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A climate services organization supporting coastal resilience: lessons from the Stone Living Lab

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Abstract
There is a growing recognition that effective climate adaptation requires organizations that can translate science into policy-relevant, place-based implementation. The Stone Living Lab (SLL) was established as a climate services organization to help bridge the gap between climate adaptation research and real-world application. In this paper, we present the Lab as a model for how universities and NGOs can partner with government agencies, Indigenous groups, and local communities to strengthen coastal resilience, highlighting the structures, guiding principles and lessons learned over the last five years. Four guiding principles shape and distinguish the Lab's approach, extending beyond the traditional focus on science and engineering research to also include climate preparedness, education and outreach and policy engagement. These principles continue to evolve in response to experience, particularly in navigating complex partnerships and engaging with stakeholder networks, which require sustained coordination, clear communication, and intentional alignment of roles, expectations, and timelines. Other lessons highlight the importance of visible, place-based solutions, knowledge sharing and maintaining a clear mission focus while balancing short-term outcomes with long-term resilience goals. Our aim here is to provide practical insights for researchers, practitioners and managers seeking to design or strengthen similar climate services organizations.

Keywords Nature-based approaches · Living lab · Climate change adaptation · Coastal resilience · Boundary organization · Translational science

1 Introduction

As a result of climate change, coastal cities around the world face mounting threats from rising sea levels, intensifying storms, and chronic flooding (IPCC, 2022; Sandifer and Scott 2021). Responding effectively to these challenges requires that scientific understanding

Extended author information available on the last page of the article

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of climate impacts be translated into timely information that can inform planning, policy and on the ground decisions (Lawrence et al. 2021). Interdisciplinary climate services that bridge science and decision-making are essential to help communities understand, anticipate, and respond to climate change (Hewitt et al. 2012). Climate services are the provision of climate information in a way that supports decision-making, involving user education, scientific credibility, and accessible delivery mechanisms (Hewitt et al. 2012). These services are critical for translating climate data into actionable insights that inform planning, policy, and public understanding. In the United States, climate service providers, particularly those based in or partnered with research universities, such as the North Carolina State Climate Office hosted at North Carolina State University and the Climate Impacts Group hosted at the University of Washington, play a critical role in this community of practice (Miles et al. 2010; Saia et al. 2023). Acting as boundary organizations (e.g. Graham and Mitchell 2016) or knowledge brokers, climate service providers are essential for ensuring that climate adaptation strategies are grounded in science, responsive to community needs, and capable of addressing climate change. However, successful climate services organizations remain rare and how they operate in practice is rarely documented.

Boston's exposure to sea level rise, coastal storms and aging infrastructure (Box 1) has highlighted the need for climate solutions that are not only scientifically robust, but also policy-relevant, scalable and implementable (Kirshen et al. 2008). Traditional approaches to coastal protection have relied heavily on hard engineered coastal flooding and erosion solutions such as seawalls, levees, and storm surge barriers (Bongarts Lebbe et al. 2021). While these structures can reduce immediate flood risks, they come with significant trade-offs (Reguero et al. 2018) and reflect a broader history of engineered approaches that prioritize control and stability over adaptability to dynamic environmental systems (Simonsen, 2006). Hard engineered structures are expensive to build and maintain, can disrupt natural sediment flows and marine habitats, may exacerbate flooding in adjacent areas, and have limited adaptability to long-term climate change (Bishop et al. 2017; Gonyo et al. 2023; Reguero et al. 2018). In many cases, hard engineering for protection alone fails to address the long-term challenges of sea level rise and can create a false sense of security that delays more adaptive planning and promotes more development (Bongarts Lebbe et al. 2021). Furthermore, hard barriers often sever the connection between people and the water, creating physical and psychological divides that limit opportunities for recreation, education and cultural engagement with coastal environments (Grothues et al. 2025). Together, these limitations underscore the need for evidence-based climate adaptation solutions that do not perpetuate the problems of traditional grey infrastructure and instead provide multiple, long-term benefits.

At the same time, decision-makers have faced a critical knowledge gap about alternatives to hard barriers. While Nature-based Approaches (NbA) and hybrid solutions have expanded, offering a potential alternative to grey infrastructure, there has been limited capacity to test these approaches under real-world conditions, translate findings into policy and support their implementation at scale. In this paper we use NbA rather than the more commonly used "Nature-based Solutions (NbS)" to reflect an understanding that these interventions are not complete or standalone solutions to climate change, but rather context-specific strategies that can support adaptation alongside efforts to reduce emissions and address underlying drivers of climate risk (Seddon et al. 2020). NbA, such as restoring wetlands, building living shorelines and deploying hybrid infrastructure learn from and work with natural systems to buffer wave energy, reduce erosion and flooding, and provide co-benefits such as biodiversity enhancement and recreational space (Seddon et al. 2020). NbA are inherently adaptive (Perricone et al. 2023), may be more cost-effective over time (Reguero et al. 2018), and can be co-designed with communities to reflect local values and needs (Basnou et al. 2020). They also allow communities to reframe their own role in local ecosystems. But many promising innovations often remain disconnected from decision-making, slowing their uptake into practice. As interest in these approaches grows, so too does the need for climate service providers who can generate, translate, and apply the science needed to implement them effectively.

The Stone Living Lab (SLL) emerged in response to this gap in climate services and commenced in 2020 after the release of a University of Massachusetts Boston (UMass Boston) report titled, "Feasibility of Harbor-wide Barrier Systems" (Kirshen et al. 2018) and a series of powerful winter storms that exposed the vulnerability of Boston's coastal systems (Fig 1). The barrier study (Kirshen et al. 2018) evaluated two major storm surge barrier options for Boston Harbor, but concluded that such approaches would be costly, slow to implement (20–30 years) and insufficient to address long-term sea level rise. As a result, the report recommended prioritizing near-term, adaptive strategies such as shoreline-based, and nature-based solutions. At the same time, the storms underscored the protective role of natural systems, including the Boston Harbor Islands, which reduce wave energy, attenuate storm surge and limit coastal erosion through their physical structure and ecological complexity, and reinforced the need for approaches that enhance, rather than replace, these natural buffering functions (Reguero et al. 2018). Together, these events and findings shifted thinking among different stakeholders toward more flexible, adaptive and multifunctional solutions, but also highlighted the absence of a mechanism to test, evaluate and mainstream these approaches.

The SLL was therefore conceived as a climate services organization from conversations among members of the James M and Cathleen D Stone Foundation, the Boston Harbor Islands Partnership, UMass Boston, and international experts such as Professor Kongjian Yu. The shared vision was to create a "living laboratory" where innovative strategies could be tested in a real-world setting, and where science and policy would converge to drive meaningful change. In this model, experimentation is not isolated from decision-making, but embedded within it, enabling continuous feedback between research outcomes, planning instruments, regulatory processes and community priorities (Fig 2).

Fig. 1 The origins and evolution of the Stone Living Lab from 2018–2024 with major milestones included

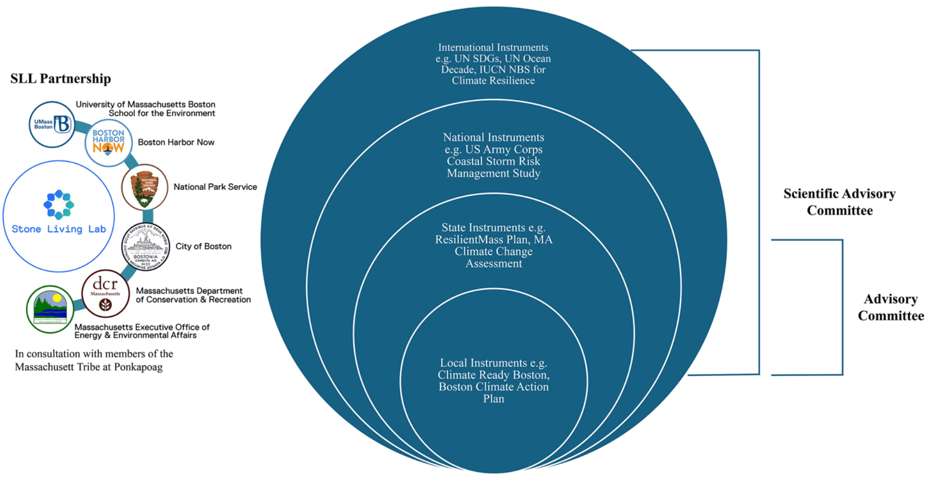

Fig. 2 Stone Living Lab partnership and connections to local, state, national and international policy instruments through our supporting committees

2 The Stone Living Lab and Partnership

In this section we describe the current multi-partner collaboration of the SLL to provide background for the complexity of this effort and to ensure the reader understands the context from which we support our "Guiding Principles" and draw our "Lessons learned from the First Five Years" in the sections below. The SLL operates through a core partnership that provides strategic direction, two lead organizations responsible for implementation, and a set of advisory and operational committees that ensure scientific rigor, stakeholder engagement and effective delivery of activities (Fig 3).

The core SLL Partnership, which includes UMass Boston, Boston Harbor Now, the National Park Service, the Massachusetts Department of Conservation and Recreation, the Massachusetts Executive Office of Energy and Environmental Affairs, and the City of Boston, as well as representation from the Massachusett Tribe at Ponkapoag, provides strategic direction and ensures that research aligns with local needs and regional climate resilience goals. This whole-of-government and cross-sector approach reflects best practice in climate adaptation, where coordination across institutions is essential to address complex challenges (Huitema et al. 2016). The Lab's conversations with Elizabeth Solomon, an elder of the Massachusett Tribe at Ponkapoag have also highlighted the need for reciprocal, long-term collaboration with Indigenous representatives. These efforts align with growing recognition that effective climate adaptation requires integrating diverse knowledge systems (Norström et al. 2020).

Day-to-day implementation is led by two organizations with complementary roles typical of climate services partnerships. UMass Boston, a minority public university located on a peninsula in Boston contributes scientific expertise, research infrastructure, and training capacity. Boston Harbor Now (BHN) is a nonprofit organization focused on public access and harbor stewardship and plays a critical role in translating research and aligning projects with regional planning priorities. This integration of academic and community-facing insti-

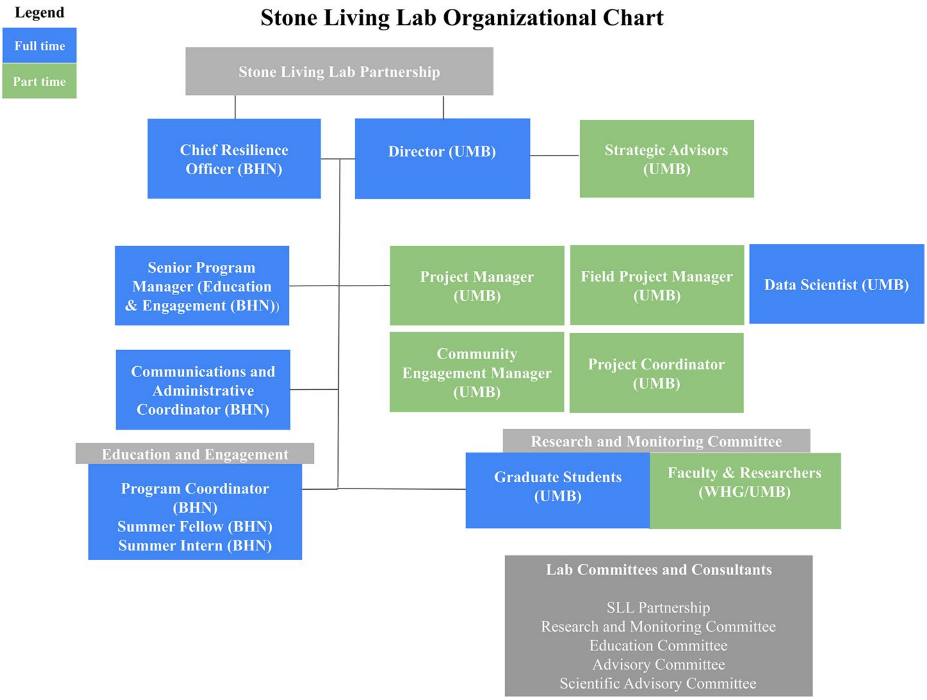

Fig. 3 The Stone Living Lab organizational chart highlighting key personnel and organizations as well as committees

tutions reflects established climate services frameworks that emphasize co-production of knowledge and alignment with user needs (Cann et al. 2024).

Supporting the SLL Partnership are several advisory and operational bodies that ensure the Lab's work remains scientifically robust, policy-relevant and responsive to stakeholder needs. The Scientific Advisory Committee (SAC) brings together experts in coastal science, engineering, and environmental policy to guide the Lab's research agenda and ensure scientific integrity. The Advisory Committee connects the Lab's work to broader stakeholder networks, including community organizations and the private sector, helping to amplify impact and support knowledge exchange. Internally, the Research and Monitoring Committee (RMC), a hands-on team of biophysical scientists, social scientists, urban planners, engineers, and educators, plays a critical role in co-designing research questions, coordinating monitoring across sites and projects, and ensuring that data collection supports decision-making. Additional structures, such as the Education Committee and partnerships with initiatives like the UMass Boston Sustainable Solutions Lab, are beginning to extend the Lab's effectiveness as a climate services organization by supporting climate preparedness, workforce development, community engagement and social justice.

Together, these strategic groups enable the Stone Living Lab to link science, policy and practice, while addressing the need for tested and scalable climate adaptation solutions. We present the Lab as a model for how climate services organizations can support cities like Boston in moving from risk assessment to implementation for effective climate adaptation.

3 Guiding principles of the Stone Living Lab

The Stone Living Lab follows four guiding principles that serve as the pillars of its climate services. First, it conducts scientific and engineering experiments to enhance the resilience of coastal systems while optimizing environmental and social benefits. Second, it promotes creative and adaptive coastal strategies to prepare for and respond to climate change. Third, the Lab shares learnings with communities through education and outreach programs. Finally, the Lab collaborates across disciplines including biophysical and social sciences, urban planning, and engineering to inform effective policy development. The following sections discuss each of the guiding principles with current examples from the Lab.

Research - Conducting experiments in science and engineering to observe, understand and increase the resiliency of natural and built coastal systems while maximizing co-benefits.

Stone Living Lab uses real-world experimentation to inform coastal resilience by measuring physical protection as well as environmental co-benefits. Demonstration projects such as local tests of cobble berms for erosion mitigation (Bond et al. 2025) and Living Seawalls for biodiversity enhancement (Bishop et al. 2022) provide testbeds for NbA across Massachusetts. These pilots provide site-specific evidence of how such interventions can reduce erosion, buffer storm surge, and/or enhance biodiversity, and add data to a growing evidence base on the efficacy of NbA (Paxton et al. 2024). By embedding these experiments in dynamic coastal environments like Boston Harbor, the Lab generates insights into local permitting, design, performance, and maintenance requirements for scaling these strategies more widely (Vozzo et al. 2024). Importantly, the Living Seawalls are also part of a global network of sites that is providing evidence of how the intervention performs under different environmental scenarios, directly addressing a major knowledge gap in the field (Firth et al. 2024).

To support this experimentation, the Lab has established monitoring infrastructure, including real-time and long-term periodic (seasonal and/or yearly) biophysical data collection. Lab researchers and monitoring instruments track environmental conditions, topographic and bathymetric change, and ecological responses, creating a strong evidence base for decision-making. The Lab has received funding from the Stone Foundation and the Executive Office of Energy and Environmental Affairs to establish and expand a Climate Change Observatory that includes a full meteorological station; two wave buoys that track wave heights, wind speed and direction; many sonar- and radar-based tide gauges and water level sensors to detect and measure overland flooding (Fig 4); terrestrial laser scanning surveys that monitor shoreline change and erosion patterns; vessel-based acoustic surveys to map the nearshore marine system coupled with Unoccupied Aerial System (UAS), or drone surveys, to map the terrestrial system; and biological surveys that monitor species diversity and habitat use. Other periodic data collection also includes the deployment of Acoustic Doppler Current Profilers (ADCPs) and tilt current meters to characterize nearshore hydrodynamic and fine-scale water flows near NbA sites. These methods together enhance the long-term assessment capacity of the Lab, providing data streams that are essential for evaluating the effectiveness of nature-based approaches over time and under varying climate conditions. As Paxton et al. (2024) note, site-specific monitoring is crucial for understanding how NbA perform in dynamic coastal environments. Similarly, Moraes et al. (2022) emphasize that robust monitoring frameworks are key to scaling and replicating NbA, yet many projects still lack the detailed performance metrics needed for broader adoption.

Fig. 4 An example of overland flooding along Border St in East Boston that now has an overland flood sensor installed as part of the Stone Living Lab Climate Change Observatory. Image taken on 13th February 2024 by Brittany Knotts

The social co-benefits of NbA, such as improved water quality, enhanced recreational opportunities from landscape improvements, building a connection to nature and a sense of place, better access to green space or water bodies, access to local food sources, and righting past injustices, have resulted in significantly increased interest in NbA flood-risk-reduction and erosion measures (Chausson et al. 2020; Stroud et al. 2022). To meet this need, the Lab has also supported case studies on how to ensure that the social benefits of NbA can accrue to local stakeholders (A Better City 2024; Griffin 2024; Luna and Neumann 2024). Future plans include direct measurements of social co-benefits accrued from NbA implementation in local communities.

The Lab's research has been co-designed with a broad network of partners from universities and nonprofits to government agencies. The Lab's study on cobble berms, for example, is demonstrating how soft coastal engineering approaches can naturally stabilize shorelines (Bond et al. 2025) and may enhance biodiversity compared to hard engineering. Co-funded by the Stone Foundation and Massachusetts Office of Coastal Zone Management (CZM), the project evaluated the effectiveness of cobble berms in reducing coastal erosion while enhancing ecological value. The potential co-benefit of engineering resilience and ecological enhancement (Morris et al. in prep; Bosma et al. in prep), has made cobble berms an attractive option for coastal adaptation by municipalities such as the Town of Hull who have implemented additional sites.

Fig. 5 Living Seawalls panels installed on existing seawalls in East Boston at Condor Street Urban Wild These modular panels mimic the complexity of natural intertidal habitats, providing refuge for marine organisms

In addition to cobble berms, the Lab's implementation of Living Seawalls habitat enhancement panels (Bishop et al. 2022) provides another example of how engineered infrastructure can support biodiversity. Installed on existing seawalls in the Seaport District at Fan Pier, and in East Boston at Condor Street Urban Wild, these modular panels mimic the complexity of natural intertidal habitats, providing refuge for marine organisms (Fig 5). The interdisciplinary project is a collaboration with marine ecologists, engineers, and local agencies, and includes ongoing monitoring to assess ecological outcomes such as species colonisation. Like the cobble berms, the Living Seawalls installations demonstrate how science-driven design can yield multifunctional infrastructure (Dafforn et al. 2015).

Climate Preparedness - Promoting creative, equitable, and flexible coastal adaptation while preparing for and responding to climate change.

The Stone Living Lab convenes diverse stakeholders and fosters cross-sector collaboration through a series of conferences and seminars. The Lab seminar series offers regular opportunities for researchers, practitioners, policy makers, and community members to engage with emerging science and share insights on NbA, climate justice, community resilience, and adaptive design. These conversations complement the Lab's larger convenings, such as its inaugural 2021 virtual conference, *Resilient Boston Harbor: Research for a Sustainable Future*, which brought together over 125 participants to identify research needs and explore new innovations in NbA. Building on this momentum, the 2023 in-person conference at UMass Boston emphasized place-based science, community engagement, and policy integration. The 2025 conference continued the focus on nature-based resilience in urban coastal settings, drawing over 300 attendees across disciplines and sectors and was organized around four core themes: permitting, policy and finance; project design and assessment; urban ecology and engineering; and community engagement, equity and workforce development.

These convenings are designed to share research as well as create structured dialogue between scientists and decision-makers around the barriers and opportunities for climate adaptation implementation. For example, sessions focused on permitting, policy and finance brought together regulators, engineers and scientists to discuss how emerging evidence from demonstration projects could inform approval processes and investment decisions. This approach has contributed to greater awareness and consideration of NbA within regional planning efforts, including the integration of cobble berms and Living Seawalls into state-level resilience planning frameworks such as the Massachussetts ResilientCoasts Initiative. These outcomes have highlighted the importance of directly sharing scientific evidence with planning and decision-makers, while also strengthening relationships and networks that are essential for climate preparedness.

Education - Education and outreach programs that promote innovation, community involvement, and facilitate hands-on research activities inclusive to all.

The Stone Living Lab shares knowledge with local communities through inclusive education, outreach, and participatory science. By integrating students and educators into its work, the Lab hopes to cultivate a new generation of leaders who understand and can apply different approaches to climate adaptation such as NbA. Undergraduate and graduate students contribute directly to research through lab and field work, while K–12 educators are supported through initiatives like the Summer Teacher Institute. This is a free, five-day workshop that explores climate change through place-based learning and participatory science. Now in its fourth year, the Institute has built a growing network of over 50 alumni educators. The Lab also seeks to involve local high schools in the monitoring of and education about NbA trials, such as East Boston High School, located near the Condor Street Urban Wild Living Seawalls. Teachers at East Boston High have participated in the Lab's Summer Teacher Institute and now apply experiential learning directly linked to the Lab's research projects.

The Lab also collaborates with more than 30 education organizations to support climate education programming across the region. Through partnerships with groups like Boston Children's Museum, New England Aquarium, Museum of Science, Save the Harbor/Save the Bay, the Trustees' Waterfront Ambassadors, and the National Parks of Boston Stewardship Corps, youth gain hands-on field science experience and exposure to environmental careers. Participatory science initiatives, such as beach profiling, intertidal monitoring, and flood observation have invited residents to contribute directly to research. For example, during a one-year project, a UMass Boston graduate student from the Lab led an effort that involved local volunteers collecting 172 beach profiles at 12 different beaches around Boston Harbor (O'Connell, et al. 2023). The student developed step-by-step materials for each of the 12 volunteer teams, taught the teams in-person at their respective beaches, and followed up for data collection and to answer questions. At the end of the project a social event was conducted for all participants to share stories and observations about what they learned about themselves and the beaches they we're studying. Many commented that the work taught them much more about a beach that they were familiar with and they had gained a greater understanding of data collection and analysis conducted by scientists. Notably, when the teams were told that their data largely corroborated the impacts of a modelled storm from a local study (Kirshen, et al. 2020) to an actual storm that occurred during the project, there was a widely expressed sense of satisfaction from the volunteers. The graduate student training in the Lab also exemplifies our commitment to workforce development and in this example, the student was hired by an engineering firm on graduation.

Public education is further amplified through creative outreach tools like the Climate Cart, which appears at events and cultural institutions across the city, including the Museum of Science, the New England Aquarium, and the Boston Children's Museum. The Lab's High Tide Trail and accompanying audio tour, developed with the National Parks of Boston, offers year-round opportunities for the public to explore the impacts of sea level rise and the city's adaptation efforts. These programs not only raise awareness but we also hope they will eventually create feedback loops, where community insights help shape future research and design.

Policy - Collaborating broadly to conduct research on policy and planning, *disseminate scientific findings and inform policy development.*

The Stone Living Lab shares its findings in a variety of dissemination materials to inform the policy frameworks that govern coastal adaptation. This includes identifying where existing regulatory processes may limit the implementation of nature-based and hybrid approaches and providing evidence-based insights to support more equitable, flexible, and ecologically sound infrastructure. In this context, the Lab's role is not to advocate for specific policy positions, but to serve as a boundary organization that generates and communicates knowledge to inform decision making. For example, the Lab contributes expert knowledge to policy papers such as supporting reports by the Urban Ocean Lab (Carter et al. 2025) that explain the role of NbA in urban coastal planning. Members of the Lab have also provided expert testimony on state legislative bills and offer technical feedback on state planning documents, helping to align policy with the latest scientific findings. These efforts ensure that climate adaptation strategies are not only innovative, but also implementable within existing governance structures.

To bridge the gap between research and practice, the Lab engages directly with municipal planners, engineers, and conservation professionals through field courses and technical training sessions. These immersive experiences have been developed as part of the Lab's cobble berms project to allow practitioners to observe the berms in action, understand their design and performance, and explore how they might be adapted to other coastal contexts. This model of knowledge exchange and capacity building strengthens the bridge between science and practice, enabling faster and more informed adoption of innovative solutions (Norström et al. 2020). As a result, the cobble berm approach is now influencing applications at additional sites such as in the Town of Hull, demonstrating the power of research-practitioner partnerships in scaling climate resilience.

4 Lessons learned from the first five years

Over the last five years (2020-2024) since its founding, the Stone Living Lab has navigated multiple challenges as an emerging climate services organization. This section reflects on key lessons learned ranging from organizational structure and stakeholder coordination to community collaboration and knowledge sharing. These insights are informing the Lab's future directions, and we offer them here to provide support for other similar initiatives.

One of the key lessons learned through the development of the Stone Living Lab was the value and complexity of a hybrid organizational structure. The leading organizations in the partnership include a smaller and more agile nonprofit, Boston Harbor Now, and a well-resourced research institution, UMass Boston, which work together to develop scientific projects with potential impact for multiple stakeholders. Boston Harbor Now brought flexibility, responsiveness and community connectivity, enabling the Lab to engage quickly with stakeholders and adapt to emerging needs. For example, Boston Harbor Now supported the early development and delivery of education and outreach programming by the Lab by sharing existing climate education materials for public-facing initiatives, and has enabled faster contracting and invoicing processes than would typically be possible within a university setting, allowing projects to respond more quickly to emerging opportunities. The organization has also expanded access to diverse funding sources, including state and philanthropic funding streams, and helps to share out the Lab's activities with regional networks such as the Boston Harbor Islands Partnership and the Boston Green Ribbon Commission. Meanwhile UMass Boston has contributed diverse research expertise, capacity building in undergraduate and graduate students, a permanent academic home, and critical infrastructure, such as vessels, lab facilities and convening spaces to support scientific inquiry and stakeholder collaboration.

However, this model also presented operational challenges. Personnel have been spread across multiple locations, making coordination and communication sometimes difficult during time-sensitive projects. Differences in organizational structure and work culture between UMass Boston and Boston Harbor Now have further contributed to these challenges. For example, faculty and graduate students at UMass Boston are typically engaged in the Lab on a project basis, often contributing only a portion of their time while balancing teaching, other research and administrative responsibilities. In contrast, Boston Harbor Now staff have worked in full-time roles with greater continuity of availability and focus on the Lab. These differences in time allocation and working patterns have sometimes resulted in misaligned expectations around timelines, responsiveness and deliverables. Additional challenges have resulted from the functional distribution of expertise across organizations. Most scientific research activities have been based at UMass Boston, while public engagement, education and communications staff have been primarily located at Boston Harbor Now. While this division created strong complementary capacity, it also required additional effort to ensure alignment between research outputs and their translation into community-facing programs. Navigating these structural and cultural tensions has required a willingness to learn partners' perspectives, intentional leadership, open and regular communication including weekly to monthly meetings of different groups supporting the lab, quarterly newsletters and shared summaries of research activities. Over time, these practices, combined with a shared commitment to the Lab's overarching mission, have helped build trust, improve coordination and strengthen the effectiveness of this hybrid organizational model.

Another key lesson learned in the development of the Stone Living Lab was how to balance the priorities and needs of government partners to access diverse expertise and perspectives. The Lab has benefitted from the diverse perspectives of its strategic groups, including the SLL Partnership, Scientific Advisory Committee and Advisory Committee, with each individual representative on these committees contributing unique expertise, priorities, and lived experiences. These partnerships have strengthened the Lab's approach to climate services by ensuring that decisions are informed by a broad and inclusive range of viewpoints. The Lab also learned that consensus-building across such a diverse group of stakeholders takes time and intentional effort and is sometimes not possible because definitions of success often vary. For example, within the academic context, success is often linked to securing research funding, generating new knowledge and producing high-impact peer-reviewed publications. In contrast, the Lab's government partners have defined success in terms of actionable outcomes, such as having sufficient evidence and confidence in NbA to support implementation, permitting and investment decisions. These differing priorities can lead to variation in timelines and preferred outcomes (from coastal protection to adaptation to restoration). As a result, the Lab has needed to invest in building trust between and among individuals and organizations, clarifying roles, and developing a shared understanding of how different measures of success can be aligned or balanced within individual projects. This was done through iterative feedback sessions with each committee and the development of shared Terms of Reference that individuals agreed to on behalf of their organizations, but that will continue to be reviewed as they are operationalized. The Lab emphasised the importance of complementing rather than duplicating partner initiatives to avoid confusion and maximize collective impact. These experiences highlighted the need for a nuanced understanding of partner goals, activities and constraints, and for ongoing dialogue to align efforts while respecting each entity's autonomy and priorities.

The Lab also found that, in some cases, demonstrating a potential solution through implementation was essential to build trust, maintain momentum and engage partners. While researchers routinely share work in progress through academic channels and with selected end-users, the Lab's experience highlighted the importance of visible, place-based demonstrations that stakeholders could directly observe and evaluate in real-world contexts. Early applications, such as the Living Seawalls installations where colonisation of panels by mobile species occurred quickly, helped generate enthusiasm and trust, showing that the Lab could deliver measurable biodiversity benefits. In this context, research that could be experienced directly through site visits, field demonstrations and public engagement proved especially valuable and allowed the Lab to illustrate possibilities and spark more dialogue. This model differs from a more traditional scientific model of research to publication pathway not in the timing of communication, but in the emphasis on implementation, co-observation and iterative feedback within real-world systems. While this required some adjustment in workflows and timelines, it has strengthened relationships and supported ongoing collaboration between scientists and partners in the Lab.

The Lab has also recognized the importance of disseminating knowledge through a diverse suite of outputs tailored to different audiences and decision-making contexts. These include technical reports that document the monitoring of NbA projects, such as ongoing work on cobble berms and saltmarsh health monitoring. To support implementation the Lab has also developed targeted factsheets that distill key considerations around design, permitting and installation for interventions like cobble berms and monitoring tools like overland flood sensors. In addition to these technical products, the Lab communicates through website blogs, newsletters and social media, helping to translate emerging science into accessible narratives for practitioners and the public.

Building on these efforts, the Lab has hired a Data Scientist and is developing a data products strategy to enhance the accessibility and usability of its monitoring data. This includes simple measures such as making all data available on repositories, and also includes translational efforts such as the creation of interactive dashboards that provide access to real-time data from the Lab's monitoring network. Further public-facing tools are in development to support the interpretation and application of the Lab's data. These approaches to dissemination help to ensure that knowledge is not only generated, but also translated and delivered in formats that support decision-making, learning and wider engagement.

Additionally, we have been learning the importance of collaborating not only with core partners from government, but also with Indigenous community members including the Massachusett Tribe to meaningfully incorporate both Western science and Indigenous ways of knowing into the Lab's research projects. Early interactions with the Massachusett Tribe at Ponkapoag revealed limitations in the Lab's approach to engagement, which was largely framed around presenting pre-developed, science-driven project ideas and seeking feedback, rather than engaging in genuinely collaborative, co-design processes from the outset. These early interactions were also focused on coastal protection for human infrastructure using NbA to reduce erosion, waves and storm impacts for, and conversations with Elizabeth Solomon, elder of the Massachusett Tribe, highlighted that these objectives don't align with the Tribe's perspectives that emphasize working with natural systems, including adapting to and evolving with environmental change such as sea level rise.

Ongoing conversations with Elizabeth Solomon have played a critical role in reshaping the Lab's approach. These discussions have emphasized the need for reciprocal, long-term relationships and have challenged the Lab to reconsider assumptions about resilience, including the role of humans as part of nature, rather than separate from it. An example of this evolving approach emerged through a subsequent collaboration on Rainsford Island in Boston Harbor, where a project to restore human-nature connections was led by members of the Tribe and co-designed with researchers from UMass Boston. This project represented a shift toward shared agenda-setting and more inclusive design and while not ultimately funded, provided a valuable model for how the Lab might better support Indigenous-led initiatives in the future.

The Lab's approach to engaging local community members is also evolving to better ensure that the work reflects community needs and delivers benefits directly to communities. Early efforts included the creation of a position for a Director of Climate Engagement, whose role was to convene stakeholders, facilitate Advisory Committee meetings and lead outreach strategies. The position concluded early when the individual in the role took another position, at which point we recognized the Lab did not have the capacity to sustain the coordination, communication and convening required to fully activate the Advisory Committee and facilitate community engagement. This highlighted the challenge of requiring dedicated personnel to maintain engagement and the need for clearly defined roles and value for Advisory Committee members to ensure their continued participation. As a result, the Lab undertook a process of reflection on how to move beyond one-directional communication towards more mutually beneficial engagement. This included reconsidering how the Advisory Committee could contribute to the Lab's work, while also ensuring that members derived value through access to research, cross-sector networking and opportunities to shape future research priorities. These insights informed the transition to a restructured Advisory Committee with more clearly defined roles including the participation in working groups and disseminating Lab findings across networks. The Lab has also moved toward a more sustainable model of engagement through the establishment of a joint Community Engagement Manager position with Sustainable Solutions Lab, a community-engaged research institute at UMass Boston, that would be better placed to have long-term impact and inclusive engagement.

This evolution in focus also highlighted the importance of inclusive, region-wide collaboration, especially in the context of large-scale planning efforts like the Harbor-wide barrier study. Early collaboration efforts were concentrated within the City of Boston, despite the fact that surrounding communities would be directly affected by such interventions. The lack of collaboration with these communities created a perception that the process was Boston-centric, limiting opportunities to incorporate local knowledge and priorities further afield. In response, the Lab has broadened its collaboration strategy, conducting proactive outreach to municipalities beyond Boston, with many represented on the Lab Advisory Committee.

We have continually been reminded of the critical need to stay focused on core goals, objectives, and principles, even amid growing regional demand for a wide range of climate services. From the outset, the Lab was designed to innovate and implement NbA for coastal protection, particularly in vulnerable shoreline areas. While the urgency of climate change has generated interest in expanding the Lab's scope to address the impacts of climate change on inland regions, as well as heat resilience, the Lab has remained focused on its original mission around coastal resilience. This commitment allows us to minimize mission creep, or the tendency to take on too many roles or respond to every request, which can dilute impact, strain resources, and confuse stakeholders. Trying to be everything to everyone risks undermining the Lab's effectiveness and identity, and requires different staff expertise than currently available. Instead, the Lab has worked to align its efforts with the strategic priorities of core partners, while collaborating with other initiatives such as the Sustainable Solutions Lab (described above) to address complementary climate challenges.

The permitting process for the Living Seawalls installations in Boston offered additional key lessons in navigating complex regulatory landscapes for nature-based approaches. Securing approval required coordination across multiple jurisdictions and stakeholders, beginning with obtaining permissions from relevant landowners to access and modify sites. The project then moved through the City of Boston's Conservation Commission, where approvals were sought for a three-year demonstration. A Chapter 91 license was also required to ensure compliance with Massachusetts' public waterfront access regulations. At the federal level, the U.S. Army Corps of Engineers reviewed the project under Section 10 of the Rivers and Harbors Act, where a key challenge emerged: the potential presence of a migratory bird species in the project area. This triggered additional scrutiny and necessitated careful documentation and mitigation planning to avoid ecological disruption. The Living Seawalls installation in Plymouth, UK led by a member of our SAC, Louise Firth, had a similar experience where one requirement written into the permits was that the panels would be removed if a specific invasive oyster colonized. These experiences echo findings from Nelson et al. (2020), who emphasize that NbA often face governance hurdles due to fragmented permitting systems, unclear regulatory pathways, and the need to reconcile ecological goals with existing infrastructure and land use priorities. Similarly, recent literature underscores that permitting for NbA is rarely streamlined, particularly when projects intersect with sensitive habitats or require novel design elements that fall outside traditional regulatory frameworks (Firth et al. 2024; Vozzo et al. 2024). NbA demand understanding of site resources and conditions, early and sustained engagement with permitting agencies at all levels of government, interdisciplinary coordination, reasonable projections of climate impacts on natural and built systems, and adaptive governance structures that can accommodate ecological and climate uncertainty. The Boston Living Seawalls experience reinforces the importance of relationships and building trust with regulators, integrating ecological data early in the design process, and framing NbA not as exceptions but as components of resilient urban planning. While the specific permitting pathways and regulatory requirements encountered in Massachussetts are not directly transferable across jurisdictions, the broader lessons may be applicable. In particular, the need for early and sustained engagement with regulators, the integration of site-specific ecological data into design and the role of demonstration projects in building confidence to support implementation in other regulatory contexts, even where governance frameworks differ.

Finally, a key lesson learned through the Lab's work has been the importance of aligning actions and expectations across different timescales. In research, this has meant balancing the need for early, visible impact with the longer-term goal of building a robust scientific evidence base. NbA are not proposed as a "quick fix" and stakeholder expectations about immediate results from projects require managing so that the longer-term gains can be realised. Relationship-building has also required time and consistency through shared wins, open communication, and visible collaboration. One example was the "Habitat Housewarming" arranged after the Living Seawalls were installed that brought multiple stakeholders together. While this occurred before substantial ecological growth on the panels, the installations still served as visual and experiential tools. Seeing the intervention in place helped make the concept accessible, and the act of convening stakeholders around the site initiated new conversations about potential collaborations. Over longer timescales we expect the value of these demonstration sites to grow as ecological communities develop and monitoring data are collected and shared. Together this combination of early, visible demonstration and longer-term evidence generation have been important for building confidence and sustaining engagement.

5 Future directions

Over the past five years (2019-2024), the Stone Living Lab has evolved as a climate services organization through a series of demonstration projects that have generated valuable scientific evidence and informed permitting pathways. Looking ahead, our priority is to expand the diversity and innovation of these demonstration projects to inform the implementation of full-scale installations and policy integration. This includes testing NbA that restore or enhance natural systems, such as nearshore and offshore boulder fields and sponge-city concepts (Yu 2021) inspired by interactions with Professor Kongjian Yu, while leveraging an expanded Climate Change Observatory to provide high-quality, accessible environmental data that supports both scientific inquiry and public decision-making.

With respect to decision-making, while the Lab has been focused on building a scientific evidence base for the effectiveness of NbA, there are still tensions in how these might be implemented from a regulatory perspective. For example, connecting the science to performance standards that might be required by regulators such as FEMA, insurance companies and federal agencies such as the US Army Corps of Engineers will be important to support scaling up. Working across disciplines will also be important to understand the evidence that landscape architects, designers and engineers need when considering NbAs in their design decisions. Through the SLL Partnership the Lab has an opportunity to make these stakeholder connections and ensure that the scientific data can inform scaling at the timescales required for future coastal adaptation.

To further support this work, the Lab is committed to deepening collaboration with a wide range of partners, including the Massachusett Tribe and other local Indigenous communities, by expanding representation in projects and supporting co-learning initiatives that bridge Western science and Indigenous knowledge systems and integrate model strategies with local contexts. This approach ensures that infrastructure is co-designed with local knowledge and skills, avoiding the pitfalls of gray infrastructure that often overlook community priorities and decrease ecological benefits. We have established new Working Groups based on ideas and perspectives shared by Massachusett Tribe elder Elizabeth Solomon. These include longer-term values-based planning for the Lab. Other successful examples of community co-design of NbA include Fonseca et al. (2024) who demonstrated how integrating Indigenous plant knowledge and community governance is important for sustaining services such as clean drinking water, irrigation, fisheries, habitat conservation and other sustainable development goals. Similarly, Reitsma et al. (2019) emphasize the importance of respectful design frameworks that embed Indigenous worldviews and foster shared decision-making spaces.

Recognizing the regional nature of climate impacts, the Lab is also expanding its reach beyond Boston. The Climate Change Observatory is growing to include new monitoring sites along the coast of Massachusetts from Newburyport to New Bedford, selected in collaboration with core partners and local communities. This regional expansion is complemented by ongoing outreach to municipalities and the integration of their priorities into Lab initiatives, ensuring that our work remains responsive and equitable.

Internally, we are strengthening our hybrid organizational model to improve coordination across partner institutions. Plans are underway to establish a Stone Living Lab Hub at UMass Boston, creating a shared space for staff, partners, and collaborators. We are also piloting shared staffing structures with the Sustainable Solutions Lab to align expertise in NbA and community resilience. Revised strategic groups, including a more active Advisory Committee, will help ensure that leadership roles and decision-making processes are clear, inclusive, and responsive.

Throughout this work, we remain focused on aligning actions across timescales to deliver early, visible results while building the long-term evidence base needed for sustained impact. This includes expanding long-term monitoring programs and developing policy pathways that support both immediate action and future resilience. At the same time, we continue to navigate complex permitting landscapes by engaging regulatory agencies early, integrating ecological data into design, and advocating for adaptive governance frameworks that support innovation.

6 Box 1 – Boston's coastal vulnerability

Boston is a historic coastal city uniquely exposed to the impacts of climate change due to its geomorphology, geology and urban development patterns. The harbor includes shallow waters bordered by deeper channels that can amplify storm surge, especially during nor'easters, periodic extratropical storm systems that are among the most impactful weather events for the region. These often occur in winter, bring intense winds, heavy precipitation, and prolonged coastal flooding, particularly when coinciding with high tides.

Much of Boston's modern urban fabric is built on reclaimed land which further contributes to flooding challenges. Since colonial times, extensive landfilling has transformed tidal flats, salt marshes, and estuaries into neighborhoods such as the Back Bay, South Boston, and parts of East Boston. These low-lying areas are often just a few feet above sea level and are therefore especially vulnerable to sea level rise (SLR) and storm-driven inundation. The underlying geology comprises glacial till, marine clay, and artificial fill, which can exacerbate flooding and complicate drainage, while also posing challenges for infrastructure stability under changing climate conditions.

The natural habitats that once buffered the city from coastal hazards have been significantly reduced or fragmented by urbanization. Saltmarsh, eelgrass and dune ecosystems historically played a critical role in absorbing wave energy, filtering runoff, and supporting biodiversity. Their loss has diminished the city's natural resilience and increased reliance on engineered defenses, many of which are aging or inadequate for future conditions.

Climate projections for Boston underscore the urgency of adaptation. Average annual temperatures have already increased by more than 2 °F since the 19th century, with more frequent extreme heat days expected. Sea levels in Boston Harbor have risen by approximately 9 inches since 1950 and are projected to rise another 1.5 to 3 feet by 2050, depending on emissions scenarios. This rise will exacerbate tidal flooding, particularly in neighborhoods built on fill. Combined with more intense precipitation events and higher groundwater levels, the risk of compound flooding is growing.

Boston's vulnerability is not only physical but also social. Many of the city's most flood-prone areas are home to historically marginalized communities, where climate impacts intersect with existing inequities in housing, health, and access to green space. These dynamics highlight the importance of inclusive, place-based approaches to resilience that integrate ecological restoration, community engagement, and climate justice.

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Declarations

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