with the Med-IREN demonstrations because they are essential to society's smooth, uninterrupted functioning in a climate "hot-spot" area. It is crucial to extend the positive effects of NBS beyond just CI by protecting local biodiversity and ecosystems, promoting local circularity, and reducing disaster risks to foster digital and green transition and enhance social well-being alongside infrastructure resilience. Therefore, the project seeks to showcase an innovative and comprehensive approach for the transformative adaptation of Mediterranean resilient CI. Essentially, it aims for a more systemic, faster, and smarter adaptation of Mediterranean infrastructure through strategies such as multi-stakeholder partnerships, local action, innovative NBS, climate hazards analytics, improved risk assessment, and tools to support the design of suitable adaptation measures and the evaluation of NBS effectiveness.

Introducing NBS to enhance climate risk management and ensure business continuity amid climate change and extreme weather events remains a key innovative objective of Med-IREN. Climate hazards such as heatwaves, droughts, heavy rainfall, floods, coastal erosion, and wildfires have been identified as priority climate pressures in the study. Another vital goal has been to demonstrate how essential enabling conditions, such as participatory governance, Public-Private-Civil Partnership (PPCP®) approach, citizen engagement, innovative financing methods, multi-dimensional urban and landscape planning, and capacity-building activities, can support the implementation, scaling, and replication of solutions within Mediterranean regions and beyond. Using Life Cycle Assessment (LCA) and Circularity concepts, the investigation adopted a holistic approach to climate proofing the Mediterranean by applying an end-to-end process that included initial design, feasibility assessment, greening of grey infrastructures, operation and maintenance, and carbon footprint reduction. These activities required comprehensive climate assessments, the calculation of relevant CI indicators, and the use of dedicated structural, operational, and demand/supply thresholds to evaluate exposure to climate change. Additionally, identifying local and regional vulnerabilities is crucial for effectively mitigating climate risks and the impacts of CI when deploying NBS-driven solutions. Along these lines, the project will pilot several Mediterranean regions, utilising NBS, digital tools, procedural innovations, and capacity-building initiatives to generate evidence-based support for the widespread adoption of systemic adaptation strategies.

In light of the aforementioned, this work focuses on developing a novel, unified methodology that combines the innovative PPCP® approach, developed by ARTELIA within the C2IMPRESS project [32], with established methods from the CI community (Critical Entities Resilience Directive 2557/2022 [33] & EU Climate Proofing Tools [34]), NBS-driven approaches (IUCN Global Standard), and practices from the climate change adaptation domain (Climate-Adapt RAST, ISO 14090 [35]). Nine regions have been selected as demonstrator and replicator case study areas, each confronting real-world challenges with the goal of rapidly strengthening regional resilience through transformative adaptation. Due to space constraints, this paper presents the blueprint developed for implementing the Med-IREN methodology specifically in the prefeasibility studies of two regions. According to the methodology, a prefeasibility study for the chosen regions was created through a co-production process based on a multi-stakeholder partnership (PPCP®) approach which promoted societal cohesion and enhances resilience [36]. Section 2 presents the relevant,

existing frameworks. Section 3 details the synthesis of NBS, CI, and CCA frameworks. Section 4 describes the methodology for creating a unified framework and its application to the study regions. Section 5 illustrates the implementation of the PPCP® approach in the project demonstrator (D) and replicator (R) regions of the cities of Egaleo (Greece) and Helsinki (Finland), respectively. Finally, the conclusions are presented in Section 5.

2. Materials and Methods

This section presents relevant climate adaptation frameworks developed independently from the context of NBS-CI communities. It illustrates how these activities could serve as the basis for the Med-IREN methodological framework at each implementation stage and characterises the assessed frameworks. Presenting these frameworks helps to identify potential gaps that can be addressed within the Med-IREN blueprint, as none of the existing frameworks have the holistic capacity to encompass the diverse and complex challenges Med-IREN aims to address. Additionally, various CCA, DRR, and climate resilience frameworks demonstrate the approach's context-specificity and flexibility.

2.1. Pertinent Frameworks

2.1.1. Regional Adaptation Support Tool—RAST

The Regional Adaptation Support Tool (RAST), available from the EU Mission on Adaptation to Climate Change platform [33], is made flexible and iterative to support local and regional authorities in implementing CCA plans and tangible interventions. Subnational policymakers can utilise the tool to gradually develop, implement, monitor, and evaluate climate strategies and plans by following a structured process. RAST also aims to highlight essential issues in regional policymaking by addressing barriers to adaptation. The tool provides generic and easily adaptable practical guidance in six (6) clear steps, aligned with the main features of climate adaptation policies and processes. These steps, as outlined in the platform, are: (1) preparing the ground for adaptation; (2) assessing climate change risks and vulnerabilities; (3) identifying adaptation options, (4) evaluating adaptation options; (5) implementing adaptation; and (6) monitoring and evaluating adaptation. RAST is presently being updated and improved by several tools developed or being developed under the ARSINOE, IMPETUS, REGILIENCE, and TransformAr projects of the EU Climate Adaptation Mission [34]. Furthermore, RAST has been employed to support the CLIMAAX framework [37] which aims to enhance climate adaptation and emergency risk management plans in a coordinated manner across European regions. Additionally, the tool has been utilised in case studies, such as those of Italian areas that adopted a multi-stakeholder and multi-level approach (e.g., [38,39]), which have recognised the need for formal adaptation policies to support changes at the local level and achieve climate neutrality and resilience at the regional level and beyond.

Monitoring and assessing adaptation efforts at the regional level requires a multi-layered approach due to the diverse impacts across sectors such as infrastructures, communities, ecosystems, and others [34]. Often, such a risk-based adaptation planning approach does not adequately consider other policy objectives, such as climate mitigation and sustainable development [40]. In fact, according to the IPCC WGII Sixth Assessment Report [41], climate-resilient development must include climate adaptation and greenhouse gas mitigation actions to support sustainable development for society and the environment effectively.

2.1.2. IUCN—Global Standard for Nature-Based Solutions

The urgent need for adaptation through NBS has often led to its misuse, such as the introduction of non-native species that disrupt local ecosystems [42,43]. This has highlighted

the need to establish guidelines and recommendations for the proper and non-threatening implementation of NBS, involving collaborations with regional practitioners to conserve biodiversity and offer sustainable benefits. The International Union for Conservation of Nature (IUCN) has developed the Global Standard for nature-based solutions [17] as an accessible framework that can be easily understood by a wide range of users, particularly those without conservation expertise. The framework recognises nature's ability to supply ecosystem services, assists in designing and implementing effective and sustainable NBS, and sets precise standards to measure the progress NBS provide. The Standard features several important qualities that provide a strong foundation for developing and evaluating NBS, serving as a valuable guide for customising NBS to address diverse societal challenges with tools and criteria to verify their impact. It is also worth noting that the Standard is regularly updated under the auspices of IUCN. Comprising eight (8) criteria and twenty-eight (28) indicators with guiding questions, the Standard helps users evaluate and improve their solutions. The eight criteria that constitute the IUCN Global Standard for NBS are interconnected. Additionally, a scoring system for each indicator can serve as a self-assessment tool to evaluate the effectiveness of interventions. Although not intended for certification, it identifies strategies to enhance interventions and better meet NBS standards [44].

The Standard has been applied in several cases for adaptation across various sectors such as urban, agroforestry, riverside, coastal, and marine environments (e.g., [45–48]). A comparison of the Standard with 29 other frameworks for NBS interventions aimed at reducing riverine flood risk has revealed that the Standard can serve as a comprehensive assessment framework due to its broad applicability [49]. Furthermore, the same study concluded that the IUCN Standard can be used to evaluate procedures such as adaptive management and stakeholder engagement in a wide range of environmental contexts and societal issues, including planned, ongoing, or completed NBS projects.

2.1.3. Critical Entities Resilience Directive

The Critical Entities Resilience (CER) Directive was introduced in response to the increasing frequency of threats to critical infrastructures, such as cyberattacks and natural disasters caused by climate change, as well as the growing need for bilateral cooperation and information sharing among sectors and stakeholders. CER came into force in January 2023 and had to be incorporated into national legislation by EU member states by October 2024 [50], replacing the European Critical Infrastructure Directive [51] and harmonising their resilience strategies. CER has established a comprehensive framework to ensure that member states develop a national strategy to improve the resilience of critical entities across the eleven (11) sectors covered in the Directive [52]. Critical entities are essential for maintaining vital services and preventing disruptions that impact public health, safety, the economy, and the environment. The main objectives of the framework include evaluating resilience and implementing risk mitigation measures to safeguard critical entities from potential hazards, improving risk assessment abilities by predicting emerging risks, and strengthening cooperation across sectors and borders among these entities [53].

2.1.4. EC Technical Guidance for the Climate Proofing of CI

The purpose of the EC Technical Guidance on the climate proofing of CI is to protect future infrastructure projects and investments from the effects of climate change, enabling well-informed decisions that align with the Paris Agreement and the EU's climate targets [54]. Specifically, the document provides guidance on incorporating adaptation and mitigation strategies and considering climate change risks into Environmental Impact Assessments (EIAs). This guidance is intended to facilitate screening and detailed analysis

when constructing or refurbishing new or existing infrastructures, creating a future that is both climate-neutral and climate-resilient.

The document guidelines clearly specify that any infrastructure project expected to extend beyond 2050 must be operated, maintained, and eventually decommissioned in a climate-neutral manner. This may involve considering circular-economy principles, such as recycling or repurposing materials. A climate risk assessment should be conducted to identify suitable adaptation measures to ensure the climate resilience of new CI projects. NBS are among the potential adaptation options and are defined in the Technical Guidance as "Nature-Based Infrastructures" (NBIs), which include elements such as sustainable drainage systems, green walls, green roofs, and natural open spaces.

2.1.5. ISO 14090—Adaptation to Climate Change

ISO 14090, introduced in 2019, is the international standard that explains how organisations of any size and type can incorporate climate adaptation. The document also provides guidance to help organisations recognise the impacts and uncertainties of climate change, enabling them to make well-informed decisions and plan for adaptation. ISO 14090 focuses on environmental management for short-, medium-, and long-term climate change adaptation efforts. It considers the timescales of potential adaptation measures and assesses adaptation options over the lifespan of these effects. Additionally, it highlights indicators that can monitor the organisation's capacity for adaptation as it develops over time and the evolution of its climate impacts.

2.2. The Med-IREN Approach

2.2.1. NBS-CI-CCA Framework Synthesis

The various NBS-CI-CCA frameworks presented in Section 2.1 each offer valuable guidance for implementing solutions within specific areas of interest. However, none of these approaches fully address the complexity and diversity of the challenges Med-IREN targets in its transformative adaptation of resilient critical infrastructures. Thus, there is a need to develop a unified CCA/CCM approach that enables comprehensive assessment, incorporates external and long-term impacts, and aligns with local, national, and EU CCA plans.

Efforts have therefore been directed toward developing a new framework to enhance the climate resilience of CI through nature-based solutions using RAST as a foundational tool. This flexible support tool can be customised to address specific requirements and integrate inputs from other tools and frameworks. Additional frameworks can be incorporated modularly, enabling the detailed representation of interconnected CCA challenges faced by specific NBS-CI communities.

The primary objective is to demonstrate effective strategies for enhancing the climate resilience of Mediterranean infrastructures in response to climate change and extreme weather events. Implementing comprehensive, functional NBS will improve infrastructure performance and generate a wide range of benefits. By integrating the ecological advantages of NBS with the structural strengths of traditional engineering, communities can optimise outcomes and mitigate limitations. The resilience of both infrastructures and communities is expected to increase when NBS are incorporated into grey infrastructures through innovative design, planning, or adaptive transformation. However, several challenges remain, including restricted intervention areas in urban environments, the extended time required for NBS to achieve full effectiveness compared to conventional grey solutions, variability in NBS performance, and complex ownership structures.

2.2.2. Methodology, Desktop Review, and Workshop

The main activities outlined in Figure 1 form the pathway towards the development of the Med-IREN blueprint document.



Figure 1. Methodology process.

For the synthesis of the NBS-CI-CCA framework, the consortium initially reviewed the various NBS-CI-CCA frameworks and their connections to the project tasks in detail, using the RAST framework as a reference as previously discussed. A workshop was held on 15–16 October 2024 in the Municipality of Egaleo, Attica, Greece. It facilitated discussions between representatives of the paired D/R regions, Egaleo and Helsinki, focusing on their shared climate adaptation strategies and NBS for implementation and replication. As part of the technical work, available data and information were collected and documented, along with any potential common issues related to NBS implementation and data gaps that could affect the project's progress. The data and information collected were organised into six activities, ensuring a well-structured preparatory phase (prefeasibility) assessment and paving the way for detailed planning, implementation, and validation, as shown in Table 1 and described below.

Table 1. Implementation activities.

Number	Categories
I.	Stakeholder Identification and Engagement Process
II.	Baseline framework assessment
III.	Co-design of a new framework
IV.	Key Performance Indicators (KPI) selection for NBS implementation
V.	Existing datasets and monitoring networks (of relevance to Med-IREN)
VI.	Validation

I. Stakeholder Identification and Engagement Process

The first activity involved collecting information and data on the NBS considered in the D/R regions. Participants suggested innovative solutions to mitigate the impacts of climate change and enhance the built environment and social infrastructure. A key task was to identify potential stakeholders to participate in the PPCP® and plan the engagement process while accounting for challenges that may arise during involvement.

II. Baseline framework assessment

The baseline assessment was the second activity and encompassed data on datasets, monitoring networks, and indicators currently established in the selected regions. These components pertained to the criticality of CI assets, climate patterns and extreme events, CI exposure to climate hazards, climate risks, CI resilience evaluation, NBS potential, biodiversity and ecosystems, political and socioeconomic conditions, community resilience, and carbon footprints.

III. Co-design of a new framework

The co-design of the demonstration (D) region was then followed by an initial overview and strategy for implementing the NBS. A preliminary summary highlighted the design aspects: (1) the local policy and regulation environment; (2) the deployment of the Lab concept combined with multi-stakeholder coordination; (3) the development of monitoring

networks and procedures; (4) evaluation protocols; (5) "NBS-by-design"; (6) upgrading into green Cl; (7) identifying key enablers for implementation; (8) the functionality of digital solutions; and (9) interpretation of the results.

IV. KPI selection for NBS implementation

This activity involved developing and selecting the most appropriate KPI for each region, along with relevant implementation guidelines for measuring Med-IREN's success. The lessons learned from previous projects also helped guide the selection of KPI to evaluate outcomes. Examples of these included (1) guidelines for designing and implementing NBS; (2) procurement procedures; (3) multi-stakeholder partnerships and community engagement; (4) assessing enabling conditions; and (5) local communication and awareness-raising initiatives. The application of the selected tools will be validated using locally collected data and through the selected KPI.

V. Existing datasets and monitoring networks

Another activity involved identifying and selecting existing datasets and monitoring networks relevant to Med-IREN (monitoring stations, Copernicus Climate Service, Municipal GIS, Digital Twins, etc.). During this process, it was crucial to consider all relevant access policies associated with the datasets.

VI. Validation

The final activity involved validating the methodological approach through PPCP workshops.

3. Results

3.1. The Framework

Aligned with the principles of the EU Climate Adaptation Strategy, the Med-IREN project will address specific challenges by showcasing solutions in the D/R regions. It aims to illustrate how to improve the climate resilience of Mediterranean infrastructures against climate change and extreme weather events by implementing comprehensive and effective NBS, as described in the following section.

3.1.1. Med-IREN Nature-Based Solutions

1. More Systemic Adaptation in Mediterranean Infrastructures
    - PPCP®: Multi-stakeholder Partnerships and Coordination

ARTELIA has developed an inclusive and participatory approach to strengthen stakeholder involvement across the public, private, and civil society sectors in disaster risk management and climate change resilience [55]. The PPCP® approach is structured around two main pillars. First, a tripartite engagement that ensures authorities, private actors, and civil society organisations all play active roles. Second, it relies on regularly organised PPCP® Lab workshops for dialogue, collaboration, and co-creation. Alongside these core principles, the approach values simple and accessible participatory tools, iterative learning, and inclusive practices that enabled every participant to contribute meaningfully. PPCP® can support the co-creation and realisation of NBS for territorial climate resilience. It seeks to foster meaningful collaboration among public authorities, private sector actors, and civil society stakeholders, recognising that resilient solutions depend on shared knowledge, responsibilities, and long-term alliances. The following diagram (Figure 2) illustrates the interactions among the three main sectors at the core of PPCP® and the types of partnerships it can establish.



Figure 2. Typology of collaborative partnerships in PPCP®. Grey color is the interaction of all colors which represents "the PPCP®".

At its core, the PPCP® is driven by co-creation: it fosters spaces for diverse actors to meet, share perspectives, and collaboratively develop strategies that can address both climate risks and local needs. Instead of relying on a pre-established plan, it builds upon local realities, existing networks, and the collective intelligence of territorial actors. PPCP® is based on a progressive implementation structured in three main stages: scoping, which focuses on analysing the local context, expectations, and stakeholder identification; operational implementation, involving the organisation of the PPCP® Labs; and capitalisation and evaluation, conducted both at the end of each Lab and the entire process itself to measure results, extract lessons learned, and determine future actions. PPCP® Labs bring Med-IREN within the NBS acceptance for the Finnish replicator and towards a new governance framework for the Egaleo demonstrator.

PPCP® enabled the regions involved to develop a localised, polycentric risk framework. It can also support the effective and efficient coordination of multi-tiered policies: disaster risk reduction, climate resilience capacity building, sustainability, biodiversity and environmental conservation, carbon neutrality, and a just and equitable transition.

- Innovative NBS

The D/R regions will implement NBS interventions. Consequently, the study will compile an NBS inventory that includes relevant details on key NBS, covering their structure, features, capabilities, constraints, limitations, benefits, and other relevant aspects.

- Financing

Different financing schemes will be examined for each case study, including the European Regional Development Fund (ERDF), the European Investment Bank (EIB), local or regional funds, and private funds, depending on the specific characteristics, modalities, and conditions of each.

- Local Action

A fundamental Med-IREN pillar is the promotion of local adaptation efforts that build on existing CCA plans and strategies. Local communities will also contribute to the project by assessing the functional and usability requirements of the digital twin.

2. Faster Adaptation in Mediterranean Infrastructures
    - Innovative Climate Hazards Analytics

A key objective is to develop and validate climate projections and microclimate models to assess the impacts of NBS in specific contexts. By considering vulnerability and exposure information at high resolution, local risks can be identified and measured. The assessment will also include exposure information, utilising publicly available GIS datasets to facilitate spatial analysis of hazards and exposure.

- Climate Risk and Resilience Maturity Models

The proposed approach will utilise the CREMA tool [56] for an innovative large-scale vulnerability evaluation and long-term risk and resilience assessment, considering cross-border and cross-sectoral interdependencies. The CREMA tool serves as a scorecard for buildings and areas when assessing their resilience to challenges such as extreme weather associated with climate change. It evaluates their current safety and preparedness and then suggests improvements to enhance safety. Designed to support local leaders and communities, it enables them to make informed decisions that protect their environment.

3. Smarter Adaptation in Mediterranean Infrastructures
    - Med-IREN Digital Toolset

The project toolset will facilitate the assessment, planning, monitoring, and engineering of NBS to enhance resilience by simplifying governance and improving the effectiveness and efficiency of managing dynamics, complexity, and specificity. Initially, functional and user requirements will be collected and a problem definition will be established within the scope of each D/R region. The Digital Toolset will support analysis of Earth Observation and in situ data, as well as enable data collection through forms and questionnaires, fostering co-creation, collaboration, and adherence to the models and methods.

Table 2 presents the synthesis of the RAST, incorporating findings from the Med-IREN workshop. This serves as a collective document capturing the specific components from the analysed frameworks. Additionally, key concepts from the Med-IREN contextual approach have been included. Therefore, the D/R regions have the potential to develop pathways to implement NBS for CI with a positive footprint.

Table 2. Proposed steps and activities to facilitate the blueprint implementation.

RAST	Frameworks	Description
Step 1 of the Regional Adaptation Support Tool (RAST) helps to assemble and organise the essential components for a well-prepared start to the adaptation planning process.		
Step 1.1		Building the evidence base
	IUCN Criterion 1	Identifying the societal challenge to which the NBS are a response
	CER	CER measures (a): (a) prevent incidents from occurring, duly considering disaster risk reduction and climate adaptation measures;/(b) ensure adequate protection
	Climate Proofing	CCA/CCM
Step 1.2		Securing political support and ownership
	Med-IREN	Localise the PPCP® framework through stakeholder selection and contextualization
		Methodology validation
Step 1.3		Setting up governance structures to support adaptation
	IUCN Criterion 5	NBS are based on inclusive, transparent, and empowering governance processes
	Med-IREN	Establish local partnerships and stakeholder engagement

Table 2. *Cont.*

RAST	Frameworks	Description
Step 1.4		Identifying your resources
	Med-IREN	Digital Resources Tool Architecture (if newly developed)
Step 1.5		Communicating adaptation and raising awareness
	CER	CER measures (f) raise awareness about the measures referred therein
	Med-IREN	Digital Tool Visualisation
Step 2: Define the essential elements of your risk assessment		
Step 2.1		Defining the core elements of your climate risk assessment
	Med-IREN	Med-IREN climate risk assessment planning
Step 2.2		Identifying risks
Step 2.3		Assessing climate risks
	Med-IREN	Co-develop and evaluate climate risks and impacts to NBS-CI communities and their interconnections
	Climate Proofing	Climate Risk Assessment—screening phase
	Med-IREN	Med-IREN Climate Resilience Assessment
Step 2.4		Defining key risks and adaptation objectives
Step 3: Identifying adaptation options		
Step 3.1		Identifying adaptation options
	Med-IREN	Assessment of the NBS, enabling conditions, guidance
	IUCN	IUCN 28 indicators
	CER	CER measures (c) respond to, resist and mitigate the consequences of incidents
	Climate Proofing	CCA/CCM screening phase assessment
Step 3.2		Taking inspiration from good adaptation practices
Step 4: Assessing and selecting adaptation options		
Step 4.1		Assessing adaptation options
	IUCN Criterion 2	Guidance of the design responding to the scale of the issue
	IUCN Criterion 6	NBS equitably balance trade-offs between the achievement of their primary goal(s) and the provision of multiple benefits
Step 4.2		Selecting adaptation options
	Climate Proofing	CCA/CCM detailed assessment phase
Step 5: Implementing adaptation policies and actions		
Step 5.1		Developing adaptation strategies and plans
	IUCN Criterion 7	NBS are managed adaptively, based on evidence
	CER	CER measures (d) recover from incidents
Step 5.2		Mainstreaming and integrating adaptation into existing plans
	IUCN Criterion 8	NBS are sustainable and mainstreamed within an appropriate jurisdictional context
Step 5.3		Funding or financing for implementation
Step 5.4		Maintaining and supporting governance for implementation
Step 6: Monitoring, evaluation, and learning (MEL)		
Step 6.1		Developing your MEL approach
	IUCN Criterion 3/4	NBS result in a net gain to biodiversity and ecosystem integrity/NBS are economically viable
Step 6.2		Defining your MEL framework
Step 6.3		Learning from results
	Climate Proofing	Recording and disseminating findings

The results in Table 2 can be interpreted in two ways: (1) elements of the developed frameworks may be integrated into the relevant tasks and planned activities in the D/R regions, aligning the proposed work with existing frameworks, tools, and indicators; and (2) a comprehensive framework specifically addressing the unique relationship between NBS-CI communities and CCA challenges can be formulated and presented as a project outcome.

3.1.2. Med-IREN High-Level Success Criteria

An overview of high-level success criteria linked to Step 6 of Table 2 is provided here to support the implementation of NBS-based CCA actions in the D/R regions. These were adapted from the RAST to reflect the characteristics of the Med-IREN project. CCA interventions should be sustainable across social, financial, and environmental dimensions, with the number of Sustainable Development Goals (SDG) indicators affected by the implementation of these solutions determined. Evidence-based actions should be informed by scientific knowledge and data, including future risks. It is important to assess the level of localisation (place-based) of CCA measures, addressing current and future risks and vulnerabilities at specific locations while also considering organisational, cultural, social, and financial resources. Potential indicators for inclusivity and social justice may be linked to key enablers and include local measures for just climate resilience. These indicators should address reducing the unequal burden of climate risks by assessing how vulnerable groups and regions are disproportionately impacted, and ensure equitable distribution of adaptation benefits and burdens. Additionally, they should promote capacity-building measures and policies that benefit all members of society equally. Finally, interventions should be flexible and iterative, allowing adaptation to uncertainties regarding future climate and socioeconomic conditions, as well as facilitating adjustments based on the lessons learned.

The subsequent sections outline how the PPCP® approach was implemented in the local contexts of the demonstrator and replicator regions, Egaleo and Helsinki, respectively.

3.2. Implementing PPCP® in the D/R Regions

This section includes the groundwork and early stakeholder engagement activities undertaken in the D/R regions. It covers preparatory actions as outlined in Table 2, such as local context analysis, stakeholder identification, and the organisation of co-creation Labs. In addition, a detailed overview of the PPCP® framework implementation in the D/R regions has been provided, including the local context, strategic goals, stakeholder engagement process and mapping, the structure and content of the initial co-creation Lab(s), the adaptation of the Local Partnership Charter (LPC), and the overall strategy for future implementation. The discussion also examines how the PPCP® approach has been tailored and adopted in the local context.

The Municipality of Egaleo identified challenges related to more complex interventions, such as road and excavation works, that may disrupt or delay adaptation plans due to the involvement of the Archaeological Agency. Additionally, Egaleo aimed to combine innovative solutions with low-cost maintenance, long durability, and no strict regulatory restrictions. It has also been noted that a local policy and regulatory framework does exist, granting the municipality the authority to determine intervention areas. Several challenges have been identified in Helsinki that must be addressed to ensure the smooth and resilient co-design and implementation of NBS. To address these challenges, it is essential to determine whether legislative, regulatory, or best-practice obstacles exist that could hinder the installation of NBS in buildings. Additionally, the integration of NBS may be influenced by the historical significance of the buildings in the region. Another factor to

consider is the impact of building materials on NBS integration in boreal climates. Finally, the sustainability of NBS in the boreal winter is a key issue that must be addressed.

3.2.1. Demonstrator Municipality of Egaleo

Context and Challenges in the Municipality of Egaleo

The demonstrator, Egaleo, is a highly urban municipality in Western Athens, Greece. This area faced several socioenvironmental challenges, including high energy poverty, limited green spaces, and seismic risks. Climate threats primarily included intensified heatwaves exacerbated by the urban heat island effect and frequent flooding. Key interventions on CI were necessary to improve community resilience through the Med-IREN project, which utilised specific NBS derived from community insights to tackle these hazards. Egaleo partners had developed a baseline assessment for the municipality, which was primarily implemented and linked to existing indicators. A monitoring system with climate and environmental stations offered real-time temperature and air quality data. The initiative also included measuring energy consumption in public buildings (including electricity, water, and natural gas). A study of the CO_2 carbon footprint complemented these monitoring tools. In parallel, a climate risk assessment has been under development. Social-economic studies that incorporated social data, map vulnerable populations and infrastructure, and used heatwave data were also included. Finally, a public GIS (Geographic Information System) provided urban planning and lighting data.

The primary focus of the Med-IREN project in Egaleo was to improve climate resilience and social well-being in a densely built urban area that faced challenges such as heatwaves, flooding, energy poverty, and limited green infrastructures. The demonstrator aimed to directly address these issues through targeted NBS, including planting trees along a major intersection road called "Iera Odos" to reduce urban heat and improve stormwater management; using bio-bricks at a municipal maker space (the municipal stadium of "Stavros Mavrothalassitis") for passive climate regulation; and establishing a network of pocket parks to provide green spaces that can mitigate heat islands while fostering community connections. The objective was not only to plan but also to implement these NBS fully, ensuring they were functional, sustainable, and integrated into the urban fabric. The project has planned to progress through all phases, from co-design and technical detailing to construction and monitoring, to create a replicable model for other metropolitan areas. Data from the climate monitoring network in the city of Egaleo, established through the TransformAr project [57], will be used to assess the impact of the selected NBS implementation. Modelling will be based on the heatwave risk assessment approach at high spatial resolution from the CLIMAAX project [58]. Notably, the process will be co-produced with local stakeholders, including the school community and the community from the stadium's neighbouring area. This participatory approach will ensure that solutions are culturally relevant, technically feasible, and collectively owned, incorporating local knowledge and fostering long-term stewardship. The study by [59] underscored that adopting participatory approaches make local policies more effective, relevant, and supportive of sustainable, climate-adaptive solutions. Ultimately, such engagement fostered more inclusive policymaking and strengthened community resilience against climate hazards.

PPCP® is an essential stakeholder engagement framework for the Egaleo demonstrator, enabling a shift from a traditional top-down approach to a collaborative governance model co-constructed by local stakeholders and centred on climate resilience. By actively involving a diverse range of stakeholders, including public-sector officials, private-sector experts, and civil society groups such as schools and residents, PPCP® turned stakeholder participation into a key asset for the demonstrator [36]. This diversity ensured that technical feasibility (private sector), regulatory support (public sector), and social acceptability (civil society)

were integrated from the outset, thus reinforcing the legitimacy and long-term sustainability of the interventions.

Following the civil society participation ladder outlined in the document, the application of the PPCP® approach in Egaleo aimed to achieve partnerships and delegate power, moving beyond mere consultation. For example, in the Egaleo demonstrator, civil society stakeholders not only provided feedback but also actively co-created during on-site visits and co-design sessions, influencing key decisions such as prioritising interventions in a significant city square (named "Kithreon Square"). This level of involvement was crucial for building trust and ensuring solutions were rooted in local knowledge and needs. Consequently, the most valuable asset of this multi-stakeholder engagement was the development of a mutual learning process. The PPCP® approach provided a structured space where municipal technical staff learned about NBS and user needs, stakeholders gained insights into technical and budgetary constraints, and private actors understood the social aspects of implementation. This process not only supported immediate project goals but also fostered a lasting culture of participation within the municipality. By focusing on shared challenges such as heatwaves and flooding, the PPCP® promoted a common language and collective ownership of climate adaptation, thereby strengthening Egaleo's overall social and institutional resilience.

Stakeholders' Identification and Engagement in the Municipality of Egaleo

The first step of the PPCP® approach, which should begin as early as possible in a project, is to identify and engage key stakeholders. In Egaleo, stakeholders were mainly identified through the Municipality of Egaleo's existing formal and informal networks, as well as the collaborating research institution (NCSR "Demokritos"). First, invitations were circulated through "municipality and school networks," followed by outreach to a pre-established "pool of stakeholders and citizens" created during the first PPCP® Lab (Lab 1). This indicated a mixed approach utilising both institutional channels (municipal departments and school communities) and earlier participatory efforts to ensure the continuity and inclusion of local civil society and private actors.

The main challenge the research team faced in balancing stakeholder groups was the underrepresentation of the private sector: only one private-sector representative, a local furniture maker, participated, underscoring the difficulty of engaging businesses despite their importance for circular-economy opportunities such as bio-brick production. Additionally, facilitators needed to bridge the age and communication gaps between adults and students, especially during transitions between activities. The technical expertise of specialists sometimes overshadowed civil society input, necessitating facilitator intervention to maintain a balanced discussion. Lastly, logistical constraints such as scheduling (e.g., avoiding exam periods) and venue accessibility influenced attendance, potentially limiting participation among older adults and full-time workers.

These challenges reflected a tension between inclusivity and practical relevance, where prioritising diverse voices could sometimes conflict with maintaining focused, technically informed discussions. The facilitators addressed this by dynamically adjusting roles and simplifying jargon. Still, future Labs could benefit from more targeted outreach to underrepresented groups (e.g., local businesses and seniors) and from structured role rotation within groups. The stakeholder composition for the Egaleo Med-IREN demonstrator demonstrated a solid base of local involvement, especially from public and civil society groups, with the potential to increase private sector participation as follows:

Strong public–civil society synergy: The project's core comprises local public institutions, such as the Municipal Green Department and schools, alongside civil society groups, including the Parents Association and an environmental NGO. These groups demonstrated

a high level of interest (Level 4) and played complementary roles: the municipality provided technical authority and implementation capacity, while civil society offered community legitimacy, local knowledge, and the potential for long-term stewardship. This partnership was essential for grassroots backing and long-term sustainability.

High interest, diverse influence: Most stakeholders showed strong interest (Levels 3–4) in NBS, but their influence differed. The Municipal Green Department had the highest influence (Level 4) due to its official capacity, while other groups had a moderate influence (Level 2). This reflected a balanced dynamic that prevented any one entity from dominating and fostered collaborative decision-making.

Underrepresentation of the private sector: The private sector has currently been the weakest link, with just one representative identified. This stakeholder had a moderate level of interest and influence (Levels 2–3), presenting both a notable opportunity and a potential risk. Increasing engagement with local businesses, such as construction, recycling, and retail, could provide access to resources, innovative materials, and circular-economy approaches. However, this will require targeted outreach to ensure their incentives align with the project's goals.

Emphasise local knowledge and long-term stewardship: A key strength was the direct involvement of stakeholders affected by the interventions, such as students, parents, NGO staff, and teachers who possessed specialised local knowledge. Their motivation to improve their environment drove active participation, ensuring that proposals were realistic and relevant to local needs. The emphasis on maintenance models underscored a shared goal of achieving long-term sustainable impacts, rather than merely implementing solutions.

The stakeholder map outlined an approach for the Egaleo demonstrator that was community-driven and publicly rooted, with strong legitimacy and support from those most affected. The main challenge was to strategically engage the private sector to provide technical, financial, and innovative value, thereby fostering a more resilient and multidimensional partnership for urban transition. The PPCP® Labs revealed that stakeholders in Egaleo saw NBS not only as technical measures but also as avenues for broader social, environmental, and economic benefits. However, significant differences existed in their priorities and concerns, largely attributable to their sectoral category and direct connection to the intervention area.

1. Commonalities—The Shared Vision: Across all stakeholder groups, there was a strong, unified view of NBS as essential tools for improving liveability, strengthening community identity, and creating demonstrators. All sectors, including public, civil, and private, were directly associated with NBS in reducing the urban heat island effect and improving thermal comfort, particularly for vulnerable groups such as students and the elderly. There was a shared understanding that green spaces, especially pocket parks, were not only ecological assets but vital social infrastructure for fostering community cohesion and supporting mental well-being. Participants universally endorsed a concentrated high-impact intervention in "Kithreon Square," viewing it as a strategic means to increase visibility and could serve as a model for wider replication.
2. Divergences—Sectoral Priorities and Concerns: The key differences in perception emerged along sectoral lines, highlighting distinct value systems and operational constraints (see Table 3).
3. Key Pattern—The primacy of pragmatism over technology: A dominant pattern across all categories was a pragmatic, cost–benefit approach. The clearest example was the collective decision to reject the high-tech Liquid3 [60] solution in favour of conventional tree planting. This was not a rejection of innovation, but a prioritisation of perceived reliability, lower maintenance, immediate aesthetic and shading benefits,

and better cost efficiency. This indicated that for NBS to be widely accepted in Egaleo, they must be viewed as practical, durable, and capable of delivering clear value.

Table 3. Stakeholders' perceptions towards NBS, key concerns, and priorities.

Stakeholder Category	Primary Perception of NBS	Key Concerns and Priorities
Public Sector (Municipality, Teachers)	Tools' selection for climate resilience and public service delivery. Viewing NBS through a lens of technical feasibility, regulatory compliance, and long-term public good.	Maintenance and Vandalism: a major preoccupation was the sustainability of interventions beyond the project lifecycle. Who will care for the trees? Who repairs a damaged bio-brick wall? This reflected their operational responsibility. Budgetary Reality: their support was pragmatic, with a strong focus on cost-effectiveness and scalability within municipal budgets.
Civil Society (Parents, NGO, Students)	Means to reclaim and improve their everyday environment. Their perception was experiential and rooted in local knowledge and direct need.	Immediate Usability and Safety: their proposals (shaded seating, play areas) focused on direct, tangible benefits. Students, as primary users, were particularly vocal about ensuring NBS did not impede existing play areas. Historical and Cultural Context: the NGO contributed to a perception of NBS as a means to enhance and protect local heritage, rather than solely for its ecological function. Ownership and Stewardship: they showed a strong desire to be involved in NBS care, perceiving it as a form of community ownership.
Private Sector (Local Maker)	A potential market opportunity and source of materials. The perception was more instrumental, focusing on practicality, cost, and the potential for a circular economy.	Cost vs. Impact: the single private representative's alignment with the group to reject Liquid Tree in favour of "real trees" was a pragmatic decision based on perceived value for money and tangible impact. Material Innovation: Showed interest in how local waste streams (e.g., sawdust) could be integrated into NBS like bio-bricks, perceiving NBS as a potential business niche.

4. Territorial Scale—An overwhelmingly local lens: All perceptions were shaped through a strictly local, highly contextual lens. Stakeholders consistently assessed NBS based on their specific impact on "Iera Odos" and "Kithreon Square." Discussions about broader climate adaptations were always redirected to local implications: "How will this affect our square?" "Will this cool down our street?" This highlighted that the success of NBS in Egaleo relied on demonstrating highly localised benefits.

Stakeholders in Egaleo viewed NBS as essential for climate adaptation, but they sought socially rooted solutions that were pragmatically selected and locally beneficial. The process demonstrated a sophisticated understanding among participants who naturally considered the trade-offs among technological innovation, cost, social benefits, and maintenance. Moving forward, aligning NBS design with these practical, community-focused views will be crucial to successful implementation and lasting sustainability.

The distribution of stakeholders across both Labs was notably uneven (see Figure 3), with a significant overrepresentation of the public sector (70–76%), mainly comprising

municipal staff, teachers, and students. Civil society was modestly represented (20–25%), while the private sector was severely underrepresented (5%), with only one local stakeholder participating. This imbalance likely resulted from the recruitment approach, which primarily relied on the municipality's and schools' existing networks. While these channels facilitated access to public and civil society groups, such as parents via schools, they had fewer connections to local businesses and industry. Moreover, scheduling site visits on a weekday may have discouraged private-sector participants who could not take time off work.

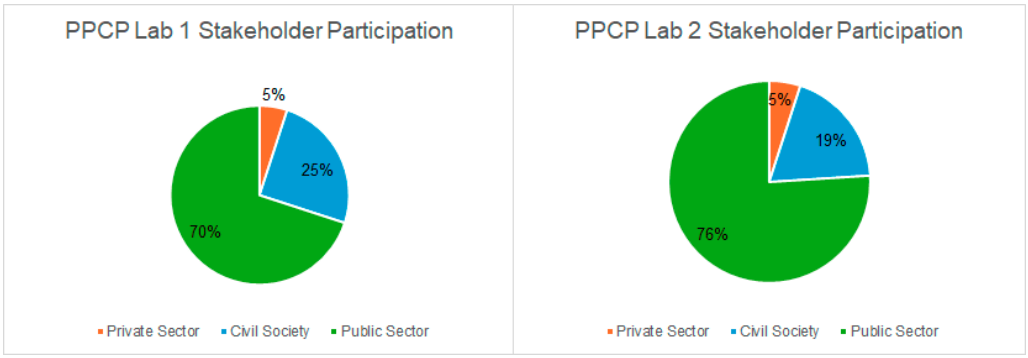


Figure 3. Egaleo PPCP® Labs stakeholders' distribution.

To correct this imbalance in future activities, targeted measures should be implemented: proactive private sector outreach by directly contacting local chambers of commerce, business associations, and relevant industries (construction, landscaping, recycling) with personalised invitations that clearly outlined the business case for participation (e.g., networking, tendering opportunities, CSR); dedicated civil society mobilisation by partnering with a wider range of community groups, neighbourhood associations, and environmental NGOs to diversify civil society participation beyond school-related parents; adapted logistics by considering holding sessions outside of standard working hours or offering hybrid participation options to lower the barrier of entry for working professionals and private entrepreneurs; and structured roles by explicitly creating and advertising roles for private sector expertise (e.g., "materials advisor," "circular economy partner") to demonstrate the specific value they would bring to the table. Future Labs can achieve more balanced and representative stakeholder engagement by implementing these measures, ensuring all relevant perspectives can be included in the co-design process.

The communication materials used to convey Med-IREN objectives, the PPCP® Labs structure, and expected outcomes to participants were as follows:

- An official invitation letter to formally announce the workshop, outline its objectives, agenda, and logistical details (date, time, location), and encourage registration. This structured document will be distributed via email and municipal/school networks.
- A Med-IREN programme overview aimed to provide context about the broader Med-IREN project, its goals, and how the specific PPCP® Lab integrated into the wider initiative. An extensive presentation (PPCP® Lab 1) offered background on the project's mission and anticipated outcomes.
- Pre-Lab presentation slides and a Miro board to visually present the outcomes of the first PPCP® Lab (collective map with stickers), introduce the technical specifications of the four NBS (bio-bricks, Liquid Tree, etc.), and stimulate initial reflection (see Figure 4). A digital board was used during the Lab's introductory session to facilitate understanding and discussion.

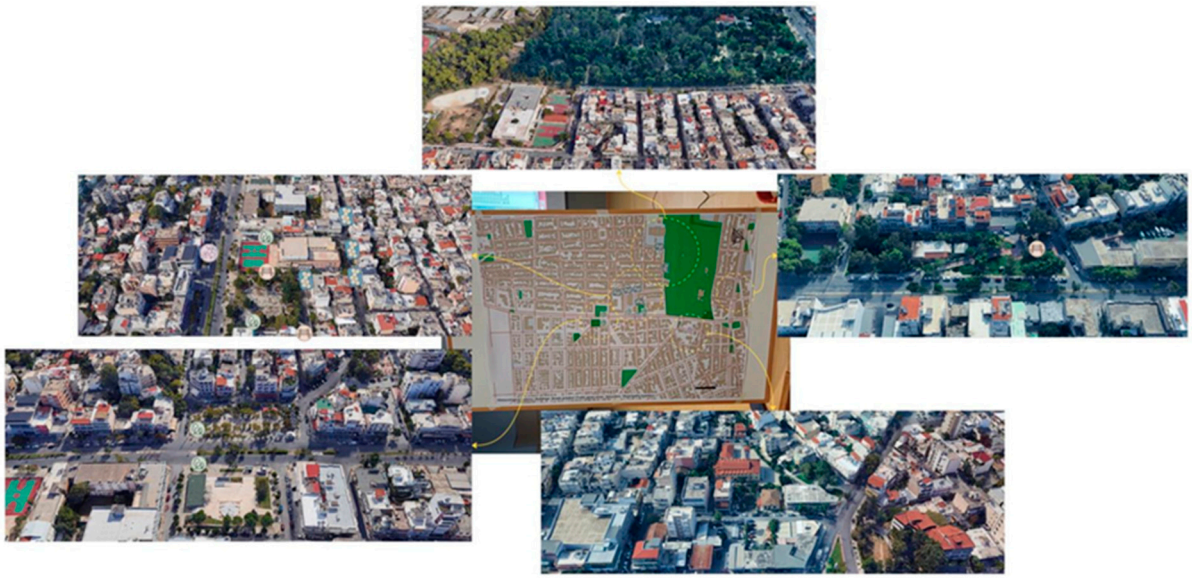


Figure 4. Presentation of PPCP® Lab 1 results, organised by case study areas on the Miro board.

- Participatory Mapping Kits to enable hands-on engagement during site visits and co-design sessions and collect site observations and proposals (see Figure 5). Printed A4 and A3 maps of the case study areas, accompanied by canvases with categories for data entry (characteristics, justifications, challenges, impacts).



Figure 5. Facilitators' canvas with site observation notes (PPCP® Lab 2).

- NBS parameter cards to enable informed decision-making and discussion by offering precise, comparable data on each solution. The scoring system used a five-star scale to rate each NBS solution across cost (purchase, raw materials, installation), applicability

(installation time, preparatory work, maintenance), and environmental impact (effectiveness in achieving measurable results), allowing stakeholders to easily compare and select the solution that best suited their preferences (tree planting, Liquid Tree, bio-bricks, [61], etc.) (see Figure 6) [61].



Figure 6. Coloured cards representing different NBS (e.g., tree planting, Liquid Tree, bio-bricks) with three parameters (cost, environmental impact, and ease of application) and their respective ratings.

3.2.2. Replicator City of Helsinki

Context and Challenges in the City of Helsinki

The duration and severity of heatwaves have been increasing in the boreal region. The city of Helsinki identified heat as a high-risk factor that was expected to become more prominent over the next 5 to 15 years. The mortality rate among Helsinki residents during heatwaves is currently about 2.5 times higher than in the HUS hospital district [62]. Older adults are particularly vulnerable to heat exposure and thermal stress. In 2010, the most significant increase in heat-related deaths occurred in healthcare treatment facilities. Beyond technical cooling solutions, there was a need for urban green and blue spaces, a comprehensive understanding of their impacts, an enhanced preparedness in healthcare and care homes, and the development of early warning systems.

The Helsinki replicator aimed to create new knowledge and tools to support further implementation of NBS to mitigate heatwaves and urban heat island effects, with a particular emphasis on resilience of social infrastructure. Simulations of greening solutions on and around buildings, including associated cooling effects, were conducted for facilities such as care homes, retirement homes, hospitals, and daycare centres. The initial focus encompassed green roofs, green walls, and urban greening strategies such as parks, trees, and forests; the integration of green and technical cooling solutions; and the assessment of social acceptability across various heat-mitigation strategies. Specific NBS like green roofs and walls were considered to alleviate urban heat due to their extensively documented impact on energy savings and cooling potential in warmer climates, such as the Mediterranean (e.g., [63,64]). In Nordic winter conditions, green roofs have been documented to provide insulative benefits, potentially contributing to saving building energy [65] and having lower runoff compared to standard roofs, albeit with lower retention for mixed rain and snow events [66]. This suggested that the design of building-integrated NBS needed to consider freezing conditions and snow accumulation. The project's outcomes aimed to support advocacy for nature-based cooling solutions and inform climate adaptation decision-making. High-resolution modelling and monitoring can generate data to inform this decision-making and facilitate broader implementation and scaling of NBS in the city, particularly within the built environment. Additionally, Helsinki intended to adapt and expand digital solutions implemented in the Mediterranean region, particularly in the city of Egaleo, while accounting for the unique conditions of the boreal climate.

The core elements for developing a baseline assessment for the replicator region included GIS and flood exposure analysis (sea and storms), preliminary analysis of heat exposure, Regional Climate Roadmap, the Uusimaa Smart Specialisation Strategy, the regional land-use plan, data on green roofs and their potential in the Helsinki metropolitan region, as well as other available data related to land cover and green infrastructures in the Helsinki metropolitan area (e.g., carbon sink mapping).

The PPCP® Labs enabled collaboration among key stakeholders to share knowledge and co-design strategies for advancing the implementation of NBS to mitigate heatwaves. The primary objective of the first two PPCP® Labs was to foster dialogue among local stakeholders and establish a shared understanding of urban heat as a hazard and the potential of NBS for mitigation. It was deduced that PPCP® Labs could strengthen local cooperation and support the Helsinki replicator in identifying local needs, including barriers to implementing NBS, as well as the necessary tools and data to facilitate planning and future implementation of NBS. Ultimately, PPCP® Labs could enhance the resilience of the Helsinki region and promoted the broader adoption of NBS for long-term heat mitigation.

Stakeholders' Identification and Engagement in the City of Helsinki

The project partners, Forum Virium Helsinki Oy (FVH) and Teknologian Tutkimuskeskus VTT Oy (VTT), implemented the work plan for the Helsinki replicator and began contacting organisations for PPCP® Labs. FVH and VTT leveraged their internal and external networks to share project goals and collaborated with other ongoing NBS, urban greening, and climate adaptation projects. A diverse range of stakeholders from various public-sector organisations participated in PPCP® Labs 1 and 2. The three largest cities in the Helsinki metropolitan area, Helsinki, Espoo, and Vantaa, took part in the workshops, with participants from multiple city units (e.g., the Urban Environment Division and the Social Services, Health Care and Rescue Services Division). Other local public stakeholders included the Helsinki-Uusimaa Regional Council, Helsinki Region Environmental Services, and Helsinki University Hospital. Participants also included other EU-funded projects, local universities, and a company specialising in landscape planning and green roof installations. To incorporate more national and regional perspectives, attendees from the Finnish Meteorological Institute and the Centre for Economic Development, Transport and the Environment were also present.

To further identify suitable NBS and key stakeholders in Helsinki, Forum Virium Helsinki organised an additional workshop in addition to the first two PPCP® Labs. This workshop brought together seven planning experts (the city of Helsinki) and university researchers (Aalto University and the University of Helsinki) specialising in the urban heat island effect and adaptation planning. It mirrored the Lab 2 agenda, featuring presentations on the project and the Helsinki replicator's objectives, followed by guided discussions on the barriers and enablers to NBS implementation, as well as the main stakeholders to be involved in planning and executing it. The insights gained from this workshop complemented data from the PPCP® Labs and further refined the objectives for the Helsinki replicator.

Before the Lab activities, a stakeholder mapping exercise was conducted to identify relevant project participants. Furthermore, in Lab 2, a specific activity was conducted to identify key stakeholders crucial to the planning and implementation of NBS in Helsinki. During the group work phase, participants used a bull's-eye diagram to categorise primary, secondary, and tertiary stakeholders (see Figure 7).

Participants identified several stakeholder groups for the project. Primary stakeholders encompassed property and building owners (including companies as owners and users), housing companies and associations, city planning and building control services (such as zoning and building permit officials), and schools. The interface between primary and

secondary stakeholders included private-sector representatives and citizen groups. Secondary stakeholders included contractors (who also maintained parks and infrastructure), citizen associations, academic and research institutions, municipal authorities, and cultural organisations, such as the city museum and the board of antiquities. Tertiary stakeholders included company representatives, institutional tenants, and the wider community, collectively described as "Everyone in Helsinki."

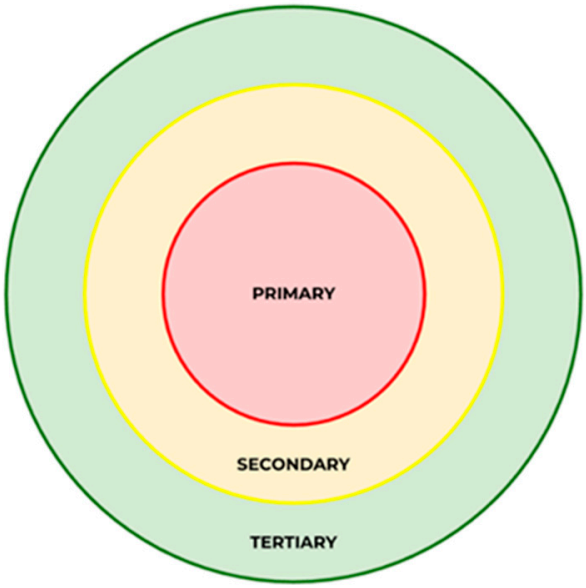


Figure 7. Bull's eye diagram used in PPCP® Lab 2 to map stakeholders.

Stakeholder participation in the Labs' engagement activities was uneven, underscoring the need to gather additional perspectives on NBS and heat risk in Helsinki, particularly from underrepresented groups. Private-sector participation in PPCP® Labs 1 and 2 was relatively low, accounting for 22.2% versus 77.8% from the public sector. Despite inviting various consulting and construction firms involved in environmental assessment, landscaping, and urban planning, few chose to participate. Future Labs aim to facilitate dialogue with a broader range of private-sector and civil-society actors through interviews, collaborative meetings, and site visits to existing NBS examples, such as green roofs and green walls in the Helsinki area.

4. Discussion

4.1. Assessment of the Egaleo PPCP® Labs

The activities across the two PPCP® Labs were carefully selected to create a logical sequence, from raising awareness and generating ideas to practical, site-specific co-design, thereby aligning with the main aim of progressing from concept to realisation. PPCP® Lab 1 concentrated on Building Awareness and Generating Ideas, while Lab 2 focused on Deepening Understanding and Co-Designing Solutions.

More specifically, Lab 1 focused on introducing the concept of NBS and gathering initial broad community input through targeted activities. Expert presentations on local climate risks and NBS types provided a necessary common knowledge base, while participatory mapping with stickers allowed participants to identify potential locations for different NBS by placing coloured stickers on large printed maps of Egaleo. These activities were chosen to educate and empower participants, with the sticker-based mapping offering a low barrier to entry as it was intuitive and interactive, enabling everyone to contribute

their local knowledge without requiring technical expertise. The overall goal was to spark dialogue and generate a first round of community-driven proposals.

Lab 2 was designed to refine the initial ideas through technical learning and site validation. It began with a recap and a technical deep dive, including a presentation that revisited the outcomes of Lab 1 and detailed the technical and financial aspects of the shortlisted NBS. Participants then participated in a thematic site visit, splitting into groups to walk the study area, validate proposals, assess site conditions, and document specific locations with photographs. In the co-design session, groups synthesised their site observations using A3 maps and NBS parameter cards to create detailed master plans. This was followed by plenary presentations and a focus group discussion, during which groups presented their proposals and engaged in structured discussions on challenges such as cost and maintenance. This sequence was chosen to ground ideas in reality and foster ownership. The site visit was crucial for bridging the gap between abstract maps and real-world constraints and opportunities. At the same time, the co-design session provided a structured framework for translating observations into actionable plans. The plenary discussion enabled critical evaluation, consensus building, and the prioritisation of interventions through collective reasoning. The hands-on iterative activities intentionally transformed participants from commentators into co-creators.

The facilitation team was organised into two coordinated roles: facilitators and observers. Facilitators were assigned to specific thematic working groups, such as bio-bricks and tree planting. They were responsible for guiding discussions, clarifying technical details, and documenting ideas on maps and canvases. Observers monitored group dynamics and non-verbal cues, discreetly identifying fewer vocal participants or points of confusion and relaying this information to facilitators in real time. This structure enabled a responsive and adaptive process, allowing facilitators to proactively address challenges, promote equitable participation, and sustain both the workshop's momentum and inclusivity.

These Labs produced two main types of results: tangible outputs and intangible outcomes, both of which were essential to Med-IREN's progress. Tangible results included detailed participatory maps, master plans prioritising NBS for "Kithreon Square," and technically informed proposals that were collectively reviewed for feasibility, such as the rejection of Liquid Tree. Additionally, the process generated key intangible benefits: a community-driven and refined list of intervention priorities, a strong sense of local ownership among stakeholders, and valuable insights into maintenance and co-stewardship models. Med-IREN can directly utilise these results in various ways. The co-designed master plan (see Figure 8) functions as a binding blueprint for implementation, ensuring that technical work aligns with community priorities. The collected data on costs and maintenance provided essential criteria for participatory budgeting and financial planning in the next phase. Furthermore, the established trust and co-design methodology created a replicable model of citizen engagement for other demonstrators, transforming local outcomes into a transferable knowledge product for the entire project.

The organisation of the PPCP® Labs demonstrated effective coordination between the Municipality of Egaleo and NSRC "Demokritos." The process was structured to progress from awareness-raising in Lab 1 to technical co-design and site-specific planning in Lab 2, following a logical sequence of participatory methods, including presentations, on-site visits, and hands-on mapping. These methods fostered trust and engagement among stakeholders. Logistical preparation was comprehensive, with tailored materials such as NBS cards and printed maps supporting productive dialogue and realistic outcomes. Although challenges emerged, including maintaining balanced stakeholder representation and managing time during transitions, facilitators adapted to ensure inclusive collaboration and tangible results, notably the master plan for "Kithreon Square." The Labs established

a foundation for community involvement and technical clarity, supporting the following stages of implementation.

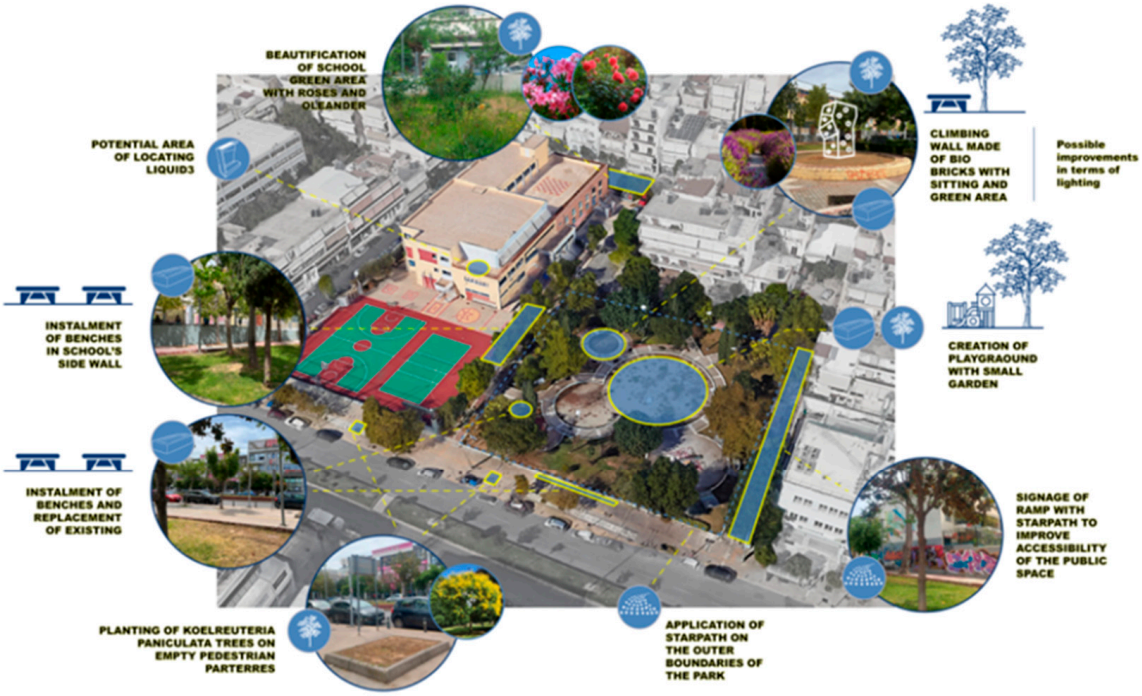


Figure 8. General master plan of proposed interventions for "Kithreon Square" in Egaleo by the three teams of PPCP® Lab 2.

While successful, the PPCP® Labs organisation encountered several predictable yet impactful constraints, including stakeholder availability, logistical complexity, and emerging engagement fatigue. Scheduling sessions outside working hours was necessary to ensure the inclusion of students and teachers. Still, it likely contributed to the severe underrepresentation of the private sector, as they could not easily step away from professional commitments. Furthermore, the timing near the school exam period limited flexibility. The transition between the high-energy on-site visits and the focused indoor co-design session proved challenging, particularly in maintaining the younger participants' concentration. This shift among different activities required careful facilitation to manage energy levels and focus. Additionally, the technical complexity of specific NBS (e.g., bio-bricks construction, Liquid Tree functionality) initially overwhelmed some participants, leading to brief periods of disengagement. While some participants were vocal, others were hesitant to present formally, indicating a need for more varied and inclusive formats to sustain energy and ensure profound, equitable contribution. To improve the effectiveness and inclusivity of future Labs, the following strategies are suggested:

- Targeted and flexible scheduling: Implement a dual-track invitation system. Public and civil society actors should continue leveraging existing networks. For the private sector, engage directly through local business associations and provide flexible participation options, such as shorter, focused technical sessions or hybrid (online) attendance, to address availability challenges.
- Structured role rotation: To combat fatigue and technical voices' dominance, introduce rotating roles within working groups (e.g., 'note-taker,' 'spokesperson,' 'timekeeper'). This formalises participation, ensures equitable contribution, and maintains engagement by giving everyone a straightforward task.
- Pre-Lab technical primers: Create and share simplified, visual explainers (e.g., short videos, infographics) on key NBS technologies in advance. This will demystify tech-

nical jargon, level the knowledge field, and enable Lab time to focus on creative co-design rather than basic explanations.

- Enhanced data integration tools: To ease the transition from outdoor to indoor activities, use a shared digital workspace such as Miro in real time during site visits. Facilitators can upload photos and pin comments directly onto a digital map on a tablet, thereby providing an immediate foundation for the co-design session and enhancing the process's fluidity and engagement.

Future Labs can mitigate these limitations by actively implementing these strategies, resulting in more balanced representation, sustained engagement, and enhanced productivity. Moreover, the following recommendations are proposed to strengthen future Labs: (1) Conduct targeted private sector outreach to address representation imbalances. (2) Provide pre-Lab technical primers, such as short videos, to streamline sessions. (3) Implement structured debriefs after active phases to facilitate effective focus transitions. (4) Rotate group roles, such as note-taker, to ensure equitable participation. (5) Present transparent budget visualisations early in the agenda to ground discussions in financial considerations. These measures are expected to promote more inclusive, efficient, and pragmatic co-design outcomes.

Building on the success of the first two Labs, organising and guiding PPCP® Labs through participatory approaches was the way forward. The focus should be on creating a series of interconnected activities, developing customised materials that simplify complex technical details, and promoting an environment of open dialogue and co-creation among diverse stakeholders. Tailoring methodologies, such as site visits and participatory mapping, to the local context fostered nuanced discussions and produced tangible results. However, challenges typical in multi-stakeholder processes persisted. It was challenging to ensure balanced representation, particularly from the private sector, which remained underrepresented despite targeted outreach efforts. Keeping participants engaged across diverse demographics was also difficult, particularly when maintaining students' focus during transitions from outdoor sessions to detailed indoor technical work. Furthermore, managing the scope of discussions and balancing ambitious ideas with budgetary and practical constraints required careful facilitation to ensure productive, realistic conversations. Finally, two additional Labs were planned to achieve the ultimate goal of establishing a new governance framework aligned with the NBS strategy in Egaleo.

4.2. Assessment of the Helsinki PPCP® Labs

The main objectives of the Helsinki PPCP® Lab 1 were to create synergies and interest in the project by involving relevant partners directly in the Lab activities, build a collective understanding of heat as a hazard and the potential of NBS to mitigate the heat island effect, and identify and then map other relevant stakeholders to engage during the project. PPCP® Lab 1 was also used to communicate project expectations and objectives to relevant stakeholders and gather participants' input to refine the local focus. Additionally, the activities were designed to foster collective understanding and engage various stakeholders in discussing different NBS, their impacts, and implementation, including barriers and enablers.

Helsinki PPCP® Lab 1 was organised in two sections: presentations and a workshop, bridged by a Mentimeter ice-breaker activity. The presentations introduced the Med-IREN project, detailed the aims of the Helsinki replicator case, and provided a background on urban heat, vulnerability, and approaches to managing these concerns. In the workshop, participants used an NBS card game (see Figure 9) to collectively identify and prioritise the leading causes, vulnerabilities, and effects of urban heat in Helsinki, as well as to brainstorm both NBS and alternative solutions. At the end of the session, participants

placed their chosen solutions on a prioritisation matrix and each group shared their results. The session concluded with a discussion of ranking challenges, the evaluation of NBS and other solutions, and the finalisation of their placement on the prioritisation matrix.



Figure 9. NBS cards used in the group activity.

Building on the results of Lab 1, PPCP® Lab 2 brought together a broad range of stakeholders to explore NBS in greater depth, focusing on their effects, implementation barriers, and supporting factors across various urban settings. This approach enabled stakeholders to compare perspectives across the region and helped clarify the shared goals and desired outcomes for the Helsinki replicator's activities. PPCP® Lab 2 aimed to raise awareness about the project, emphasise heat as a significant risk, and introduce NBS as possible interventions. The session also brought together experts to refine the direction of the Helsinki replicator, promoted the exchange of viewpoints on approaches to mitigate the impacts of heatwaves on CI, and identified key stakeholders to expand NBS implementation. To meet these goals, Lab 2 featured detailed discussions of suitable NBS for different urban environments, examinations of both supportive and hindering policies, and stakeholder mapping by role and influence on NBS decision-making and implementation.

Participants in the PPCP® Lab discussions acknowledged that urban heat was a pressing and under-addressed challenge in Helsinki. It was noted that, to date, NBS had primarily been applied to rainwater and flood management; however, there was a common understanding of the role that vegetation and green spaces play in mitigating heat. While all forms of NBS were considered valuable for mitigating the effects of heatwaves and the urban heat island phenomenon, stakeholders held differing views on the feasibility of implementing these solutions in urban areas. The discussions highlighted strong regional commitment to tackling heat vulnerability and expanding green spaces. Yet, stakeholders

agreed that the overall public understanding of heat risk remains limited, and heatwaves often catch people off guard, as evidenced by sudden spikes in fan purchases. Additionally, heat as a hazard in Finland has been exacerbated by certain building design features, such as south-facing orientations, expansive windows, and dark roofs, as buildings have been designed to retain heat. Participants identified a clear need for better data to monitor and evaluate the effectiveness of NBS, particularly in neighbourhoods with many vulnerable residents and small apartments, with special attention to CI such as hospitals, care homes, daycare centres, and schools. The lack of green infrastructure was especially problematic for vulnerable groups and near-essential facilities such as care homes and hospitals.

Participants identified specific adaptation measures, such as strategically planting trees, preserving existing green areas, creating cool schoolyards, and adding greenery to streets, as both highly effective and relatively easy to implement, with shading considered the most practical and directly beneficial aspect (see, e.g., Figure 10). Other actions, such as installing green roofs and facades, establishing green corridors, constructing planted retention basins, and developing urban parks with tree canopies, were recognised as impactful but more challenging to implement, whether at small or large scales. Stakeholders differed in their views on the feasibility of implementing various NBS, noting that the suitability of specific solutions depended on the area type, the stakeholders involved, and other existing obstacles. Lastly, the lack of collaboration between the public and private sectors was identified as a key impediment to knowledge exchange and the broader implementation of NBS.



Figure 10. NBS cards placed on the impact–implementation matrix.

Overall, PPCP® Labs 1 and 2 played a significant role in shaping the aims of the Helsinki replicator. Stakeholders' feedback emphasised the importance of convening

stakeholders to share knowledge on new climate adaptation strategies and to enhance awareness and interest in NBS. Future phases of the project will maintain active stakeholder involvement through Lab sessions, interviews, site visits, and focused workshops with particular stakeholder groups. It was also considered crucial for all participating regions to exchange practical tools such as templates, invitations, and participatory methods, along with lessons learned from workshops and actual implementations throughout the project. Importantly, upcoming PPCP® Labs 3 and 4 will focus on developing a practical feasibility roadmap to further guide the implementation of NBS in Helsinki.

5. Conclusions

In summary, this paper presented the Med-IREN project's approach to articulate a holistic and anticipatory strategy for fortifying the resilience of CI against climate-related hazards, particularly those posed by extreme weather events, through the systematic integration of NBS across pivotal sectors of CI such as energy, transportation, information and communication technology (ICT), water, and social services. The project underscored the necessity of protecting vital infrastructures, fostering ecosystem health, advancing sustainability objectives, and minimising disaster risk through systemic and innovative adaptation pathways. Central to this endeavour were robust partnerships, community-driven initiatives, advanced analytical methods, and robust risk assessment tools which collectively facilitated transformative, efficient, and responsive adaptation in regions vulnerable to climate impacts. Nevertheless, the widespread deployment and mainstreaming of NBS remains contingent on overcoming substantive barriers at the local level, notably the need for comprehensive climate assessments to appraise impacts and vulnerabilities, particularly within high-risk communities.

The blueprint developed in the current study can serve as a foundational framework for unified climate adaptation of CI through NBS, thereby enhancing societal resilience amid escalating climate pressures in Mediterranean contexts. The blueprint incorporated frameworks (e.g., RAST, IUCN, ISO 14090, CER) that do not synergistically consider all elements in such studies, enabling the prioritisation of interventions to implement NBS and strengthen the resilience of CI. This new framework can analyse the contexts of various frameworks while considering local characteristics, helping to resolve conflicts between interventions and frameworks and set local policy priorities. Specifically, this study focused on operationalising the blueprint framework via the PPCP® approach in two urban infrastructure case studies centred on heatwave adaptation, thereby identifying tailored NBS-based adaptation strategies with pronounced social benefits. The methodology validation was conducted during these PPCP® workshops through expert feedback. This was achieved through the exchange of opinions and recommendations among participants which informed the refinement of the methodology.

Subsequent research will entail the practical application of the blueprint methodology to guide the selection, implementation, monitoring, and evaluation of NBS within the designated case study areas. Additionally, particular emphasis will be placed on conducting comprehensive risk and resilience assessments of CI. Further investigation will assess the extent to which the deployment of NBS can effectively mitigate the risk associated with CI.

Author Contributions: Conceptualization, D.V. and A.S.; methodology—validation, D.V., I.Z., A.S., J.R., A.J., M.D., V.S. and D.T.; formal analysis, D.V., I.Z., A.S., J.R., C.F., A.J., V.S., M.D. and D.T.; investigation, I.Z., A.S., C.F., A.J., V.S. and D.T.; resources, I.Z., A.S., C.F., A.J., M.D., V.S. and D.T.; writing—original draft preparation, D.V.; writing—review and editing, D.V., I.Z., J.R., C.F., A.J., M.D. and V.S.; project administration, A.S., C.F., V.S. and D.T.; funding acquisition, A.S., C.F., V.S. and D.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union's Horizon Programme, European Climate, Infrastructure and Environment Executive Agency (CINEA), HORIZON-MISS-2023-CLIMA-01, Grant Agreement Number 101157707—Med-IREN.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors acknowledge the kind participation of workshop participants from the communities of Egaleo and Helsinki.

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

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