OFFICE FOR URBANIZATION

THE CARBON COST OF
COASTAL ADAPTATION

A Performance Evaluation Methodology for Nature-based Solutions

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HARVARD UNIVERSITY GRADUATE SCHOOL OF DESIGN

The Carbon Cost of Coastal Adaptation: A Performance Evaluation Methodology for Nature-based Solutions

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Contents

Outer Banks in Rodanthe, North Carolina on Jan. 7, 2023.
Image: Jahi Chikwendiu, The Washington Post via Getty Images

ABSTRACT

If left unchecked, the carbon emissions from coastal adaptation efforts could potentially contribute more than two gigatons of greenhouse gases (carbon dioxide equivalent/CO2e) to global warming by 2050, equivalent to adding the annual emissions of New York City for the next forty years.[1]

According to this study's findings, 45%-64% of those embodied carbon emissions can be avoided now to meet the global 1.5ºC goals, primarily through informed decisions made by the design team regarding sourcing and specifying materials, as well as collaborating with contractors and manufacturers.[2] However, complete nature-based adaptations, with up to 91% improved carbon impacts and 30% less cost, will not be fully realized without support from clients, owners, and municipalities. Carbon limitation requirements are emerging for buildings but do not yet exist for site infrastructure.[3] Sixty-two percent of coastal adaptations within this study exceed the established upper carbon emission limits for buildings, a largely overlooked pattern that will persist without intervention.

When fully implemented, Nature-based Solutions (NbS) can course-correct coastal adaptations from contributing to climate change to becoming net positive solutions.[4] These benefits are not only through adaptation—preventing 173 million lives impacted globally by 2050—but also from mitigation through carbon sequestration, the avoidance of future emissions, and a myriad of ecological benefits.[5]

This case study methodology examines thirteen coastal adaptations from twelve notable U.S. projects, revealing ways to shift from business-as-usual, largely high-emitting site infrastructure to solutions that can fully address both the climate and biodiversity crises.

1 New York City Mayor's Office of Sustainability, "Inventory of New York City Greenhouse Gas Emissions in 2016," The City of New York, 2017, https://www.nyc.gov/assets/sustainability/downloads/pdf/publications/GHG%20Inventory%20Report%20Emission%20Year%202016.pdf.

2 IPCC AR6 Working Group III, "The evidence is clear: the time for action is now. We can halve emissions by 2030. — IPCC," IPCC, 2022, https://www.ipcc.ch/2022/04/04/ipcc-ar6-wgiii-pressrelease/.

3 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

4 International Union for the Conservation of Nature (IUCN), "Guidance for using the IUCN Global Standard for Nature-based Solutions," IUCN Library System 1, no. 1 (7): 78, 2020, https://doi.org/10.2305/IUCN.CH.2020.09.en.

5 E. Kirezci et al, "Projections of global-scale extreme sea levels," 2020; Fred Pearce, "Nature-Based Solutions," 2022.

INTRODUCTION

By 2050, rising sea levels, groundwater rise, and increased stormwater flooding will impact thousands of miles of shoreline in communities around the world unless adaptation measures are taken. Although it is generally understood that NbS can address these risks while providing economic, ecological, and social benefits, these solutions are not yet widely implemented in coastal adaptation efforts, and there is no proven methodology for evaluating their effectiveness.

Without a methodology for evaluating the performance of living infrastructure compared to traditional engineering practices, communities are at a disadvantage. They miss out on potential cost savings, reduced emissions, increased carbon sequestration, enhanced biodiversity, cooling, improved human health, and water infiltration and re-use, as well as opportunities to address inequities.[6]

This study examines various shoreline adaptation techniques in the United States and sheds light on common challenges, including societal perceptions, conflicts with existing policies, and a lack of investment in Nature-based Solutions. Insights from this study will inform the infrastructure needed for 2050, 75% of which is yet to be built.[7] This presents an opportunity to create low-carbon, nature-based infrastructure instead of exacerbating the climate crisis. By developing and testing this methodology, the results of this study may pave the way for widespread implementation of nature-based adaptation solutions.

THE UNREALIZED POTENTIAL OF NATURE-BASED SOLUTIONS

Climate change is accelerating sea-level rise and jeopardizing inhabited coastlines globally, amplifying risks to communities, ecosystems, and infrastructure.[8] As defined by the American Society of Landscape Architects, Nature-based Solutions "are actions designed to work with and enhance natural habitats to take advantage of the ability of healthy natural and managed

6 Fred Pearce, "Why Are Nature-Based Solutions on Climate Being Overlooked?" Yale School of the Environment, 2022, accessed May 9, 2024, https://e360.yale.edu/features/why-are-nature-based-solutions-on-climate-being-overlooked.

7 António Guterres, "Climate Change: An 'Existential Threat' to Humanity, UN Chief Warns Global Summit," United Nations News, May 2018, accessed May 9, 2024, https://news.un.org/en/story/2018/05/1009782.

8 Siddharth Narayan et al., "The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences," Environmental Science and Policy 63 (2016): 63–91, https://doi.org/10.1016/j.envsci.2016.03.014.

ecosystems to sequester carbon and support biodiversity recovery."[9] NbS have emerged as valuable tools for developing adaptive, resilient, and low-carbon coastal designs that safeguard vulnerable populations while providing ecological benefits.[10] By emulating natural coastal features—such as wetlands and dunes—NbS, also referred to as green infrastructure, can offer layered benefits, including wave attenuation, habitat creation, and flood mitigation, which can enhance resilience in ways that traditional engineering cannot.[11]

This study examines the claims that NbS not only strengthen coastal protection and ecological benefits but also hold promise for reducing embodied carbon in essential built environment projects, a key consideration for sustainable adaptation.[12] The implementation of NbS remains limited within the fields of landscape architecture, civil engineering, urban design, natural resource management, and restoration ecology. One of the most pressing knowledge gaps lies in understanding and comparing the carbon impact and costs of NbS versus "gray" or more traditional engineering-forward infrastructure as a critical determinant in the planning and design process.[13]

The initial literature review synthesizes core research and methodologies relevant to coastal adaptation and NbS, including cost-benefit analyses, comparative studies of infrastructure approaches, and evaluations of ecological and economic outcomes.[14] This analysis identified gaps in existing literature and projects, particularly regarding the assessment of embodied carbon, which is crucial for rebalancing business-as-usual gray infrastructure approaches with nature-based alternatives.

This study highlights the significant, untapped potential of Nature-based Solutions (NbS) in providing resilient, cost-effective approaches for coastal adaptation. The findings advocate for cohesive frameworks prioritizing carbon

9 American Society of Landscape Architects, "The Changing Roles of Landscape Design in Nature-Based Solutions," The Field, July 7, 2022, https://thefield.asla.org/2022/07/07/the-changing-roles-of-landscape-design-in-nature-based-solutions/.

10 Ioannis Gidaris and Ioannis Taflanidis, "Construction Cost-Based Effectiveness Analysis of Green and Grey Infrastructure in Controlling Flood Inundation: A Case Study," Science of the Total Environment 697 (2019): 134242, https://doi.org/10.1016/j.scitotenv.2019.134242.

11 Desmond E. McNamara et al., "Estimating the Costs and Benefits of Protecting a Coastal Amenity from Climate Change-Related Hazards Using Nature-Based Solutions," Coastal Management 51, no. 1 (2023): 1–23, https://doi.org/10.1016/j.ecolecon.2022.107499.

12 Anna Biasin, Mauro Masiero, Giulia Amato, and Davide Pettenella, "Nature-Based Solutions Modeling and Cost-Benefit Analysis to Face Climate Change Risks in an Urban Area: The Case of Turin (Italy)," Land 12, no. 2 (2023): 280, https://doi.org/10.3390/land12020280.

13 Gidaris and Taflanidis, "Construction Cost-Based Effectiveness," 2019.

14 Marcus Wishart, Tony Wong, Ben Furmage, Xiawei Liao, David Pannell, and Jianbin Wang, "Valuing the Benefits of Nature- Based Solutions: A Manual for Integrated Urban Flood Management in China". World Bank. (2021). http:// hdl.handle.net/10986/35710.

accounting and sustainable materials, positioning NbS at the core of urban coastal adaptation strategies.

RESEARCH GAPS

A broad literature review identified critical gaps in NbS studies, particularly the lack of embodied carbon accounting across twelve case studies. For example, *The Effectiveness, Costs, and Coastal Protection Benefits of Natural and Nature-Based Defenses* examined wave attenuation across sixty-nine global coastal sites. However, it omitted embodied carbon, a recurring oversight.[15] Likewise, *Construction Cost-Based Effectiveness Analysis of Green and Grey Infrastructure in Controlling Flood Inundation* compared green and gray infrastructure in China without addressing carbon implications.[16] While the ecological and social advantages of NbS are well-documented, a holistic carbon analysis is missing.

Moreover, assembling cohesive research on NbS is challenging due to fragmented data sources and methodologies. For instance, *On the Cost-Effectiveness of Nature-Based Solutions for Reducing Disaster Risk* reviewed over 20,000 global projects, examining 155 articles in-depth that led to the selection of eighty-seven case studies.[17] Roberts, David, and Surminski highlight that co-benefits, such as biodiversity restoration and improved water quality, are often understudied and "are likely to be underestimated" due to the complexity and expense of valuation techniques required to quantify them.[18] They allude to the carbon savings of NbS being one of these difficult-to-enumerate co-benefits. Other studies, like *Valuing the Benefits of NbS for Urban Flood Management in China*, relied on environmental databases, while localized studies used site-specific surveys and climate data.[19]

These studies are spread across a wide range of journals—including *Ecological Economics, Environmental Science and Policy*, and *Global Change Biology*—with only *Inland Adaptation: Developing a Studio Model for Climate-Adaptive Design* sourced from a design-focused publication, *Landscape Journal*.[20] The indexed methodologies originate from interdisciplinary yet disparate research, which complicates efforts to synthesize findings and integrate NbS consistently within design practices. As a result, while these studies underscore the resilience potential of NbS, they expose a significant gap in evaluating long-term impacts

15 Siddharth Narayan et al., "Effectiveness, Costs and Coastal Protection Benefits," 2016.
16 Gidaris and Taflanidis, "Construction Cost-Based Effectiveness," 2019.
17 Marta Vicarelli et al., "On the Cost-Effectiveness of Nature-Based Solutions for Reducing Disaster Risk," Science of the Total Environment 947 (2024): 174524, https://doi.org/10.1016/j.scitotenv.2024.174524.
18 Marta Vicarelli et al., "Cost-Effectiveness of Nature-Based Solutions," 2024.
19 Marcus Wishart et al, "Valuing the Benefits of Nature- Based Solutions," 2021.
20 Katrina Brown and Rachel Cooper, "Inland Adaptation: Developing a Studio Model for Climate-Adaptive Design as a Framework for Design Practice," Landscape Journal 35, no. 1 (2016): 37–55, https://doi.org/10.3368/lj.35.1.37.

and cumulative carbon costs, which is essential for coastal adaptation that does not exacerbate climate change.

While reports[21] allude to NbS being 50-75% more cost effective than traditional gray infrastructure, this evaluation amongst others compares relatively disparate contexts, for example, an urban concrete seawall versus the restoration of mangroves in a wildland. While there is merit to those high-level cost evaluations, a study comparing various shoreline adaptations has not been made available or documented in an effective way to inform how to implement more cost effective and lower carbon adaptations in developed coastal areas. This study seeks to answer that question.

21 Fred Pearce, "Nature-Based Solutions," 2022.

MATERIALS AND METHODS

APPROACH

This study aims to catalog the carbon and construction costs of regionally diverse case study projects in various stages—planning, design, and post-construction—to elucidate the potential of NbS in coastal adaptation. It considers the claims of NbS as capable of delivering substantial ecological, social, and economic benefits at a fraction of the carbon footprint and cost associated with gray infrastructure solutions. This study seeks to establish a framework that evaluates embodied carbon as a decisive factor in coastal adaptation, fostering informed, sustainable design decisions for future resilience endeavors.

This effort was based on the collection and evaluation of a range of shoreline adaptation projects. The methodology is drafted herein and tested, evaluating business-as-usual approaches, compared to nature-based alternatives. A rigorous evaluation of the various metrics, including cost, structural performance, greenhouse gas emissions and sequestration, flood reduction, and associated benefits illuminate comparative factors for consideration. Key findings are culled, organized, and the most insightful examples are highlighted with the intent of helping others overcome common barriers to implementation.

The carbon and cost performance of thirteen case studies and twelve projects twelve case studies were assessed to advance a new methodology for integrating NbS into coastal design. For each case, embodied carbon was measured (using Pathfinder 3.1), project costs were enumerated and standardized by using RSMeans, and the alternative design interventions were evaluated, highlighting potential performance improvements.[22]

Understanding adaptation costs per unit length enables a standardized comparison across the twelve cases. The study provides a comparative overview, focusing on the carbon and cost advantages of NbS in coastal adaptation. Project location, urban context, and ecological benefits are factors also considered. A potential second, future phase will compile universal design and planning lessons for coastal adaptation projects.

LITERATURE REVIEW

The literature review evaluated twelve methodology studies on nature-based

22 Climate Positive Design, "Pathfinder LCA 3.1," 2025; Gordian, "RSMeans Data," 2025.

solutions (NbS) for climate adaptation in coastal urban settings. Out of a wide range of diverse methodologies—such as field data analysis, cost-benefit analysis (CBA), and scenario planning—none of the reviewed methodologies accounted for embodied carbon in their evaluation. This oversight suggests that these projects, while addressing immediate climate risks, may unintentionally increase long-term carbon emissions, thus potentially undermining broader climate goals.

Additionally, as gleaned from the literature review, costs remain the number one driver for support and design of nature-based adaptations. Therefore, the following methodology study focuses on evaluating the carbon and cost efficacy of coastal adaptations.

CASE STUDY SELECTION PROCESS

To refine over twenty initial coastal adaptation projects, specific criteria were applied:

- **Coastal Location:** Projects had to be situated along North America's coastline.
- **Regional Diversity:** A balanced selection from Northeast, Southeast, Pacific West, and Pacific Northwest.
- **Adaptation Necessity:** All projects address essential adaptation needs in response projected flooding impacts.
- **Nature-Based Solutions:** Each project integrates an NbS element or presented a potential NbS opportunity.

Twelve projects met these criteria, representing diverse typologies. Critical factors in the final selection included access to detailed documentation, allowing comprehensive assessments of embodied carbon and project costs. Additional factors influencing selection included the availability of information (such as design team contacts and access to drawing sets), project scale, and implementation status. The projects include a range of design proposals and phases, including in-progress documentation required for local conditions, requirements, partners etc.

The case study projects are compared using select filters: integration of NbS and gray infrastructure, adaptation approaches for sea-level rise (SLR), co-benefits, and financial metrics. Project data and drawings were collected from public sources and the design teams. When available for questions, the design teams provided clarifications on assumptions and provided further detail on design specifics. The following projects are included in the analysis (additional project detail is available in the Appendix).

CASE STUDY INVENTORY

East Coast Projects

Twelve case study projects were selected across four U.S. coastal regions: Northeast, Southeast, Pacific West, and Pacific Northwest.

1. Moakley Park Resilience Plan (Boston, MA)

The *Moakley Park Resilience Plan* aims to protect South Boston's waterfront park from sea-level rise and flooding. The project includes elevated landscapes, stormwater management features, and over 500 new trees to mitigate flood risks and enhance biodiversity.[23]

Commissioning Entity: Boston Parks and Recreation
Design Lead: STOSS Landscape Urbanism
Major Consultants: Weston Sampson, Nitsch Engineering, ONE, Woods Hole Group, SGH Inc., HR&A

2. East Boston Waterfront (Boston, MA)

The *Boston Waterfront* project aims to strengthen the waterfront and to protect against sea level rises and storm surges while creating recreational spaces, tidal habitat, and shoreline plantings integrated into coastal riprap edges.[24]

Commissioning Entity: City of Boston
Design Lead: STOSS Landscape Urbanism, Kleinelder, ONE
Major Consultants: Woods Hole Group

3. Eastside Coastal Resilience Park (New York, NY)

The Eastside Coastal Resilience Park (ESCR) aims to reduce flood risk due to coastal storms and rising sea levels on Manhattan's East Side from East 25th Street to Montgomery Street. The level of flood protection provided by ESCR is equal to the region's "worst-case" anticipated 100-year storm in the 2050s.[25]

Commissioning Entity: NYC Department of Design and Construction, the Mayor's Office of Resiliency, and the Department of Parks and Recreation
Design Lead: AKRF-KSE Joint Venture

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23 STOSS Landscape Urbanism, "Moakley Park", accessed July 28, 2025, https://www.stoss.net/projects/resiliency-waterfronts/moakley-park-resiliency-waterfronts.

24 STOSS Landscape Urbanism, "Coastal Resilience Solutions for East Boston & Charlestown", accessed July 28, 2025, https://www.stoss.net/projects/resiliency-waterfronts/east-boston-charlestown.

25 New York City, "East Side Coastal Resiliency Project", City of New York, accessed July 28, 2025, https://www.nyc.gov/site/escr/index.page.

Major Consultants: Arcadis, Mathews Nielsen, BIG, Munoz, CH2M Hill

4. Pier 6 Redevelopment (Brooklyn, NY)
The *Pier 6 Redevelopment* in Sunset Park is a five-acre filled pier which is not currently publicly accessible due to its pre-construction condition. The New York City Economic Development Corporation plans to stabilize and redesign the pier to serve as public space for residents, visitors, and workers to reconnect with nature. It's design features tide pool reconfiguration to welcome rising waters, along with ecological preservation and restoration.[26]

Commissioning Entity: New York City Economic Development Corporation
Design Lead: Arcadis
Major Consultants: SCAPE Landscape Architecture, Matrix New World Engineering, Sam Schwartz Engineering, Johnson & Asberry, JK Muir

5. Hunters Point Park South (New York, NY)
Hunters Point Park South in Long Island City, Queens, has a resilient landscape that helps reduce the impact of sea-level rise and storm surge. The park features wetlands, bioswales, and elevated pathways that absorb stormwater and buffer against coastal flooding. These elements make the park critical in protecting the surrounding urban area from extreme weather events, including Hurricane Sandy, which made landfall during project construction.[27]

Commissioning Entity: Port Authority of New York
Design Lead: Arup
Major Consultants: Thomas Balsley Associates and WEISS/MANFREDI

6. Resilient Norfolk Coastal Storm Risk Management (Norfolk, VA)
The Resilient Norfolk Coastal Storm Risk Management (CSRM) project is designed to reduce the city's risk from coastal flooding and damage from nor'easters, hurricanes, and other significant storm events. The US Army Corps of Engineers (USACE) developed the project which combines structural measures with natural and nature-based solutions (NbS) to enhance coastal resilience, protect infrastructure, and provide ecological benefits.[28]

Commissioning Entity: USACE, City of Norfolk, Virginia
Design Lead: AECOM
Major Consultants: Moffatt & Nichol (M&N)

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26 New York Economic Development Corporation, "Pier 6 Redevelopment", accessed July 28, 2025, https://edc.nyc/project/pier-6-redevelopment.
27 SWA / Balsley, "Hunter's Point South Waterfront Park", accessed July 28, 2025, https://www.hunterspointparks.org.
28 U.S. Army Corps of Engineers, City of Norfolk, "Resilient Norfolk Coastal Storm Risk Management", accessed July 28, 2025, https://www.resilientnorfolk.com.

7. Peninsula Perimeter Protection Project (Charleston, SC)

The Peninsula Perimeter Protection Project is a design proposal from the U.S. Army Corps of Engineers to build a +12-foot-high seawall to protect the city from sea-level rise and storm surges. Initial concepts combine a floodwall with stormwater improvements and landscaped berm to establish a robust barrier safeguarding Charleston's historic peninsula. [29]

Commissioning Entity: USACE, City of Charleston
Design Lead: One Architecture and Urbanism (ONE)
Major Consultants: Biohabitats, DesignWorks

8. Morningside Park Resilient Shoreline Project (Miami, FL)

The Morningside Park Resilient Shoreline Project aims to protect the city's vulnerable coast from sea-level rise and storm surge. Utilizing a unique funding partnership with The Nature Conservancy, this project integrates a living shoreline with mangroves and native plants to stabilize the coastline, reduce erosion, and absorb storm impacts. The project enhances Miami's resilience by restoring natural habitats while providing valuable ecological and recreational benefits.[30]

Commissioning Entity: City of Miami
Design Lead: Curtis + Rogers Design Studio
Major Consultants: Coastal Systems, Basulto & Associates

9. Elliott Bay Seawall Project (Seattle, WA)

The Elliott Bay Seawall Project replaces the deteriorating seawall with a resilient structure designed to withstand earthquakes and accommodate projected sea-level rise. To enhance biodiversity, the project incorporates light-penetrating surfaces in the sidewalk above, allowing sunlight to reach the water and support marine life. Additional texturing was applied to the concrete to encourage marine life growth on "habitat shelves," the project's primary nature-based inclusion. [31]

Commissioning Entity: Seattle Office of the Waterfront and Civic Projects, DOT
Design Lead: Parsons Corporation
Major Consultants: Field Operations, Jacobs, MKA, Perteet, Shannon & Wilson

10. Mission Rock / China Basin Park (San Francisco, CA)

China Basin Park is a multifunctional, resilient public space that incorporates nature-based solutions such as stormwater gardens, native vegetation, and

29 U.S. Army Corps of Engineers, "Charleston Peninsula Coastal Storm Risk Management Study", accessed July 28, 2025, https://www.sac.usace.army.mil/Missions/Civil-Works/Charleston-Peninsula-CSRM-Project/Feasibility-Study/.
30 CHUBB, Environment: "A resilient approach: Protecting Miami's vulnerable coast", accessed July 28, 2025, https://about.chubb.com/stories/chubb-partners-with-nature-conservancy-to-protect-miamis-vulnerable-coast.html.
31 City of Seattle, Office of Waterfront and Civic Projects, "Waterfront Seattle", accessed July 28, 2025, https://waterfrontseattle.org.

soft shorelines to manage flooding from sea-level rise while offering recreation and open spaces. The park is designed to flood during extreme tides, demonstrating a flexible approach to waterfront design and urban resilience. [32]

Commissioning Entity: Mission Rock Partners: San Francisco Giants and Tishman Speyer, Port of San Francisco
Design Lead: SCAPE Landscape Architecture
Major Consultants: Min Design, Miller Company, BKF Engineers

11. Treasure Island / Cityside Park (San Francisco, CA)

The *Treasure Island Redevelopment* project was the catalyst for current sea level rise adaptation policies throughout the San Francisco Bay area. Its Adaptation Management Plan includes elevating existing grades, shoreline setbacks for new development, raised structures to protect historic assets, and long-term coastline migration. The nature-based features along the Cityside Park western edge include tidal shelves designed to incorporate coastal plantings into an existing rocky shoreline.[33]

Commissioning Entity: Treasure Island Development Group, Treasure Island Development Authority
Design Lead: CMG Landscape Architecture
Major Consultants: BKF Engineers, Freyer & Laureta, M&N

12. De-Pave Park (Alameda, CA)

De-Pave Park aims to transform a former naval airfield's paved tarmac into a thriving ecological park. The design focuses on sustainability by recycling 100% of onsite materials and creating restored wetlands that adapt to future sea-level rise. The park strives to serve as a model for climate-positive resilient landscapes, providing public access and environmental education opportunities.[34]

Commissioning Entity: City of Alameda
Design Lead: CMG Landscape Architecture
Major Consultants: Carlson, Barbee & Gibson, H.T. Harvey, ENGEO

32 SCAPE Landscape Architecture DPC, "China Basin Park", accessed July 28, 2025, https://www.scapestudio.com/projects/china-basin-park/.
33 CMG Landscape Architecture, "Treasure Island Parks + Open Space", accessed July 28, 2025, https://www.cmgsite.com/places/treasure-island-parks-open-space/.
34 CMG Landscape Architecture, "De-Pave Park", accessed July 28, 2025, https://www.cmgsite.com/places/depave-park/.

INVENTORY FACTORS

The projects reflect a range of approaches, including:

Nature-Based Solutions (NbS)

NbS-dominant projects like De-Pave Park, Cityside Park, Hunter's Point, Morningside Park Resilient Shoreline Project, and Pier 6 projects leverage natural elements (e.g., wetlands, riprap, and living shorelines) to provide flood protection and ecosystem benefits without extensive concrete or steel use.

Hybrid Projects

Hybrid projects, like the Peninsula Perimeter Protection Project and Moakley Park combine gray infrastructure (e.g., concrete floodwalls, sheet piles, and seawalls) with ecological enhancements like riprap or habitat features. A common strategy involves concrete or steel seawalls with NbS elements, like wetlands, mangroves, or oyster reefs, layered on or around the gray infrastructure core. This approach attempts to balance ecological health with flood protection.

Gray Infrastructure Projects

Projects with substantial concrete use, such as Eastside Coastal Resilience Park and Elliott Bay Seawall feature large-scale flood defenses like retractable gates and extended seawalls. These urban projects prioritize immediate protection for densely populated areas yet lack the biodiversity and carbon sequestration advantages that Nature-based Solutions offer.

Sea Level Rise (SLR) Adaptation Approach

Out of twelve projects, only five—Hunters Point Park South, Mission Rock China Basin Park, Treasure Island Cityside Park, Pier 6, and De-Pave Park—primarily use NbS to mitigate SLR. While Hunters Point Park South was not originally designed for SLR, it exceeded expectations during Hurricane Sandy by protecting Long Island City's coast and earned its inclusion in this study. Most projects are elevated to account for anticipated SLR and variability due to storm surges.

Co-Benefits and Financial Metrics

Projects offer various co-benefits beyond flood protection. For example, De-Pave Park and Mission Rock China Basin Park emphasize biodiversity, urban cooling, and water quality improvements. These green elements provide additional community benefits like recreational space and improved air quality.

Project costs vary widely, from smaller investments like the $8M Morningside Park Project to the over $2B Resilient Norfolk Coastal Storm Risk Management project. Cost efficiency often correlates with project size, with more significant investments potentially delivering long-term savings through reduced storm damage and enhanced resilience. However, publicly available costs can include development fees and buildings not related to the adaptation, which makes deciphering the cost of the actual coastal adaptation an impossible effort without access to the actual adaptation costs themselves.

This study aims to determine if NbS provides financial savings over gray infrastructure adaptation. The chosen projects represent a variety of typologies and approaches for protecting diverse urban coastal conditions across the U.S., ranging from small parks to large-scale infrastructure projects. Access to comprehensive planning and design documents was the final essential criteria, enabling accurate assessments of embodied carbon and project costs.

EVALUATION PROCESS

ADAPTATION TYPOLOGY MODELING AND MATERIAL QUANTIFICATION

Site Analysis

In all but one project, a standard cross-section was selected based on the most typical or representative transect of the project, while remaining unique between the projects to avoid redundancy. One deviation was included from the Eastside Coastal Resilience Park project to highlight another unique but typical condition within the study.

Section Detailing

Based on technical section drawings provided by design teams or via public sources, a cross-section was drawn to scale horizontally and vertically. This provided the basis for material quantity calculations and the axonometric illustrative graphics.

Material Quantification

Quantities were calculated based on a standardized ten-foot deep section multiplied by the section length required for the specific coastal adaptation technique. This was to ensure a balanced comparative analysis between the various project adaptations. The design teams provided confirmation or clarifications to questions when available.

GREENHOUSE GAS (GHG) EMISSIONS ACCOUNTING

Out of the twelve case study sites, De-Pave Park in Alameda, California, was the only project that publicly considered GHG emissions. This likely suggests that project-level carbon impacts (in all phases of work: planning, design development, and implementation) in North America are not being studied, tracked, or published.

Life Cycle Assessments (LCAs), which account for GHG emissions, are not commonly required for site and infrastructure projects in North America and are a relatively new performance metric compared to buildings, for example. There are also limited tools and standardization requirements which leads to inconsistent data across projects even when measured.

GHG Assessment Methodology

To ensure tracking of the latest and most suitable data, the Pathfinder 3.1 LCA tool, publicly available by Climate Positive Design, was utilized for the study.[35] This dataset and methodology aligns with the latest architecture, engineering, and construction (AEC) industry standardization from the Carbon Leadership Forum Embodied Carbon Harmonization and Optimization (ECHO) Project.[36]

As an estimated 80% of GHG emissions from site infrastructure projects come from embodied carbon, it is the focus of this study.[37] Embodied carbon emissions are the result of extraction, transportation, and manufacturing of materials in addition to their construction or installation. Typically, these emissions occur before project construction is complete.

Terms

In this study the term "carbon emissions" refer to embodied carbon and is measured in carbon dioxide equivalent (CO2e), which is a broad term that includes other greenhouse gases (such as nitrous oxide, methane etc.), but at a lower overall percentage.

"Business-as-Usual" (BAU) within this study is used to describe the as-built condition or the as-designed proposed condition for each project.

"Net carbon" is measured in kilograms per the AEC industry standard (kgCO2e) and refers to the sum of both the embodied carbon emissions and carbon sequestration, or carbon dioxide drawdown from the atmosphere from trees and plants.

"Net intensity" (kgCO2e/m2) is the "net carbon" per surface area of the project adaptation typology. In some cases, the surface area or the section width of the

35 Climate Positive Design, "Pathfinder Life Cycle Assessment (LCA) 3.1." [Computer Software], Climate Positive Design, accessed May 25, 2025, https://climatepositivedesign.org/education/.

36 Carbon Leadership Forum, "Project Life Cycle Assessment Requirements - ECHO Recommendations for Alignment." Embodied Carbon Harmonization and Optimization Project (ECHO), 2024, https://www.echo-project.info/publications.

37 Climate Positive Design, Inc., "Beyond Neutral 2023 Annual Report", Climate Positive Design — Updates, 2024, https://climatepositivedesign.org/wp-content/uploads/2024/04/Climate-Positive-Design_Beyond-Neutral_2023-Annual-Report.pdf.

adaptation may change due to the optimized alternative suggestion.

“Emissions intensity” (kgCO2e/m2) is the carbon emissions per surface area of the adaptation typology.

COST ESTIMATION

Like carbon metrics, cost comparisons can vary widely due to ranging geographic costs for materials and construction. To provide comparative cost evaluation of the various adaptation typologies, the most widely utilized industry standard cost database, RSMeans—a paid platform provided by Gordian, was utilized to inform standardized unit costs and was recommended by the Contractor’s Commitment industry program.[38]

Note that the costs are representative of an average North American cost for the adaptation typology itself, not the cost estimate of the overall project. This method was defined to provide a standardized comparison between the various typologies to identify which ones had the lowest cost.

The same carbon analysis quantities were utilized in the following costing approach:

1. **BAU Cost Estimation:**
Using RSMeans, evaluated costs for the ten-foot deep section

2. **Alt 1 Cost Estimation:**
Evaluated costs with low risk, easy potential modifications

3. **Alt 2 Cost Estimation:**
Evaluated costs with more structural changes to implement NbS

38 Gordian, “RSMeans Data: Construction Cost Estimating Software,” [Computer Software], RSMeans Data from Gordian: Core Subscription, accessed May 25, 2025, https://www.rsmeans.com.

PROJECT IMPROVEMENT CONSIDERATIONS

The alternatives presented in this study are for hypothetical consideration only and are not exhaustive. Each project has a unique set of criteria, requirements, and constituents, all of which must be evaluated before recommending changes. While this study does intend to illuminate potential priority shifts, many factors need to be evaluated which include, but are not limited to, the following:

Design Considerations

Stakeholder priorities must be considered when evaluating design adjustments that may have implications to use, access, or other goals of the space. Any tradeoffs should be openly communicated and transparent to achieve community support for any modifications. Local knowledge, conditions, and context should always inform design, for example the need to specify saline-tolerant species in intertidal zones, which is a limitation of this study.

Structural Considerations

The potential structural modifications in this study have not been reviewed by an engineer. Any structural shifts require performance validation from project engineers, including the condition of the sub-grade etc. In some cases, this study seeks to provoke the conversation on the need for certain structural aspects– perhaps they are remnants from outdated code, are over-designed, or are worth confirming their requirements from the local jurisdictions where the interpretation can be different from one site immediately adjacent to another. The study seeks to highlight those potential questions to counter high carbon emissions and costs due to structural (over) design. Safety remains an upmost priority for any designs or design modifications.

Durability

Changing materials (e.g. shifting from a stainless-steel guardrail to a wooden one) may change the element lifecycle which might require additional replacements, but the change could have lower emissions and costs overall. This provokes the topic of the “time value of carbon” which places a higher value on time sensitive carbon emissions reductions within the current “decisive decade.” Decisions made now will determine the fate of our planet even as some long-term climate thresholds may already have been surpassed or locked in.

Maintenance

Changing paved surfaces to planting areas may increase maintenance and related ongoing costs but these are not accounted for in this study as the focus is primarily on embodied carbon. Shifting from turf lawn to shrubs, groundcovers, or ecosystem restoration may not require a noticeable increase in costs but it may require additional training for maintenance workers on the proper care for those less-typical planting typologies.

Sea Level Rise Scenarios

The projects highlighted in this study include a range of planning and design scenarios for adapting to sea level rise and increasing storms. For future analysis, evaluating the exact same projection scenario, regardless of which one was utilized on the project, may lead to more direct comparative analysis of the adaptation typologies. This would better align emissions associated with future adaptation requirements.

Review and Approvals

Any design change may require a review and approvals process to confirm and approve the proposed redesign. Projects considering the addition of shoreline fill may be required to engage in a process to ensure that the fill is mandatory to optimize nature-based benefits. Fill mitigation for “beneficial fill” may be required by the jurisdiction, in terms of fees or removal of fill from other parts of the water body.

Policy Changes

In some cases, the addition of shoreline fill may be the best option to fulfill the nature-based adaptation potential. While fill in water bodies should be limited due to potential negative impacts on ecosystems, jurisdictions may consider including policy amendment clauses for “beneficial fill” which could waive fees or other mitigation requirements and dismantle this roadblock to nature-based solution implementation.

Removing existing shoreline fill or water body “shadows” can improve shoreline habitats but may also warrant specific approval revisions such as permitting process streamlining or financial incentives.

Material Innovations

Lower carbon alternatives to typical construction materials like cement are rapidly advancing, however additional material alternatives are needed for infrastructure and site projects. Those needs include, but are not limited to, accessible stabilized crushed stone paving with increased levels of durability and more available options for lightweight fill that is commonly used to raise elevations while preventing settlement or subsidence in shoreline adaptation projects.

Lightweight fill options, like geofoam, cellular concrete, and foamed-glass aggregates, do exist but their high strength / low weight characteristics equal high embodied carbon emissions due to the intensive processing of synthetic materials. Lower-carbon lightweight fill options are emerging, such as expanded clay aggregates and shale in Europe, but compliance with municipal requirements in North America slows widespread adoption of these alternatives. Review and approval by structural engineers and meeting jurisdictional requirements should always be a priority.

Supplementary cementitious materials (SCMs) are finely ground materials that partially replace Portland cement in concrete mixes and help reduce the high embodied carbon associated with traditional cement production. Common SCMs include slag, fly ash, glass pozzolan, or silica fume. These SCMs can increase the performance of the concrete mix design but some are fossil fuel by-products with limited emissions reduction potential. Other alternatives exist, such as Limestone Calcined Clay Cement (LC3), which replaces half of the cement with calcined clay and limestone and has lower heating requirements that reduces emissions by an even higher percentage.

Sourcing

To source items such as recycled materials (steel, aggregates etc.), LC3, expanded clay aggregates, and local/hyperlocal providers it is recommended to initiate conversations with the client/owner, contractor, and design team early on to begin the procurement process and allow for required lead times.

Additional Benefits of Nature-based Adaptations

Many of the projects incorporated additional nature-based features such as stormwater gardens, intertidal wetlands and mangroves. While this study doesn’t focus on quantifying these additional benefits beyond carbon and cost, it is worth noting the performative value of stormwater gardens is reducing inland flooding and additional pressure on coastal flooding, and intertidal wetlands and mangroves reduce impacts of coastal storms and sea level rise while supporting biodiversity and carbon sequestration.

RESULTS AND CONSIDERATIONS

Project Case Study Performance Analysis

Per the methodology, the following describes the findings for each project individually from both a carbon and cost standpoint.

For each project, the shift from Business-as-Usual to Optimized Alternative 1 would largely be imperceptible, relying on changes to material composition, sourcing, content, and below-grade applications. The use, program, and aesthetics largely remain the same.

Changing from Business-as-Usual to Optimized Alternative 2 builds on the minor modifications introduced in Alternative 1 and any substantial structural changes that may require additional coordination, permitting changes, or design approval with the client/owner and team. These changes are necessary to incorporate a truer nature-based solution as the foundation of the adaptation design.
All optimizations are contingent upon confirmation of structural integrity by the project engineer.

The net carbon improvements are described and partitioned below. Note that carbon performance changes with less than 1% impact are not listed.

New York, NY

1A | EASTSIDE COASTAL RESILIENCE PARK

The BAU section illustrated for the Eastside Coastal Resilience (ESCR) Park is of a typical condition, located on the southern end of the park along the East River. As designed, this adaptation typology includes fill to raise and extend the shoreline, reinforced with a metal sheet pile wall. A paved path is along the shoreline edge with planted park space inland.

Overall Project Approach: Gray Infrastructure
Adaptation Typology: Backfilled Seawall (Typology 1)
Nature-based Features: Inland Park
Sea Level Rise Scenario: 2.5' in 2050 with 1% annual chance storm
Drawing Set Reference: New York City Department of Design and Construction, "East Side Coastal Resiliency Project, Appendix C1e", Dated: July 18, 2019.[39]

Figure 01: Key map for the Eastside Coastal Resilience section 1A

39 New York City Department of Design and Construction, East Side Coastal Resiliency Project, Appendix C1e: Preferred Alternative – Esplanade Structural Plan and Cross Sections, Dated: July 18, 2019, accessed July 28, 2025, https://www.nyc.gov/assets/escr/downloads/pdf/FEIS/Appendices/ESCR-EIS-Appendix-C1e-Preferred-Alternative-Esplanade-Structural-Plan-and-Cross-Sections.pdf.

1A | ESCR TYPOLOGY 1: BACKFILLED SEAWALL

Potential Modifications from Business-as-Usual to Optimized Alternative 1

74% reduction in net carbon impact intensity (partitioned below) and 0.39% cost reduction from:

- Lightweight Fill: structural cellular concrete > expanded clay aggregates = 34%
- Backfill / Aggregates: virgin/local > recycled/hyperlocal = 26%
- Sheet Pile: standard steel > recycled steel = 7%
- Planting Soil: local > hyperlocal = 4%
- Trees: adding one large deciduous tree (net) = 1%
- Concrete Mix Design: no supplementary cementitious materials (SCM) > Limestone Calcined Clay Cement (LC3) = 1%

The most significant carbon emissions reduction is changing cellular concrete lightweight structural fill to expanded clay aggregate lightweight fill. Note that while expanded clay aggregates are widely used and available in Europe, availability is currently somewhat limited in North America. The second-most significant impact would be using 100% recycled aggregates, hyper-locally sourced along with the backfill–within a ten-mile radius from the site rather than a local, one-hundred-mile radius.

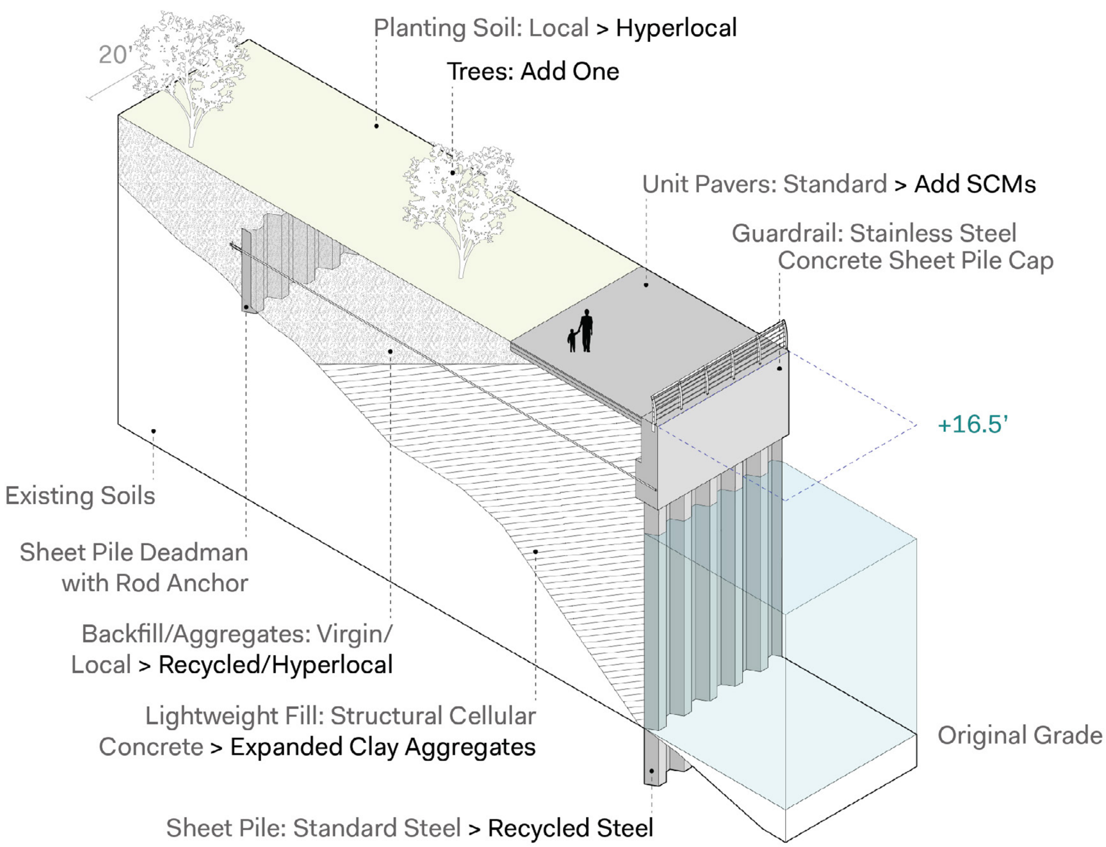


Figure 02: Business-as-Usual / Alternative 1

Potential Modifications from Business-as-Usual to Optimized Alternative 2

87% reduction in net carbon impact intensity (partitioned below) and 54% cost reduction from:

- Lightweight Fill: Removed due to step back = 45%
- Backfill: Reduced quantity due to step back = 24%
- Wall: Reduced height of sheet pile cut-off wall due to step back = 8%
- Planting Soil: local > hyperlocal = 3%
- Wall: Sheet pile deadman and rod anchor > concrete wall with foundation, gabion retaining walls with tiebacks = 2%
- Concrete Mix Design: no supplementary cementitious materials (SCM) > Limestone Calcined Clay Cement (LC3) = 1%

The greatest emissions reduction potential is reducing the quantity of lightweight fill and backfill due to a shift from a vertical wall to a stepped back condition. The overall park width at this condition is approximately 360-feet wide. The stepped condition would remove approximately fifty feet, or 14% of the width from public access but provide that potential amount of shoreline habitat. As noted in the introduction, all tradeoffs must be considered holistically.

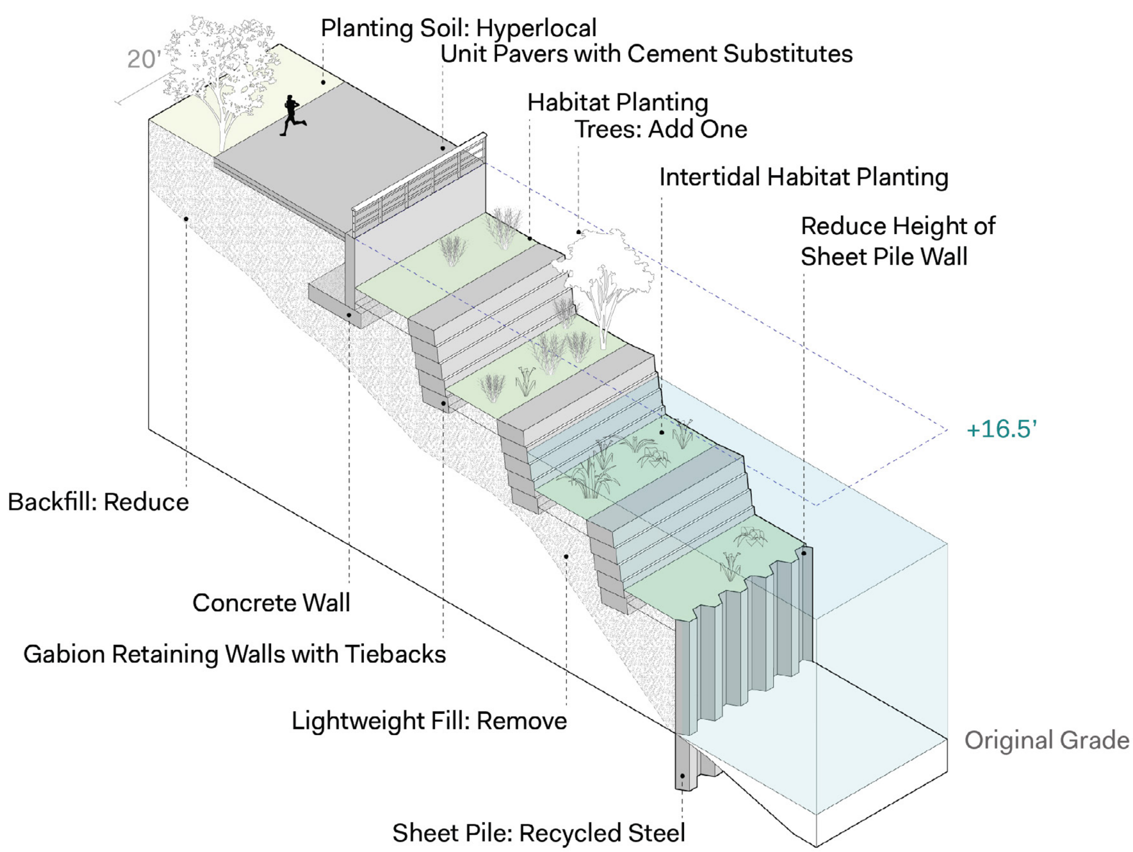


Figure 03: Optimized Alternative 2

Table 01: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/m2)	Total Cost	Cost per SF
Business-as-Usual	151	2,216*	157	2,304*	$126,570	$172
Optimized Alt 1	39	573*	47	690*	$126,070	$172
Optimized Alt 2	22	289	27	354*	$64,015	$78

* Emissions exceeding recommended carbon upper limit for buildings (350kgCO2e/m2)[40]

Table 02: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
74%	70%	87%	0.39%	49%	0.39%	54%

While the emission reductions potential from BAU to Alt 1 and Alt 2 are significant, the emissions intensity still exceeds the recommended upper limit for building structures per area (350kgCO2e/m2), identified above. When factoring in sequestration, the net is reduced to fall below this cap, but there are currently no documented regulations that factor sequestration into the emissions limitations. There is also no current public guidance on embodied carbon limitations for infrastructure or sites, thus the only comparison available for this study is structures.

40 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

New York, NY

1B | EASTSIDE COASTAL RESILIENCE PARK

The BAU section illustrated at the Eastside Coastal Resilience (ESCR) Park is of a typical condition, located in the middle of the park. As designed, this adaptation typology includes fill to raise the shoreline, along with a paved extension along the shoreline above an existing structure, reinforced with a metal sheet pile wall. Park space is located inland of the shoreline path.

Overall Project Approach: Gray Infrastructure
Adaptation Typology: Buried Floodwall (Typology 2)
Nature-based Features: Inland Park
Sea Level Rise Scenario: 2.5' in 2050 with 1% annual chance storm
Drawing Set Reference: "East Side Coastal Resiliency Project, Appendix C1e", Dated: July 18, 2019.[41]

Figure 04: Key map for the Eastside Coastal Resilience section 1B

41 New York City Department of Design and Construction, East Side Coastal Resiliency Project, Appendix C1e: Preferred Alternative – Esplanade Structural Plan and Cross Sections, Dated: July 18, 2019, accessed July 28, 2025, https://www.nyc.gov/assets/escr/downloads/pdf/FEIS/Appendices/ESCR-EIS-Appendix-C1e-Preferred-Alternative-Esplanade-Structural-Plan-and-Cross-Sections.pdf.

1B | ESCR TYPOLOGY 2: BURIED FLOODWALL

Potential Modifications from Business-as-Usual to Optimized Alternative 1

76% reduction in net carbon impact intensity (partitioned below) and 0.30% cost reduction from:

- Backfill / Aggregates: virgin/local > recycled/hyperlocal = 42%
- Lightweight Fill: structural cellular concrete > expanded clay aggregates = 13%
- Sheet Pile: standard steel > recycled steel = 9%
- Planting Soil: local > hyperlocal = 6%
- Concrete Mix Design: no SCMs > LC3 = 4%
- Trees: adding one large deciduous tree (net) = 1%

The most significant emissions reduction is from specifying 100% recycled aggregates, hyper-locally sourced (within a ten-mile radius) along with the backfill. The second-most significant improvement is changing the lightweight fill material from cellular concrete to expanded clay aggregates.

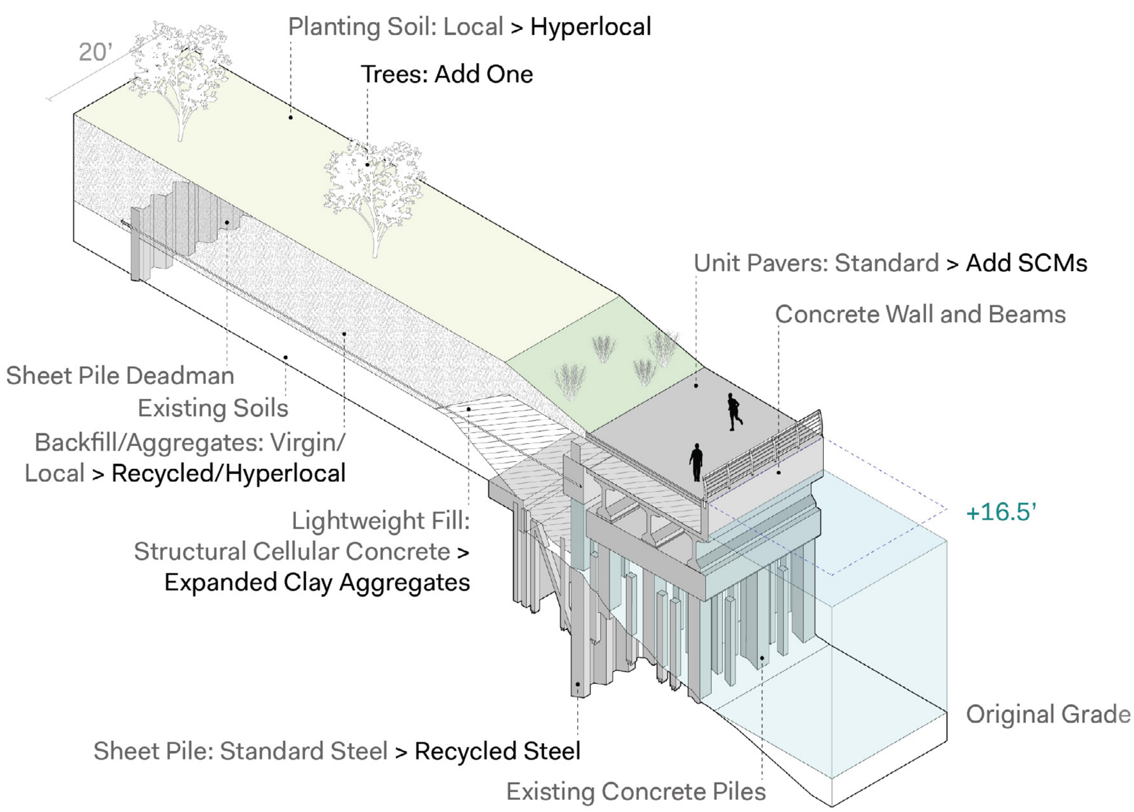


Figure 05: Business-as-Usual / Alternative 1

Potential Modifications from Business-as-Usual to Optimized Alternative 2

80% reduction in net carbon impact intensity (partitioned below) and 45% cost reduction from:

- Backfill: Reduced quantity due to step back = 40%
- Lightweight Fill: Removed due to step back = 16%
- Wall: Reduced height of sheet pile cut-off wall due to step back = 7%
- Planting Soil: local > hyperlocal = 7%
- Concrete Mix Design: no SCMs > LC3 = 5%
- Wall: Sheet pile deadman and rod anchor > concrete wall with foundation, gabion retaining walls with tiebacks = 3%
- Planting: Adding temperate perennials and intertidal plantings = 1%

The greatest emissions reduction potential comes from reducing the quantity of backfill and lightweight fill due to the shift from a cantilevered promenade to a stepped terrace. The overall park width at this condition is approximately 360-feet wide. The stepped condition would remove approximately sixty feet, or 17% of the width from public access but provide that potential amount of shoreline habitat.

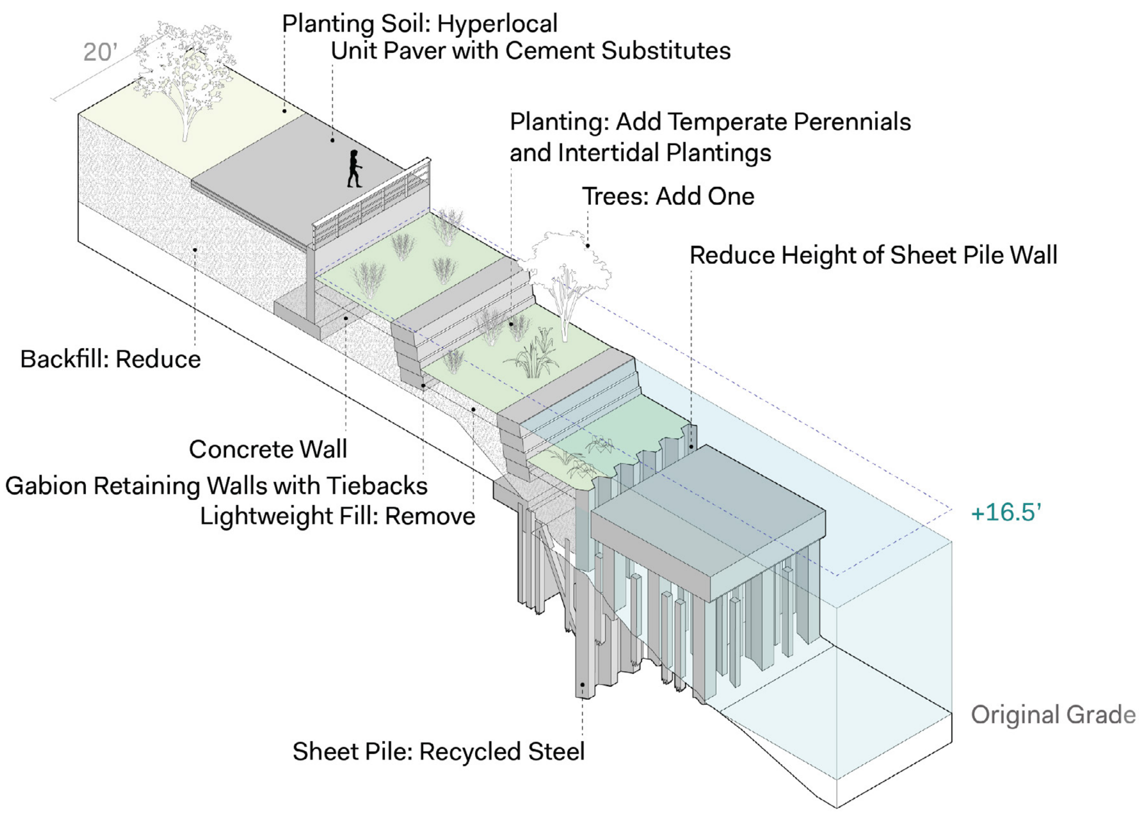


Figure 06: Optimized Alternative 2

Table 03: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/ m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/ m2)	Total Cost	Cost per SF
Business-as-Usual	139	1,361*	145	1,420*	$121,334	$110
Optimized Alt 1	33	326	41	404*	$120,970	$110
Optimized Alt 2	22	265	27	335	$67,202	$76

* Emissions exceeding recommended carbon upper limit for buildings (350kgCO2e/m2)[42]

Table 04: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
76%	72%	80%	0.30%	45%	0.30%	31%

While the emissions reduction potential from BAU to Alt 1 and Alt 2 are significant, the emissions intensity in Alt 1 still exceeds the recommended upper limit for building structures per area (350kgCO2e/m2), identified above. Alt 2 falls below the emissions intensity cap, and when factoring in sequestration, the net is reduced below this cap for both Alt 1 and Alt 2.

42 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

Seattle, WA

2 | ELLIOTT BAY SEAWALL PROJECT

The BAU section illustrated for Seattle's Elliott Bay Seawall is of a typical condition, shown near the central waterfront in downtown. As designed and constructed, the edge condition is a cantilevered concrete wall extending over the bay. The pedestrian walk is adjacent to the roadway and below is a marine mattress which connects to the existing riprap slope.

Overall Project Approach: Gray Infrastructure
Adaptation Typology: Cantilevered Seawall
Nature-based Features: Light-penetrating surfaces to support marine life. Texturing applied to the concrete to encourage marine life on "habitat shelves."
Sea Level Rise (SLR) Scenario: 4.2' SLR in 2100
Drawing Set Reference: Seattle DOT, "Preferred Alternative, Proposed Land/ Water Condition", Dated: March 18, 2016.[43]

Figure 07: Key map for the Elliott Bay Seawall section

43 Seattle Department of Transportation, Seattle Historic Waterfront Association, Federal Highway Administration, "Preferred Alternative, Proposed Land/Water Condition", Dated: March 18, 2016, accessed July 28, 2025, https://www.adaptationclearinghouse.org/resources/seattle-washington-department-of-transportation-seattle-dot-elliott-bay-seawall-project.html.

2 | ELLIOTT BAY SEAWALL PROJECT

Potential Modifications from Business-as-Usual to Optimized Alternative 1

13% reduction in net carbon impact intensity (partitioned below) and 2.25% cost reduction from:

- Cast-in-Place/Precast Concrete Mix Design: no SCMs > LC3 = 12%
- Aggregates: virgin/local > recycled/hyperlocal = 1%

The most significant emissions reduction is from specifying a supplementary cementitious material (SCM) in the concrete mix called Limestone Calcined Clay Cement (LC3).[44] It is used as a binder for concrete that contains calcined clay, limestone, and a small amount of clinker. It can typically achieve up to 40% emissions reduction from Ordinary Portland Cement (OPC) as it reduces the reliance on clinker, a major source of CO2 emissions in cement production.[45] LC3 is increasing in availability as it is being deployed at-scale around the globe. [46]

44 École Polytechnique Fédérale de Lausanne, “Limestone Calcined Clay Cement”, Limestone Calcined Clay Cement: LC3, 2025, https://lc3.ch.

45 ClimateWorks Foundation, Karen Scrivener, and Scott Shell, “How low-carbon cement can benefit emerging economies and the planet”, ClimateWorks Foundation: Home, accessed July 28, 2025, https://www.climateworks.org/blog/how-low-carbon-cement-can-benefit-emerging-economies-and-the-planet/

46 Rocky Mountain Institute (RMI), “Unleashing the Potential of Limestone Calcined Clay Cement (LC3)”, 2023, https://rmi.org/unleashing-the-potential-of-limestone-calcined-clay-cement/.

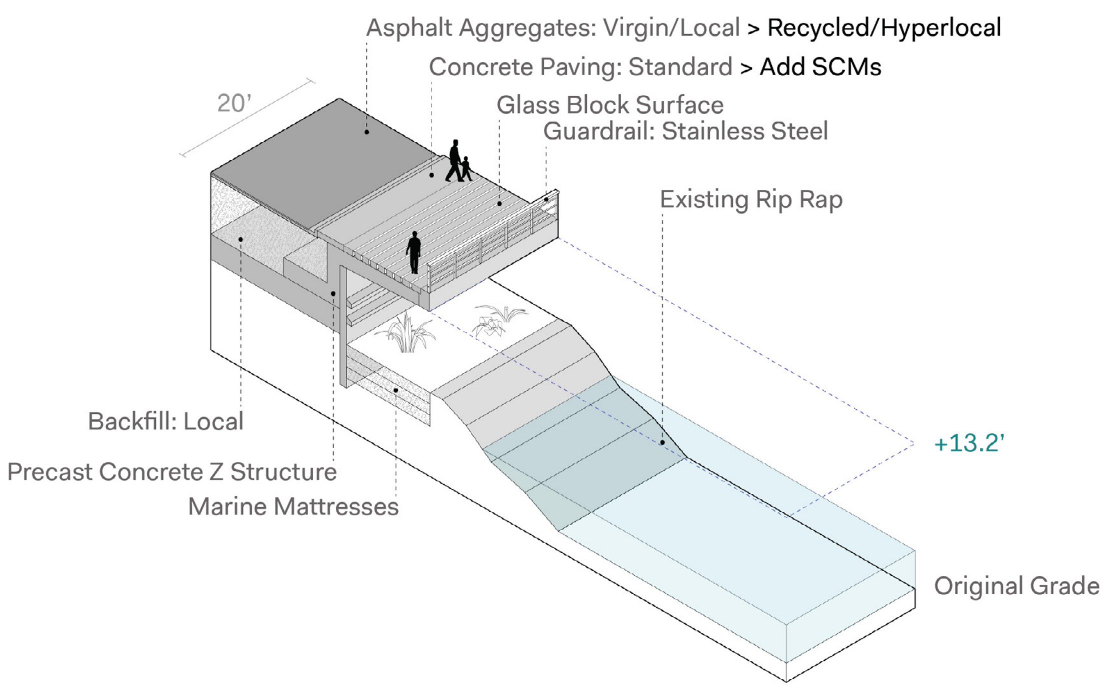


Figure 08: Business-as-Usual / Alternative 1

Potential Modifications from Business-as-Usual to Optimized Alternative 2

32% reduction in net carbon impact intensity (partitioned below) and 19% cost reduction from:

- Seawall: Removing precast cantilever and light penetrating surface elements = 26%
- Cast-in-Place/Precast Concrete Mix Design: no SCMs > LC3 = 5%
- Aggregates: virgin/local > recycled/hyperlocal = 1%
- Asphalt: Reducing quantity due to wall redesign = 1%

The most significant emissions reduction in this scenario is from removing the cantilevered section and instead utilizing the approximate eight-to-ten feet wide parking lane for the pedestrian promenade.

The BAU section illustrated at the Eastside Coastal Resilience Park is of a typical condition, located in the middle of the park. As designed, this adaptation typology includes fill to raise the shoreline, along with a paved extension along the shoreline above an existing structure, reinforced with a metal sheet pile wall. Park space is located inland of the shoreline path.

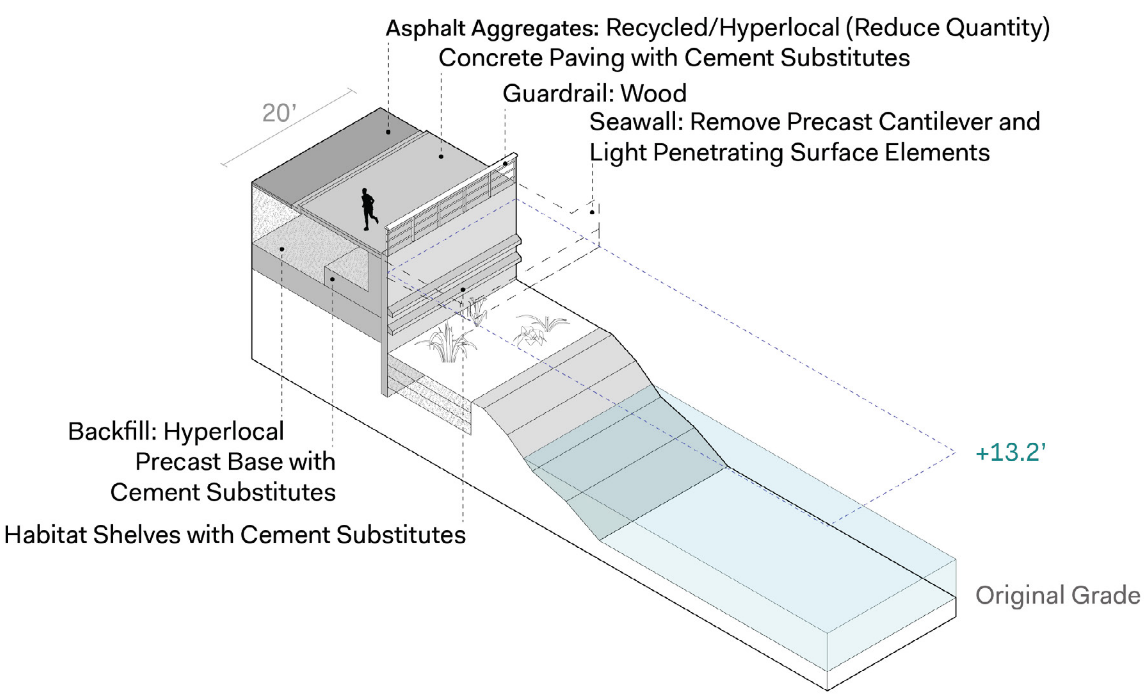


Figure 09: Optimized Alternative 2

Table 05: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/m2)	Total Cost	Cost per SF
Business-as-Usual	74	1,869*	74	1,869*	$66,550	$157
Optimized Alt 1	64	1,631*	64	1,631*	$65,050	$153
Optimized Alt 2	50	1,274*	50	1,274*	$54,006	$127

* Emissions exceeding recommended carbon upper limit for buildings (350kgCO2e/m2)[47]

Table 06: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
13%	13%	32%	2.25%	19%	2.25%	19%

While there are emissions and net intensity improvement potential between the scenarios, all still exceed the recommended upper limit for building structures per area (350kgCO2e/m2).

47 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

San Francisco, CA

3 | MISSION ROCK / CHINA BASIN PARK

The section illustrated in San Francisco along Mission Creek is a condition at the stepped shoreline portion of the park. As its BAU is designed and constructed, this adaptation typology includes a park elevated with lightweight fill, centrally located planting, and pedestrian paths on either side.

Overall Project Approach: Nature-based
Adaptation Typology: Earthen Berm
Nature-based Features: Stormwater gardens, native vegetation, and soft shorelines to manage flooding from sea-level rise
Sea Level Rise (SLR) Scenario: 1.9'SLR in 2050, 3.5' SLR in 2070, 6.9' SLR in 2100 with 1% annual chance storm
Drawing Set Reference: "China Basin Park Record Set", and "100% Design Development", Dated: May 8, 2020.[48]

Figure 10: Key map for the China Basin Park section

48 SCAPE Landscape Architecture DPC, "China Basin Park Record Set", and "100% Design Development", Dated: May 8, 2020 and accessed February 19, 2025.

3 | MISSION ROCK / CHINA BASIN PARK

Potential Modifications from Business-as-Usual to Optimized Alternative 1

74% reduction in net carbon impact intensity (partitioned below) and 3.2% cost reduction from:

- Lightweight Fill: structural cellular concrete/geofoam > expanded clay aggregates = 66%
- Planting Soil: local > hyperlocal = 3%
- Aggregates: virgin/local > recycled/hyperlocal = 2%
- Lawn Area: sod > hydroseeded no-mow fescue = 2%
- Cast-in-Place Mix Design: no SCMs > LC3 = 1%

The most significant carbon emission reduction is from substituting structural cellular concrete lightweight fill for expanded clay aggregates lightweight fill, as discussed previously. Also, a note on the BAU, different cross-sections of the park would have different embodied carbon values, as with all projects.

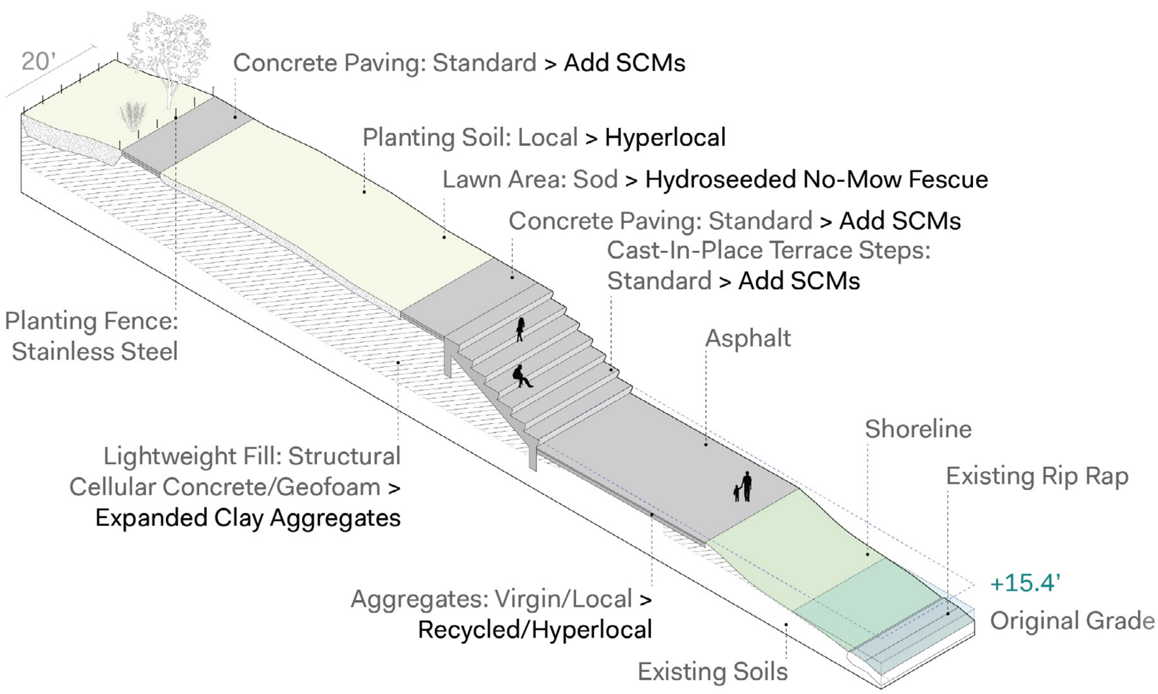


Figure 11: Business-as-Usual / Alternative 1

Potential Modifications from Business-as-Usual to Optimized Alternative 2

82% reduction in net carbon impact intensity (partitioned below) and 19% cost reduction from:

- Lightweight fill: reducing quantity due to site regrading = 69%
- Terrace Steps: removal and graded slope back = 6%
- Planting Soil: local > hyperlocal = 2%
- Aggregates: virgin/local > recycled/hyperlocal = 2%
- Lawn Area: sod > hydroseeded no-mow fescue = 2%
- Asphalt Paving > stabilized crushed stone paving (SCSP) = 1%

The most significant carbon emissions reduction is from the reduction of lightweight fill due to site regrading. Note, this change would increase the slope of the site and impact its use, however it would not reduce the amount of public space available.

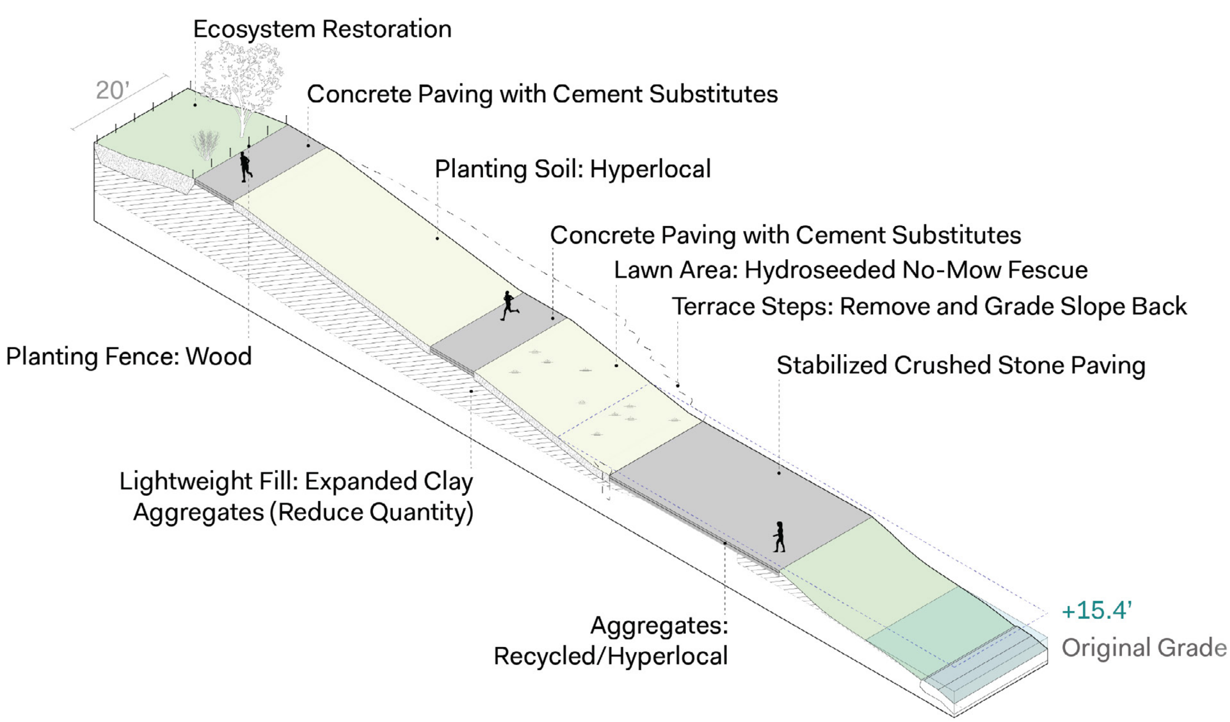


Figure 12: Optimized Alternative 2

Table 07: Carbon and cost impacts

	Net Impact (tCO_2e)	Net Impact Intensity ($kgCO_2e/m^2$)	Total Emissions (tCO_2e)	Emission Intensity ($kgCO_2e/m^2$)	Total Cost	Cost per SF
Business-as-Usual	185	1,084*	190	1,112*	$136,439	$74
Optimized Alt 1	48	281	55	322	$132,074	$72
Optimized Alt 2	33	195	40	236	$111,031	$60

* Emissions exceeding recommended carbon upper limit for buildings ($350kgCO_2e/m^2$)[49]

Table 08: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
74%	71%	82%	3.2%	19%	3.2%	19%

While there are significant emissions and net intensity improvements possible between the scenarios pushing it below the carbon cap, the built, business-as-usual approach exceeds the recommended upper limit for building structures per area ($350kgCO_2e/m^2$).

49 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

Norfolk, VA

4 | RESILIENT NORFOLK COASTAL STORM RISK MANAGEMENT

The BAU section illustrated for Resilient Norfolk is of a constrained condition, shown at the Elizabeth River Trail at Harbor Park Stadium. As designed, this adaptation typology includes an elevated Harbor Walk adjacent to an inland road, and with a planted slope and living shoreline on the waterside.

Overall Project Approach: Hybrid (NbS + Gray Infrastructure)
Adaptation Typology: Elevated Harborwalk
Nature-based Features: Living shoreline
Sea Level Rise (SLR) Scenario: 1.4' SLR in 2075
Drawing Set Reference: Cross Sections (1 of 2), H2: Typical Trail Section along Floodwall, Dated: November 8, 2024.[50]

Figure 13: Key map for the Resilient Norfolk section

50 US Army Corps of Engineers, City of Norfolk. "Resilient Norfolk", Cross Sections (1 of 2), H2: Typical Trail Section along Floodwall, STA 4+36.00, Sheet PH. 1A2 / LS301, Dated: November 8, 2024, accessed July 28, 2025, https://communicateonpoint.com/wp-content/uploads/2024/11/Norfolk-CSRMPhase1A_ARBPresentation_Comp_11-15-2024.pdf.

4 | RESILIENT NORFOLK COASTAL STORM RISK MANAGEMENT

Potential Modifications from Business-as-Usual to Optimized Alternative 1

28% reduction in net carbon impact intensity (partitioned below) and 8.57% cost reduction from:

- Cast-in-Place Mix Design: no SCMs > LC3 = 13%
- Aggregates: virgin/local > recycled/hyperlocal = 5%
- Trees: adding two medium deciduous trees = 4%
- Wall: sheet pile > stepped concrete planter steps = 4%
- Guardrail: stainless steel > wood = 1%
- Breakwater: typical design > living breakwater = 1%

The greatest emissions reduction potentials are utilizing LC3 as a cement substitution and sourcing recycled, hyperlocal aggregates.

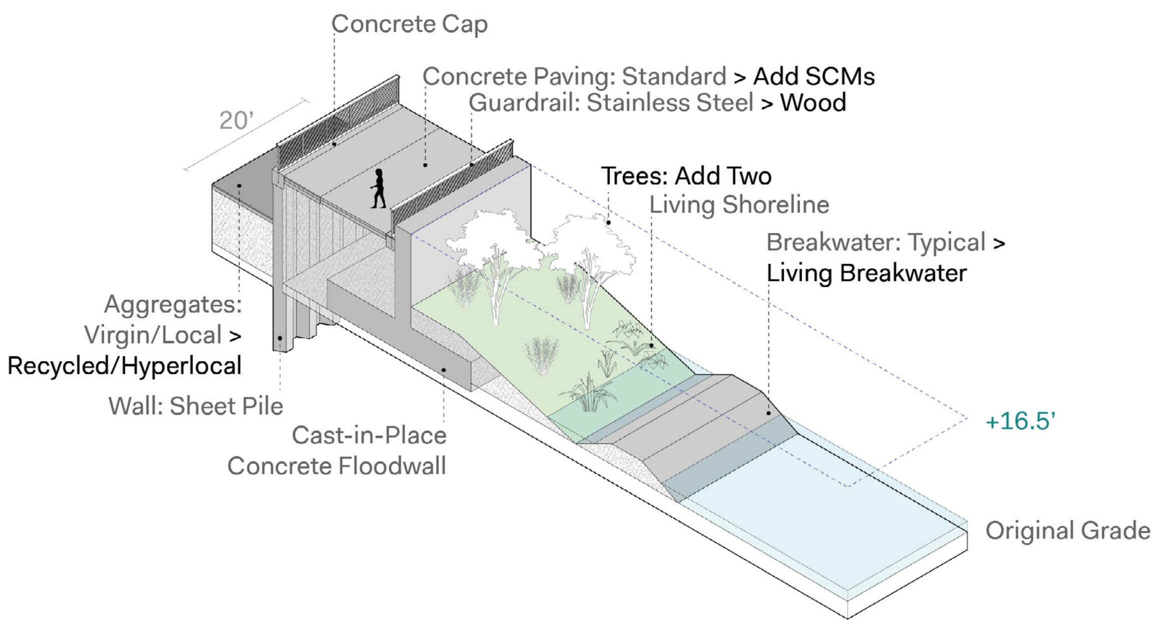


Figure 14: Business-as-Usual / Alternative 1

Potential Modifications from Business-as-Usual to Optimized Alternative 2

95% reduction in net carbon impact intensity (partitioned below) and 6% cost reduction from:

- Flood Wall: cast-in-place wall > riprap shoreline terraces = 57%
- Planting: adding hyperlocal planting soils, perennials and intertidal plantings = 13%
- Sheet Pile: removal due to regrading = 13%
- Trees: adding two medium deciduous trees in planter steps = 4%
- Cast-in-Place Mix Design: no SCMs > LC3 = 4%
- Breakwater: typical design > living breakwater = 1%
- Promenade Paving: concrete > stabilized crushed stone = 1%
- Guardrail: removal due to regrading = 1%
- Trees: adding two small deciduous trees in shoreline terraces = 1%

Shifting from a cast-in-place concrete and steel sheet pile wall system to a terraced shoreline has the greatest emissions reduction potential. This design also adds planting for carbon sequestration through an expanded "living shoreline" condition. Due to inland spatial constraints, this would require the addition of shoreline fill to the water body, which is regulated and would require approvals as "beneficial fill" for adaptation. Note, any planting added to a coastal, intertidal condition would be required to be saline tolerant.

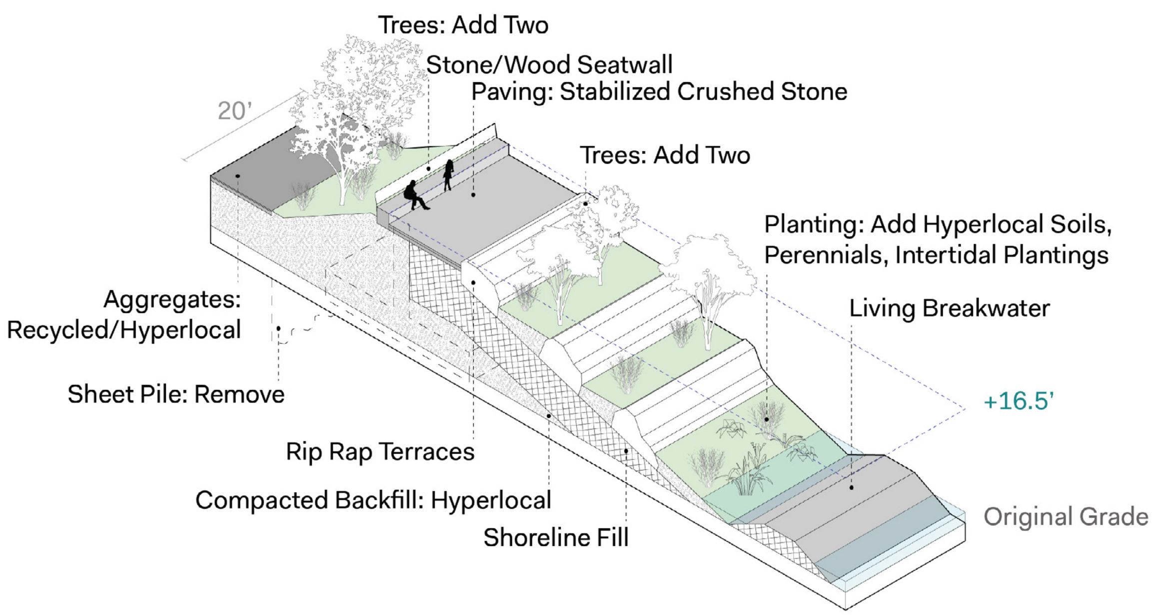


Figure 15: Optimized Alternative 2

Table 09: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/m2)	Total Cost	Cost per SF
Business-as-Usual	49	679*	50	694*	$47,006	$61
Optimized Alt 1	35	490*	38	535*	$42,977	$56
Optimized Alt 2	3	31	13	134	$44,030	$43

* Emissions exceeding recommended carbon upper limit for buildings (350kgCO2e/m2)[51]

Table 10: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
28%	23%	95%	8.57%	6%	8.57%	30%

While there are significant emissions and net intensity improvements possible between the scenarios pushing it below the carbon cap, the business-as-usual approach and emissions intensity of Alt 1 exceeds the recommended upper limit for building structures per area (350kgCO2e/m2).

51 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

New York, NY

5| HUNTER'S POINT PARK SOUTH

The BAU section illustrated at Hunter's Point Park is of a typical condition, shown near the southern end of the park. As designed and constructed, the edge condition is a gentle slope, mostly planted. Several access paths follow the slope, and a riprap edge lines the shore that protects inland wetland areas.

Overall Project Approach: Nature-based
Adaptation Typology: Living Shoreline
Nature-based Features: Wetlands and bioswales that absorb stormwater and buffer against coastal flooding
Sea Level Rise (SLR) Scenario: N/A (did not design for SLR)
Drawing Set Reference: SWA / Balsley, "Hunter's Point South Phase II Waterfront Park, Revised Conformance Documents", Dated: January 6, 2017.[52]

Figure 16: Key map for the Hunter's Point Park South section

52 SWA / Balsley, "Hunter's Point South Phase II Waterfront Park, Revised Conformance Documents", Dated: January 6, 2017, accessed March 4, 2025.

5| HUNTER'S POINT PARK SOUTH

Potential Modifications from Business-as-Usual to Optimized Alternative 1

104% reduction in net carbon impact intensity (partitioned below) and 0.71% cost increase from:

- Planting Soil: local > hyperlocal = 54%
- Aggregates: virgin/local > recycled/hyperlocal = 30%
- Sloped Lawn: sod > hydroseeded no-mow fescue = 9%
- Trees: adding two large deciduous trees = 7%
- Other additional plantings = 4%
- Precast/Cast-in-Place Mix Design: no SCMs > LC3 = 1%

Optimized Alternative 2 not included as maximum performance was achieved by Alternative 1

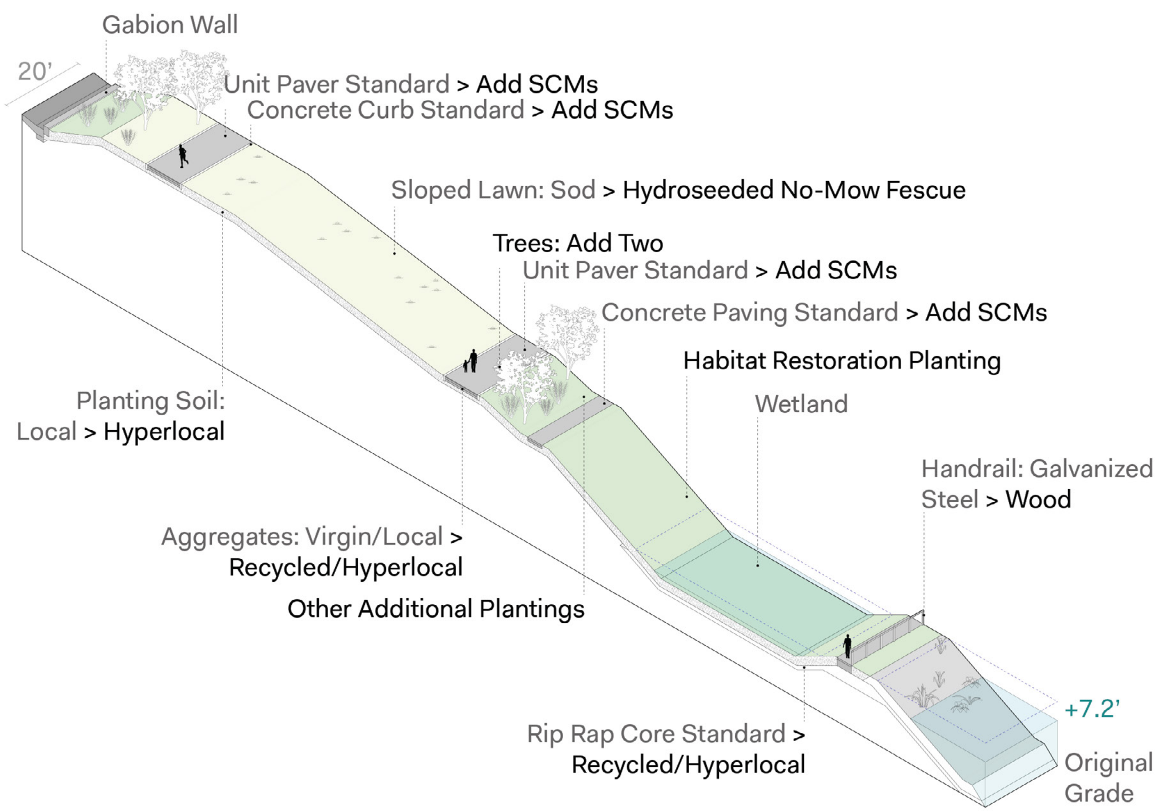


Figure 17: Business-as-Usual / Alternative 1

Table 11: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/m2)	Total Cost	Cost per SF
Business-as-Usual	59	506*	72	615*	$70,624	$56
Optimized Alt 1	-3	-22	19	159	$71,124	$57
Optimized Alt 2	N/A	N/A	N/A	N/A	N/A	N/A

* Emissions exceeding recommended carbon upper limit for buildings (350kgCO2e/m2)[53]

Table 12: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
104%	74%	N/A	-0.71%	N/A	-0.71%	N/A

N/A = not included as maximum performance was achieved through alternative 1
(-) Negative sign indicates carbon sequestration (or net positive drawdown) beyond project emissions

While there are significant emissions and net intensity improvements possible between BAU and Alt 1, the Business-as-Usual, built project exceeds the recommended upper limit for building structures per area (350kgCO2e/m2). With the optimizations included, the project adaptation typology at this cross-section could have reached net positive within the standard AEC project lifespan of 60 years.[54]

53 LETI et al, "“Embodied Carbon Target Alignment.”; City of Toronto, “Toronto Green Standard (TGS),” 2024; ILFI, “Zero Carbon Certification,” 2025; SE2050 et al, “Commitment Program 2023 Data Analysis,” 2024.

54 Carbon Leadership Forum, “Project Life Cycle Assessment Requirements - ECHO Recommendations for Alignment.” Embodied Carbon Harmonization and Optimization Project (ECHO), 2024, https://www.echo-project.info/publications.

Charleston, SC

6| PENINSULA PERIMETER PROTECTION PROJECT

The section illustrated is typical condition, shown at the southern end of Charleston's peninsula along the Ashley River. As its BAU is designed, this adaptation typology includes an elevated path with a concrete seawall on the waterside for protection from future storms. Ramps provide access to the lower grade inland which directs pedestrians to street crosswalks.

Overall Project Approach: Gray Infrastructure
Adaptation Typology: Elevated Seawall
Nature-based Features: Stormwater improvements and a landscaped berm
Sea Level Rise Scenario: 1.65' in 2082 with 1% annual chance storm
Drawing Set Reference: "A Coastal Storm Risk Management Study, Charleston, South Carolina, Engineering Appendix – B", Dated: February 2022.[55]

Figure 18: Key map for the Peninsula Perimeter Protection section

55 U.S. Army Corps of Engineers, Charleston District, "A Coastal Storm Risk Management Study, Charleston, South Carolina, Engineering Appendix – B", Figure 5.5.3:Typical section of Low Battery Wall Upgrade to EL 12.0 NAVD 88 flood protection, p. 50, Dated: February 2022, accessed July 28, 2025, https://cdxapps.epa.gov/cdx-enepa-II/public/action/eis/details?eisId=370189.

6| PENINSULA PERIMETER PROTECTION PROJECT

Potential Modifications from Business-as-Usual to Optimized Alternative 1

46% reduction in net carbon impact intensity (partitioned below) and 1.63% cost reduction from:

- Backfill / Aggregates: virgin/local > recycled/hyperlocal = 12%
- Demolition and offhaul: local > hyperlocal = 10%
- Cast-in-Place Mix Design: no SCMs > LC3 = 9%
- Trees: palm tree > large deciduous tree = 4%
- Planting Soil: local > hyperlocal = 2%
- Lawn > Plantings = 2%
- Guardrail Railings: stainless steel > wood = 1%

The optimization scenario shows the greatest project emissions reductions could come from the use of hyperlocal, recycled materials.

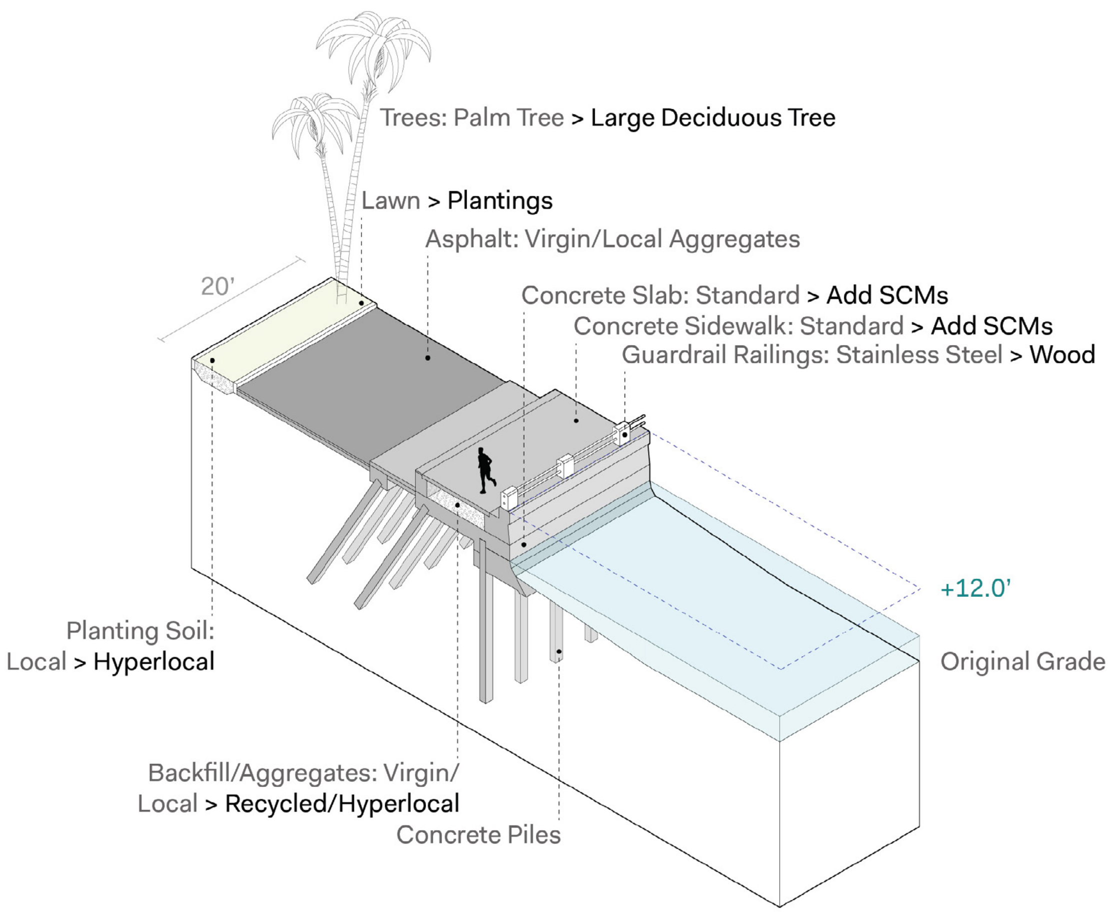


Figure 19: Business-as-Usual / Alternative 1

Potential Modifications from Business-as-Usual to Optimized Alternative 2

96% reduction in net carbon impact intensity (partitioned below) and 17% cost reduction from:

- Cast-in-Place Concrete Origin: intermediate local > hyperlocal = 32%
- Planting: added two small deciduous trees and intertidal plantings = 17%
- Backfill / Aggregates: hyperlocal > onsite = 11%
- Demolition and offhaul: local > hyperlocal = 10%
- Trees: palm tree > large deciduous tree = 7%
- Removing inner concrete retaining wall and sidewalk due to regrading = 7%
- Increasing available planting areas due to regrading = 4%
- Reducing asphalt quantity and on street parking due to regrading = 3%
- Planting Soil: local > hyperlocal = 2%
- Guardrail Railings: stainless steel > wood = 1%
- Removed lawn = 1%

In a shift from BAU to Alt 2, the greatest optimizations are found in hyperlocal concrete sourcing, repurposing one row of parking and the addition of shoreline fill which would allow for more planting and carbon sequestration. A reallocation of parking and shoreline fill would require review and approvals from the proper jurisdictions.

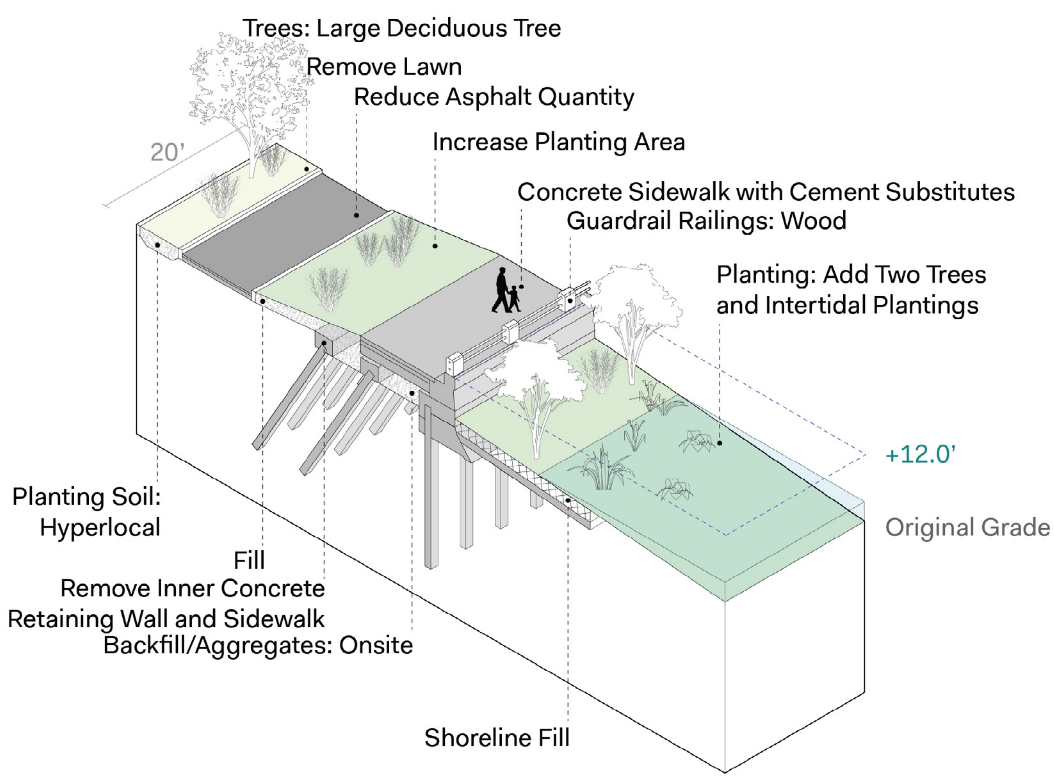


Figure 20: Optimized Alternative 2

Table 13: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/m2)	Total Cost	Cost per SF
Business-as-Usual	17	409*	18	431*	$21,463	$47
Optimized Alt 1	9	220	12	272	$21,113	$46
Optimized Alt 2	1	18	7	130	$17,874	$32

* Emissions exceeding recommended carbon upper limit for buildings (350kgCO2e/m2)[56]

Table 14: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
46%	37%	96%	1.63%	17%	1.63%	32%

While there are significant emissions and net intensity improvements possible, the Business-as-Usual design exceeds the recommended upper limit for building structures per area (350kgCO2e/m2). With the optimizations included, both Alt 1 and 2 would fall below that limit.

56 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

Boston, MA

7| EAST BOSTON WATERFRONT

The concept section illustrated in East Boston is of a constrained condition, shown at the at the Lewis Mall portion of the project along the Boston Harbor. As its BAU is designed at this stage of the project, this adaptation typology includes a raised Harbor Walk with an inland seawall for flood protection with an upper viewing deck with pedestrian access.

Overall Project Approach: Hybrid (NbS + Gray Infrastructure)
Adaptation Typology: Exposed Floodwall
Nature-based Features: Tidal habitat, shoreline plantings integrated into riprap
Sea Level Rise Scenario: 3.33' in 2070 with 1% chance annual storm
Drawing Set Reference: "WSE2101_East Boston Waterfront, Lewis Mall, Concept Drawings". (Noting this as a concept iteration.) [57]

Figure 21: Key map for the East Boston Waterfront section

57 STOSS Landscape Urbanism, City of Boston, "WSE2101_East Boston Waterfront, Lewis Mall, Concept Drawings", accessed March 25, 2025.

7| EAST BOSTON WATERFRONT

Potential Modifications from Business-as-Usual to Optimized Alternative 1

27% reduction in net carbon impact intensity (partitioned below) and 14.13% cost reduction from:

- Elevated Walkway Seawall: stainless steel > weathering steel = 17%
- Wood: thermally modified decking > redwood or cedar = 5%
- Guardrails: stainless steel > wood = 3%
- Cast-in-Place Mix Design: no SCMs > LC3 = 3%

The most significant emissions reductions could be accomplished by utilizing weathering steel in lieu of stainless steel.

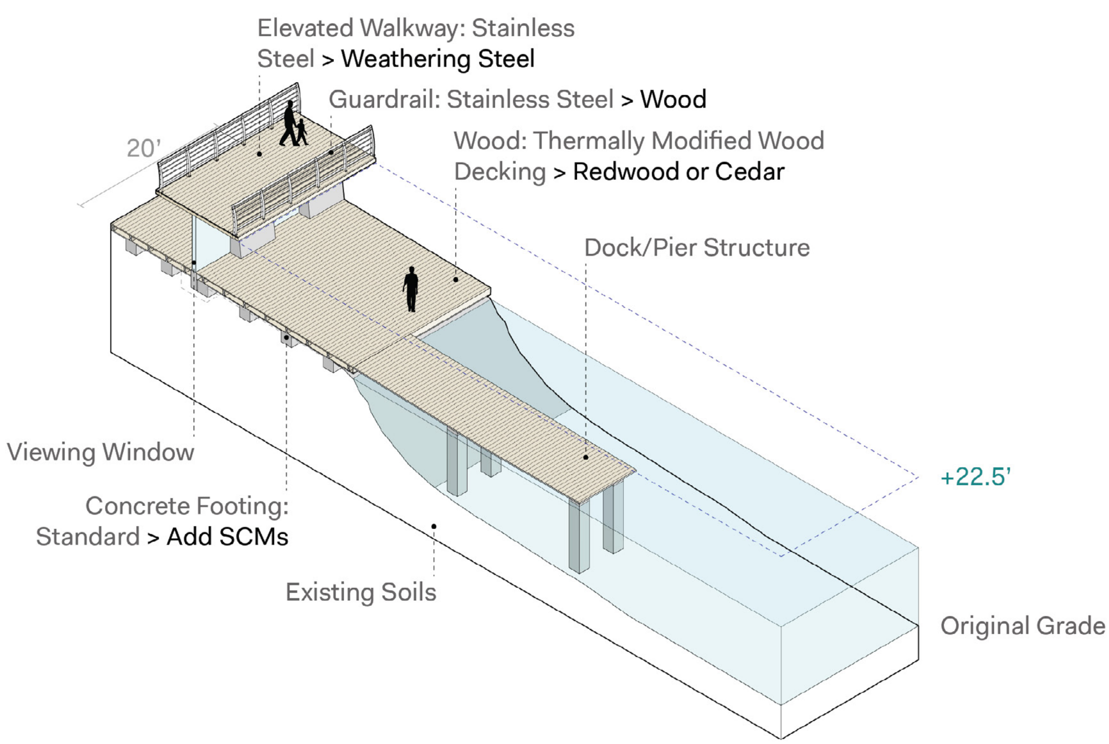


Figure 22: Business-as-Usual / Alternative 1

Potential Modifications from Business-as-Usual to Optimized Alternative 2

79% reduction in net carbon impact intensity (partitioned below) and 20% cost reduction from:

- Planting: Adding five medium deciduous trees, planting areas, hyperlocal planting soils, temperate perennials and intertidal plantings = 38%
- Reducing deck area = 16%
- Lightweight Fill (Expanded Clay Aggregates) = 11%
- Elevated Walkway Seawall: steel structure > graded berm with pathways = 7%
- Shoreline Fill = 7%

From BAU to Alt 2, the most significant carbon emissions are found in shifting from a wall and elevated walkway condition to a terraced berm which would require less materials and incorporate a significant amount of carbon sequestering plantings. To accomplish this, due to inland spatial constraints, the addition of shoreline fill is needed, which would require jurisdictional and structural engineering review and approvals.

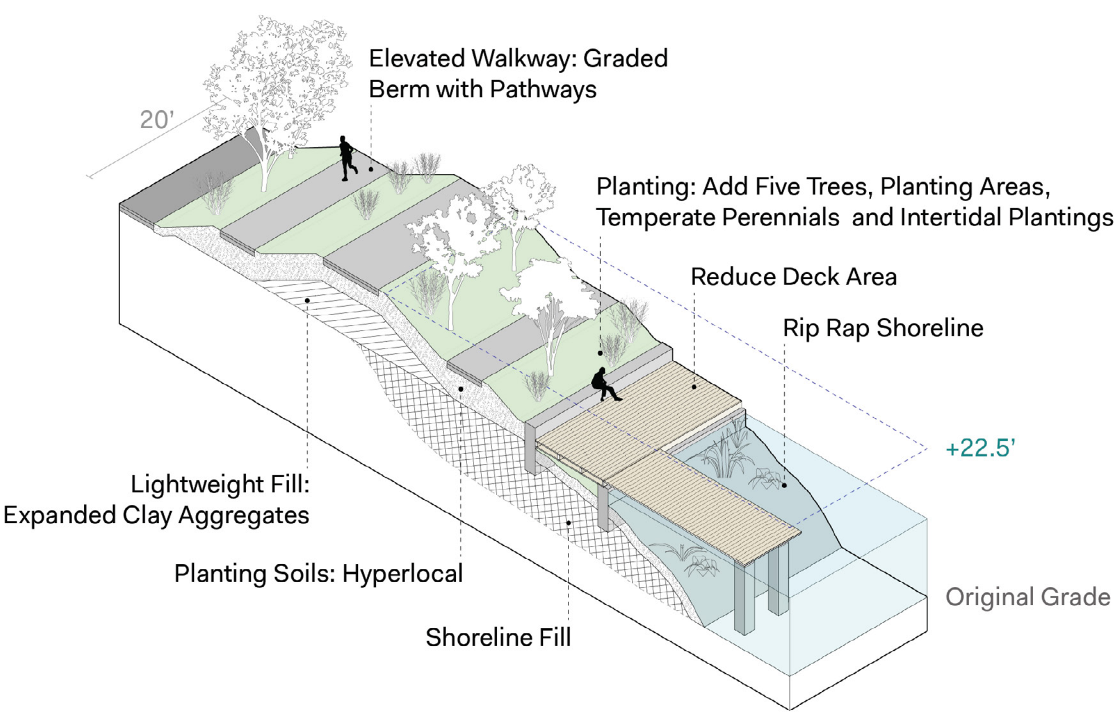


Figure 23: Optimized Alternative 2

Table 15: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/m2)	Total Cost	Cost per SF
Business-as-Usual	12	376*	12	376*	$54,507	$155
Optimized Alt 1	9	275	9	275	$46,807	$133
Optimized Alt 2	6	77	14	171	$43,422	$51

* Emissions exceeding recommended carbon upper limit for buildings (350kgCO2e/m2)[58]

Table 16: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
27%	27%	79%	14.13%	20%	14.13%	67%

While there are significant emissions and net intensity improvements possible, the Business-as-Usual design exceeds the recommended upper limit for building structures per area (350kgCO2e/m2). With the optimizations included, both Alt 1 and 2 would fall below that limit.

58 LETI et al, ““Embodied Carbon Target Alignment.”; City of Toronto, “Toronto Green Standard (TGS),” 2024; ILFI, “Zero Carbon Certification,” 2025; SE2050 et al, “Commitment Program 2023 Data Analysis,” 2024.

Boston, MA

8 | MOAKLEY PARK RESILIENCE PLAN

The section illustrated at Moakley Park is of a typical condition, shown at the northern end of the park. As its BAU is designed, this adaptation typology includes a raised berm, reinforced with a metal sheet pile wall. At the top of the berm is a paved path with planting on both sides.

Overall Project Approach: Hybrid (NbS + Gray Infrastructure)
Adaptation Typology: Bermed Floodwall
Nature-based Features: Stormwater management features, berm, planting
Sea Level Rise Scenario: 3.3’ SLR in 2070 with 1% annual chance storm
Drawing Set Reference: “Moakley Park Phase 1: 75% Construction Drawings”, dated June 7, 2024.[59]

Figure 24: Key map for the Moakley Park Resilience Plan section

59 STOSS Landscape Urbanism, City of Boston, “Moakley Park Phase 1: 75% Construction Drawings”, Core Wall Section, dated June 7, 2024, accessed September 25, 2024.

8 | MOAKLEY PARK RESILIENCE PLAN

Potential Modifications from Business-as-Usual to Optimized Alternative 1

82% reduction in net carbon impact intensity (partitioned below) and 13.35% cost reduction from:

- Lightweight Fill: foam glass aggregates > expanded clay aggregates = 26%
- Planting Soil: local import > amended onsite = 23%
- Trees: adding two large deciduous trees = 19%
- Reducing depth of sheet pile = 9%
- Aggregates: virgin/local > recycled/hyperlocal = 5%
- Cast-in-Place Mix Design: no SCMs > LC3 = 1%

The most significant emissions reductions are achieved by utilizing expanded clay aggregates in lieu of glass foam aggregates, amending soil on site, and adding trees.

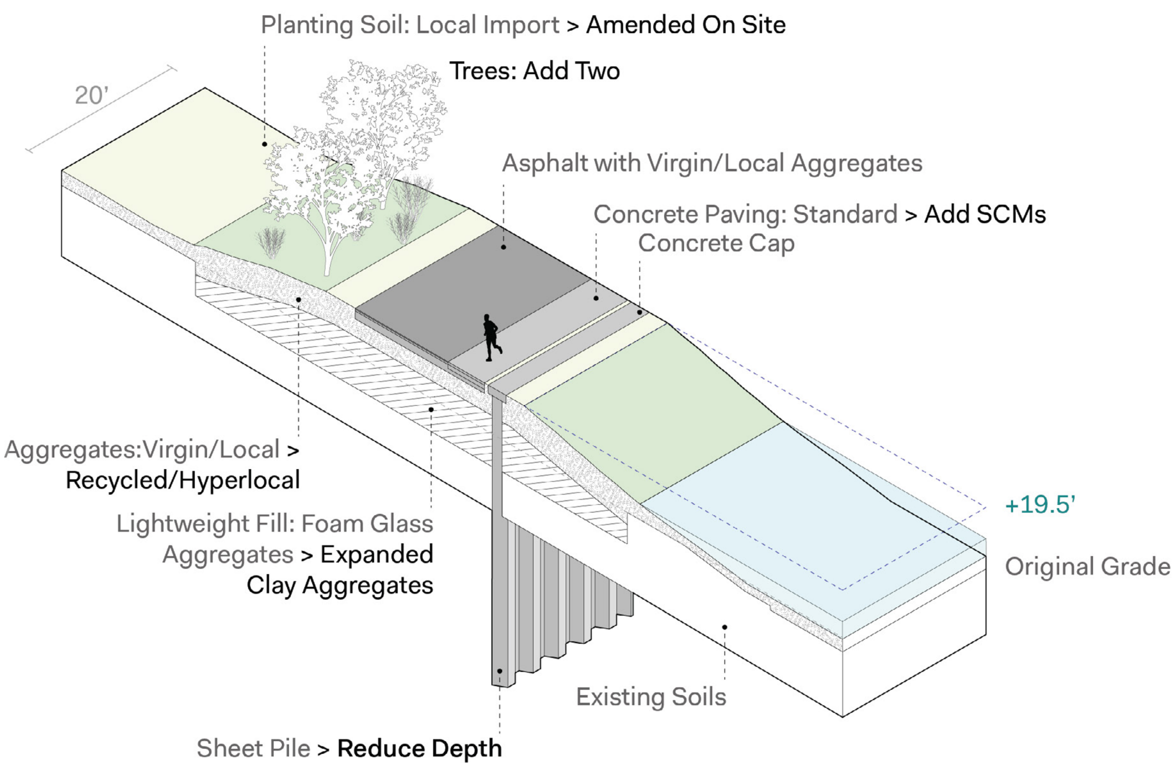


Figure 25: Business-as-Usual / Alternative 1

Potential Modifications from Business-as-Usual to Optimized Alternative 2

103% reduction in net carbon impact intensity (partitioned below) and 29% cost reduction from:

- Trees: adding three large deciduous trees = 27%
- Lightweight Fill: foam glass aggregates > expanded clay aggregates = 26%
- Planting Soil: local import > amended onsite = 23%
- Removing sheet pile wall and concrete cap = 20%
- Aggregates: virgin/local > recycled/hyperlocal = 5%
- Cast-in-Place Mix Design: no SCMs > LC3 = 1%

From BAU to Alt 2, the most significant carbon improvements can be achieved by adding trees, utilizing expanded clay aggregates, amending soil on site, and removing the sheet pile wall and associated concrete cap. A modification to the below ground structure would require engineer and jurisdictional review and approvals.

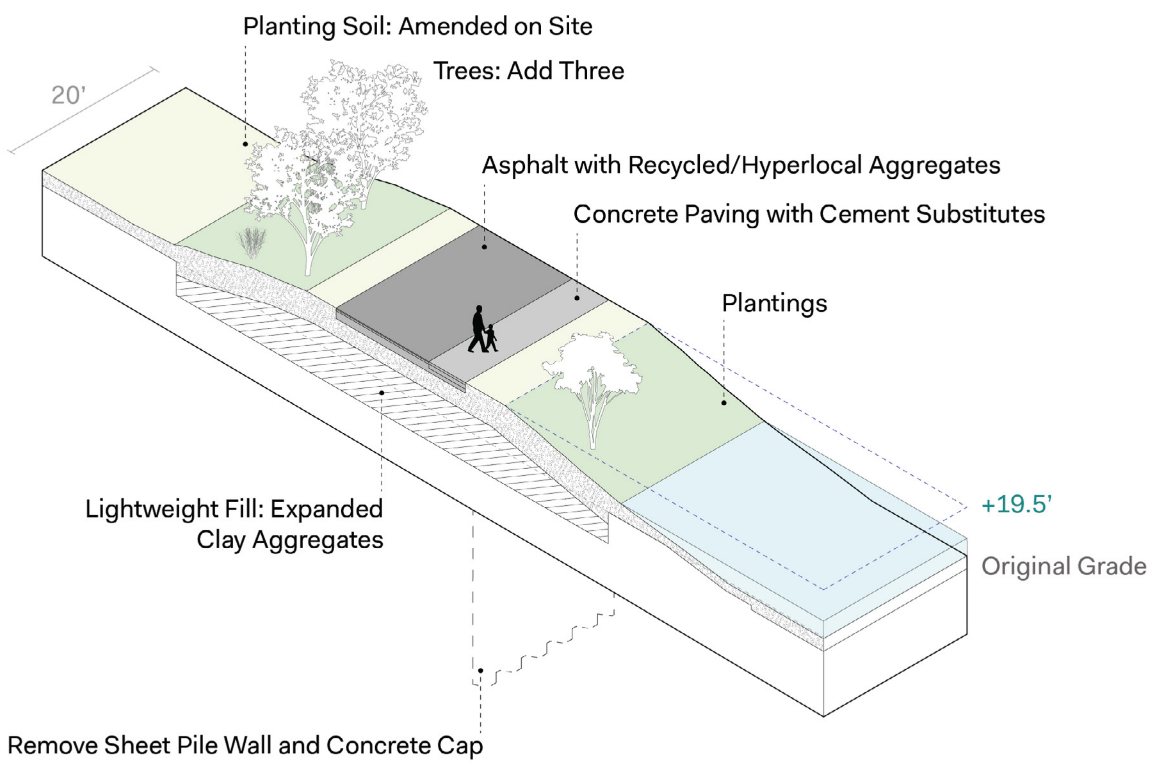


Figure 26: Optimized Alternative 2

Table 17: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/m2)	Total Cost	Cost per SF
Business-as-Usual	21	207	28	282	$52,431	$49
Optimized Alt 1	4	37	15	150	$45,430	$42
Optimized Alt 2	-1	-6	13	128	$37,378	$35

(-) Negative sign indicates carbon sequestration (or net positive drawdown) beyond project emissions

Table 18: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
82%	47%	103%	13.35%	29%	13.35%	29%

A largely nature-based approach for the Business-as-Usual design is below the upper limit for building structures per area (350kgCO2e/m2).[60] While minor modifications in Alt 1 can be achieved without significant structural shifts, the potential changes in Alt 2 can lead to a net-positive outcome over the project lifespan.

60 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

Miami, FL

9 | MORNINGSIDE PARK RESILIENT SHORELINE PROJECT

The section illustrated in Miami is of a typical condition at Morningside Park, shown at the northern portion of the project along the Biscayne Bay. As its BAU is designed, this adaptation typology includes an elevated Baywalk with coastal terraces for ecosystem restoration and wave attenuation.

Overall Project Approach: Hybrid (NbS + Gray Infrastructure)
Adaptation Typology: Multi-Purpose Levee
Nature-based Features: Living shoreline with mangroves and native plants, restoring natural habitats
Sea Level Rise Scenario: 3.3' SLR in 2070
Drawing Set Reference: "Morningside Park Waterfront Improvement Landscape Plans, 100% Drawings", dated November 30, 2022.[61]

Figure 27: Key map for the Morningside Park section

61 Curtis + Rodgers Design Studio, City of Miami, Office of Capital Improvements, "Morningside Park Waterfront Improvement Landscape Plans, 100% Drawings", dated November 30, 2022. Accessed February 20, 2025.

9 | MORNINGSIDE PARK RESILIENT SHORELINE PROJECT

Potential Modifications from Business-as-Usual to Optimized Alternative 1

102% reduction in net carbon impact intensity (partitioned below) and 0.77% cost reduction from:

- Sheet Pile: standard steel > recycled steel = 61%
- Cast-in-Place Mix Design: no SCMs > LC3 = 21%
- Aggregates: virgin/hyperlocal > recycled/onsite = 20%

The primary emissions reductions from the BAU design are attributed to a combination of specifying recycled steel, LC3 cement substitutions, and utilizing recycled onsite aggregate material.

Optimized Alternative 2 not included as maximum performance was achieved by Alternative 1

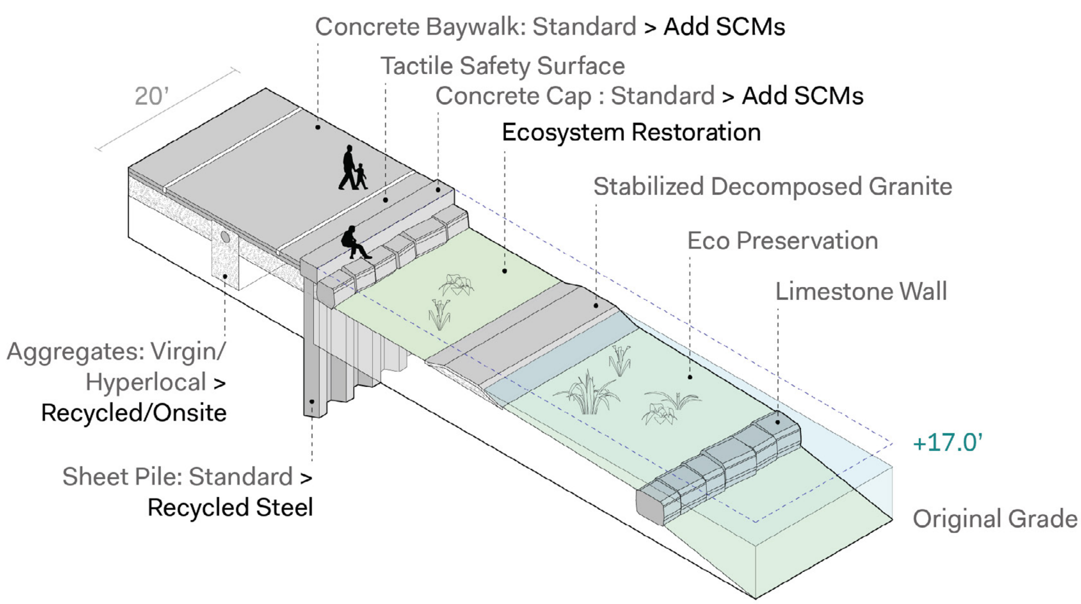


Figure 28: Business-as-Usual / Alternative 1

Table 19: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/m2)	Total Cost	Cost per SF
Business-as-Usual	59	506*	72	615*	$70,624	$56
Optimized Alt 1	-3	-22	19	159	$71,124	$57
Optimized Alt 2	N/A	N/A	N/A	N/A	N/A	N/A

N/A = not included as maximum performance was achieved through alternative 1
(-) Negative sign indicates carbon sequestration (or net positive drawdown) beyond project emissions

Table 20: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
104%	74%	N/A	-0.71%	N/A	-0.71%	N/A

N/A = not included as maximum performance was achieved through alternative 1
(-) Negative sign indicates carbon sequestration (or net positive drawdown) beyond project emissions

A largely nature-based approach for the Business-as-Usual design is below the upper limit for building structures per area (350kgCO2e/m2).[62] Minor modifications in Alt 1 could be achieved without significant structural shifts and lead to a net-positive outcome within the lifespan of the project.

62 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

Brooklyn, NY

10 | PIER 6

The BAU section illustrated for the Pier 6 Redevelopment is shown along the proposed Tide Pool reconfiguration. As designed, this adaptation typology includes removing existing shoreline material to allow water to enter the site and form shallow tide pool terraced habitats.

Overall Project Approach: Hybrid (NbS + Gray Infrastructure)
Adaptation Typology: Tide Pools
Nature-based Features: Ecological preservation, restoration, and tide pool reconfiguration
Sea Level Rise (SLR) Scenario: Did not elevate for SLR
Drawing Set Reference: "The Bush Terminal - Pier 6, 90% Design Drawings", dated January 30, 2025.[63]

Figure 29: Key map for the Pier 6 Redevelopment section

63 SCAPE Landscape Architecture DPC, New York City Economic Development Corporation, "The Bush Terminal - Pier 6, 90% Design Drawings", dated January 30, 2025, accessed February 19, 2025.

10 | PIER 6

Potential Modifications from Business-as-Usual to Optimized Alternative 1

89% reduction in net carbon impact intensity (partitioned below) and 7.48% cost increase from:

- Aggregates (except Aggregate Base Material): virgin/local > recycled/hyperlocal = 51%
- Planting Soil: local > hyperlocal = 26%
- Trees: adding two medium deciduous trees = 10%
- Path Paving: concrete > stabilized crushed stone = 2%

Most of the emissions reductions can be accomplished by specifying recycled, hyperlocal materials and planting soil.

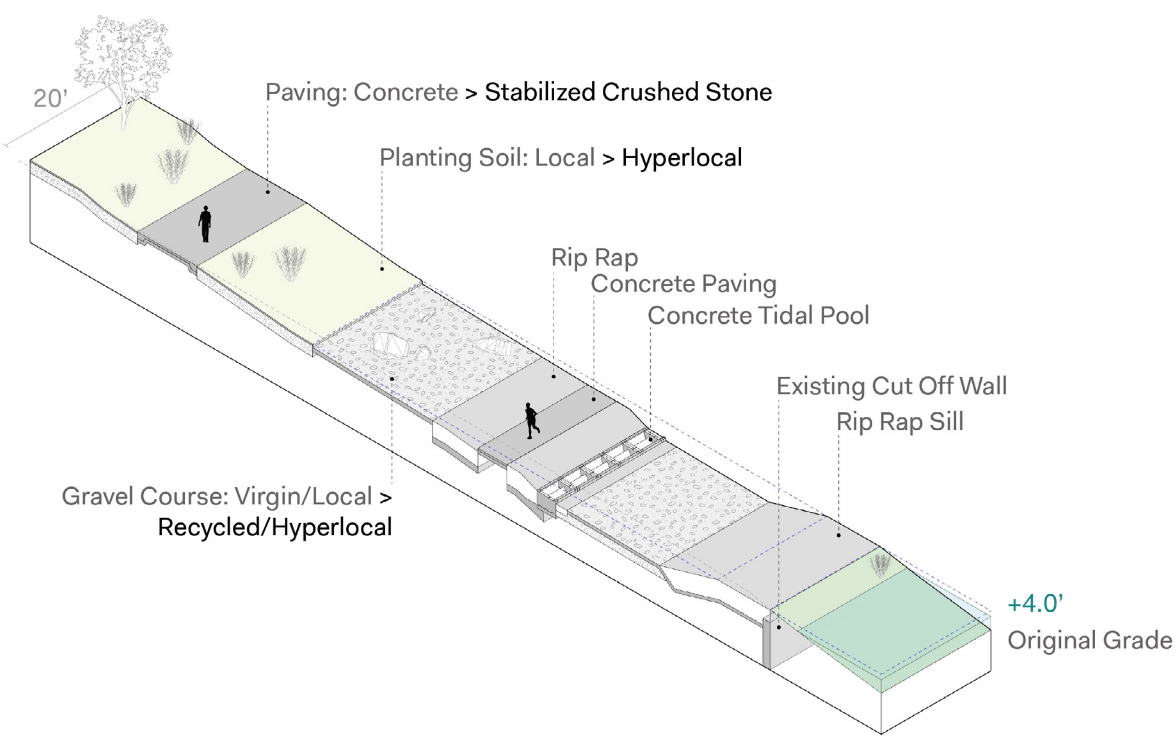


Figure 30: Business-as-Usual / Alternative 1

Potential Modifications from Business-as-Usual to Optimized Alternative 2

104% reduction in net carbon impact intensity (partitioned below) and 10% cost increase from:

- Aggregates (except Aggregate Base Material): virgin/local > recycled/hyperlocal = 49%
- Planting Soil: local > hyperlocal = 28%
- Planting: Adding temperate perennials, plants integrated into riprap and intertidal plantings = 16%
- Trees: adding three medium deciduous trees = 10%
- Path Paving: concrete > stabilized crushed stone = 2%

As found in Alt 1, most of the emissions reductions are accomplished by using recycled, hyperlocal materials and planting soil. However, from BAU to Alt 2, a significant amount of carbon sequestration could be realized by adding plants in the intertidal zone.

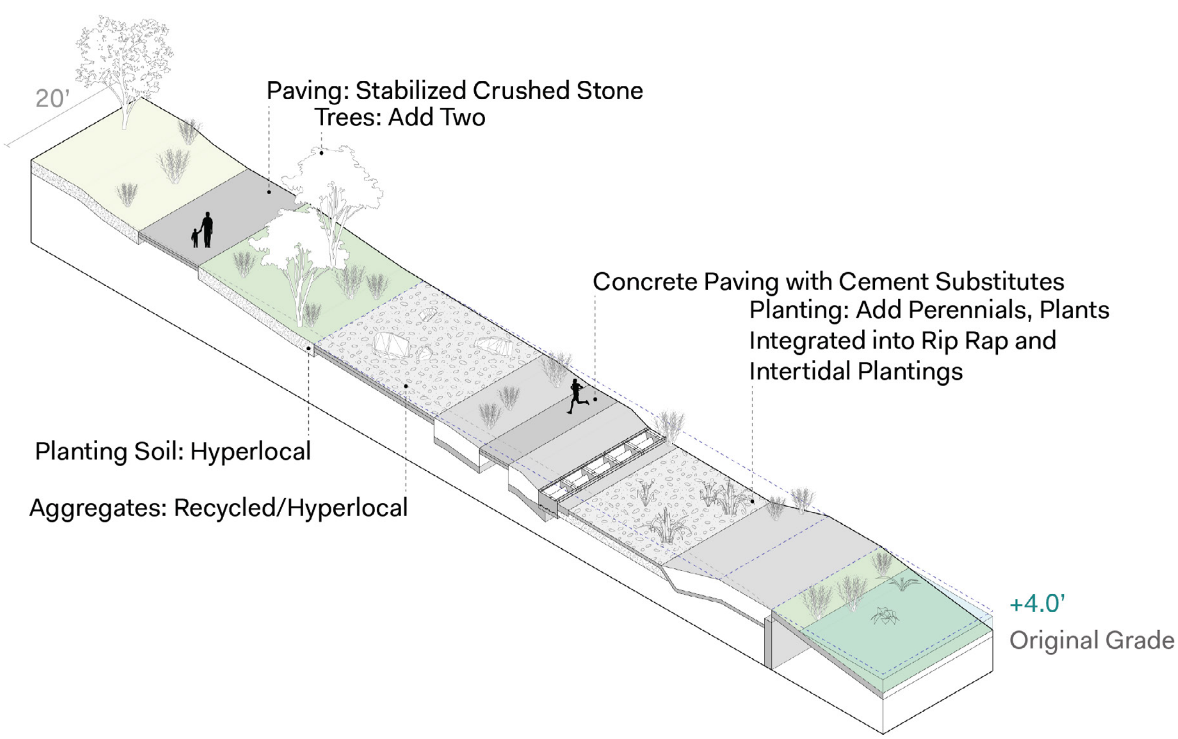


Figure 31: Optimized Alternative 2

Table 21: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/m2)	Total Cost	Cost per SF
Business-as-Usual	19	153	23	182	$28,515	$21
Optimized Alt 1	2	18	8	62	$30,649	$23
Optimized Alt 2	-1	-6	7	51	$31,357	$20

(-) Negative sign indicates carbon sequestration (or net positive drawdown) beyond project emissions

Table 22: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
89%	66%	104%	-7.48%	-10%	-7.48%	4%

A largely nature-based approach for the Business-as-Usual design is below the upper limit for building structures per area (350kgCO2e/m2).[64] Minor modifications in Alt 1 could be achieved without significant structural shifts, but a net-positive outcome could be achieved in Alt 2 by adding intertidal plantings.

64 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

San Francisco, CA

11 | TREASURE ISLAND CITYSIDE PARK

The section illustrated along Treasure Island's Citywide Park is of a coastal shelf condition that was designed and constructed in San Francisco Bay. The island's shoreline was elevated for flood protection but the riprap edge within Cityside Park includes terraced tidal shelves that allow for native intertidal planting embedded within the riprap protection zone.

Overall Project Approach: Hybrid (NbS + Gray Infrastructure)
Adaptation Typology: Terraced Shoreline
Nature-based Features: Tidal shelf along the Cityside Park edge to incorporate coastal plantings into an existing rocky shoreline
Sea Level Rise Scenario: 3' SLR in 2050 with 1% annual chance storm
Drawing Set Reference: "Treasure Island Sub-Phase 1B, 1C, & 1E, Cityside Park Phase 1 Permit Submittal", dated June 3, 2022.[65]

Figure 32: Key map for the Treasure Island Cityside Park section

65 CMG Landscape Architecture, Treasure Island Development Authority, Treasure Island Development Group, "Treasure Island Sub-Phase 1B, 1C, & 1E, Cityside Park Phase 1 Permit Submittal", dated June 3, 2022, accessed April 2, 2025.

11 | TREASURE ISLAND CITYSIDE PARK

Potential Modifications from Business-as-Usual to Optimized Alternative 1

21% reduction in net carbon impact intensity (partitioned below) and 2.66% cost reduction from:

- Aggregate Base Material: virgin/local > recycled/hyperlocal = 17%
- Promenade: concrete > stabilized crushed stone = 4%

Most of the emissions reductions shown in Alt 1 come from utilizing recycled, hyperlocal aggregate base materials.

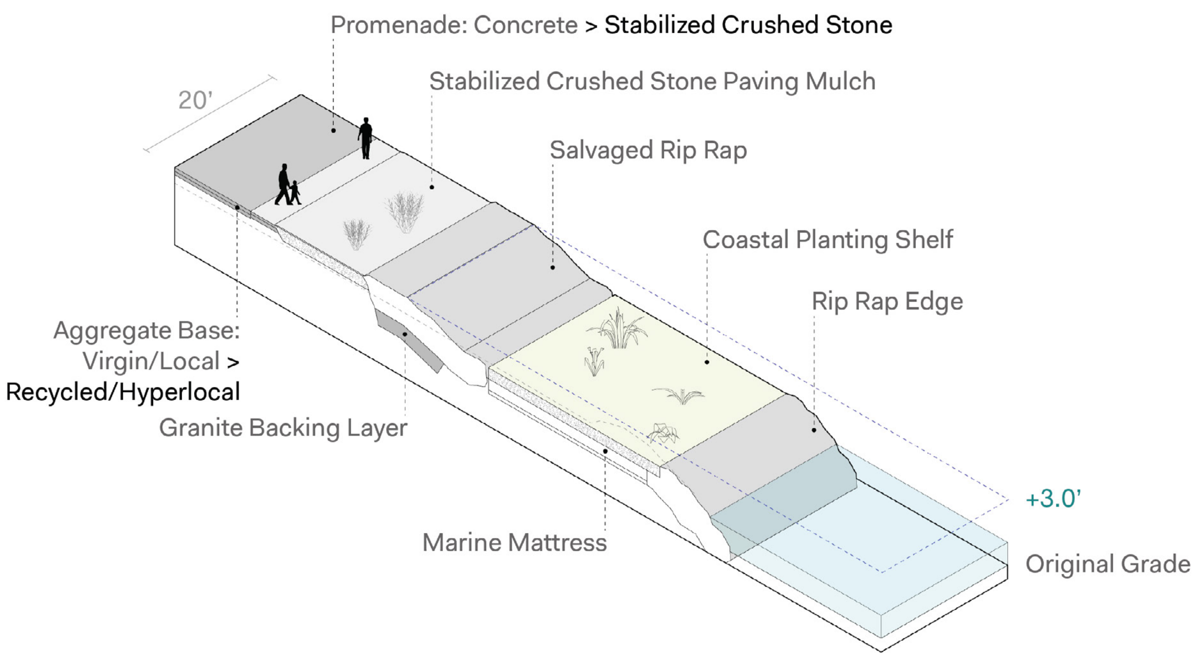


Figure 33: Business-as-Usual / Alternative 1

Potential Modifications from Business-as-Usual to Optimized Alternative 2

149% reduction in net carbon impact intensity (partitioned below) and 19% cost reduction from:

- Planting: Add two small evergreen trees, additional temperate perennials, and intertidal plantings = 126%
- Riprap: Reducing secondary improvement > increasing planting area = 17%
- Aggregate Base Material: virgin/local > recycled/hyperlocal = 3%
- Promenade: concrete > stabilized crushed stone = 3%

In Alt 2, a significant increase in carbon sequestration can occur by reducing the secondary riprap improvement and integrating more planting into the sloped area.

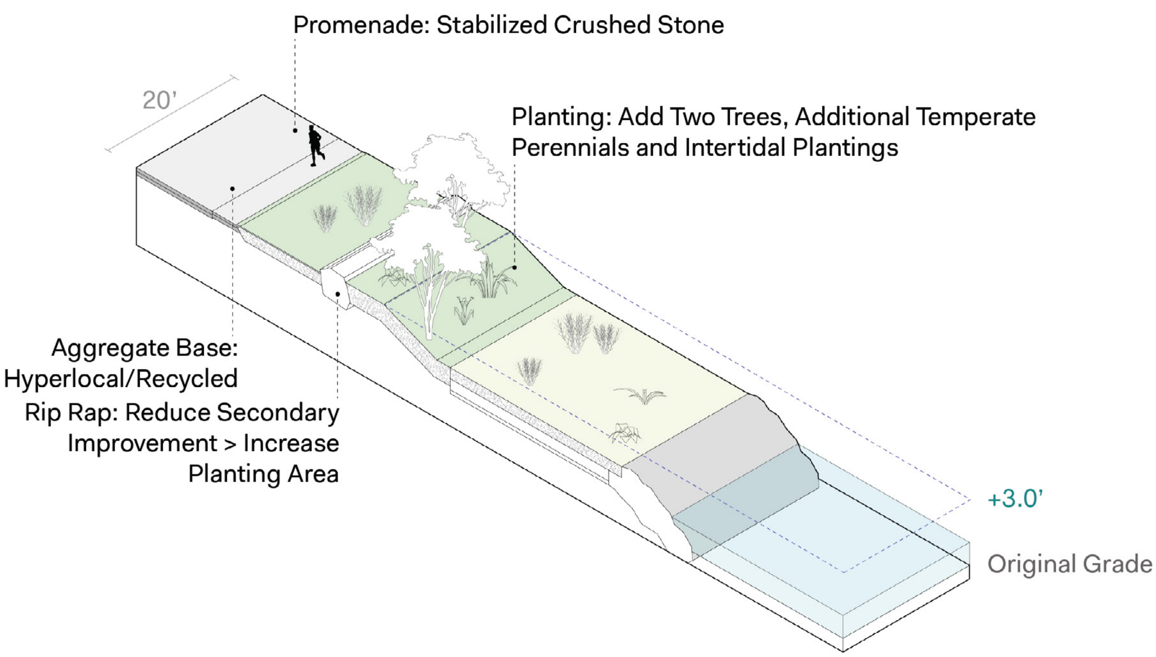


Figure 34: Optimized Alternative 2

Table 23: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/m2)	Total Cost	Cost per SF
Business-as-Usual	3	44	6	86	$22,580	$29
Optimized Alt 1	3	37	6	79	$21,980	$28
Optimized Alt 2	-1	-20	6	87	$18,383	$23

(-) Negative sign indicates carbon sequestration (or net positive drawdown) beyond project emissions

Table 24: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
21%	11%	149%	2.66%	19%	2.66%	19%

A largely nature-based approach for the Business-as-Usual design is below the upper limit for building structures per area (350kgCO2e/m2).[66] Minor modifications in Alt 1 can be achieved without significant structural shifts, but a net-positive outcome can be achieved in Alt 2 by integrating more planting into the riprap shoreline secondary improvement.

66 LETI et al, "“Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

Alameda, CA

12 | DE-PAVE PARK

The BAU section illustrated for De-Pave Park is of a typical condition, centrally located along Sea Plane Lagoon in Alameda. As designed, this adaptation typology includes reconfiguring the shoreline edge to support intertidal habitat as water levels rise, while providing recreational access with an existing inland multi-use path.

Overall Project Approach: Hybrid (NbS + Gray Infrastructure)
Adaptation Typology: Floodable Park
Nature-based Features: Restored Wetlands
Sea Level Rise Scenario: 3.5' SLR in 2070 with 1% annual chance storm
Drawing Set Reference: CMG Landscape Architecture, City of Alameda, "De-Pave Park, BCDC Design Review Board Exhibits", Dated: January 8, 2023.[67]

Figure 35: Key map for the De-Pave Park section

67 CMG Landscape Architecture, City of Alameda, "De-Pave Park, BCDC Design Review Board Exhibits", Dated: January 8, 2023, accessed March 12, 2025.

12 | DE-PAVE PARK

Potential Modifications from Business-as-Usual to Optimized Alternative 1

95% reduction in net carbon impact intensity (partitioned below) and 8% cost increase from:

- Planting: adding intertidal plantings = 95%

Most of the carbon performance improvements can be accomplished by adding intertidal plantings to the BAU design.

Optimized Alternative 2 was not included as maximum performance was achieved through Alternative 1

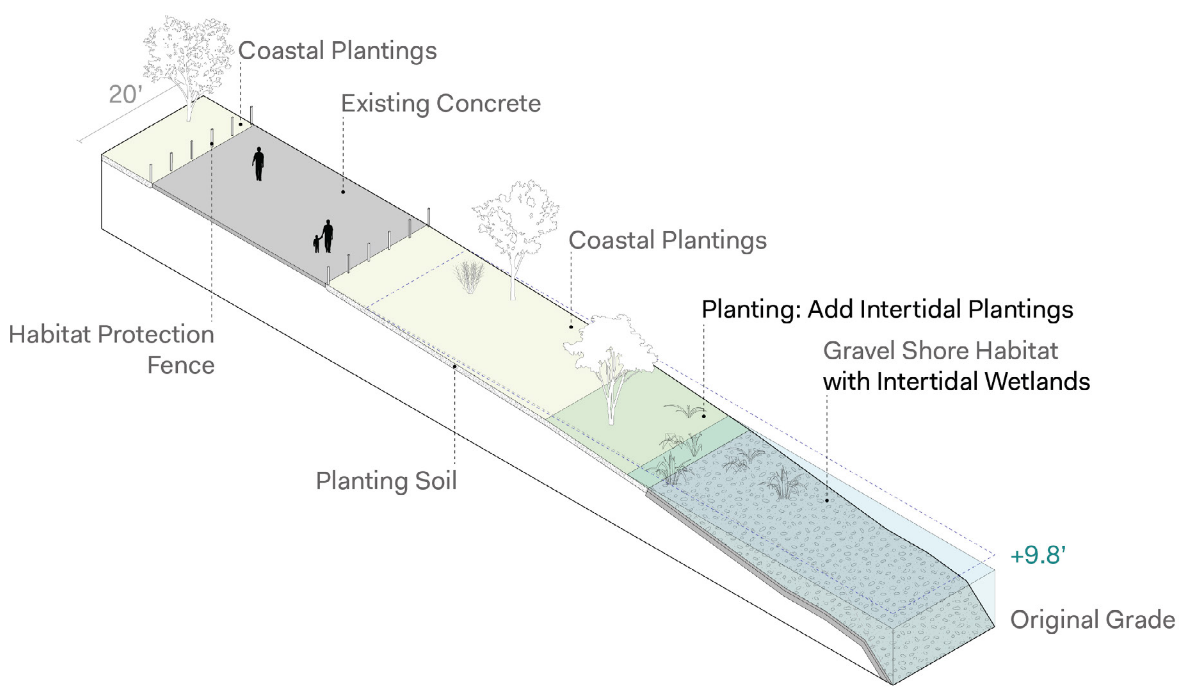


Figure 36: Business-as-Usual / Alternative 1

Table 25: Carbon and cost impacts

	Net Impact (tCO2e)	Net Impact Intensity (kgCO2e/ m2)	Total Emissions (tCO2e)	Emission Intensity (kgCO2e/ m2)	Total Cost	Cost per SF
Business-as-Usual	-2	-14	4	30	$29,996	$19
Optimized Alt 1	-4	-27	4	28	$32,396	$21
Optimized Alt 2	N/A	N/A	N/A	N/A	N/A	N/A

(-) Negative sign indicates carbon sequestration (or net positive drawdown) beyond project emissions

Table 26: Carbon and cost improvements

Improvements						
Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
95%	5%	N/A	-8%	N/A	-8%	N/A

N/A = not included as maximum performance was achieved through alternative 1

Not only is this nature-based approach for the Business-as-Usual design below the upper limit for building structures per area (350kgCO2e/m2), it is the only adaptation typology to achieve a net-positive carbon approach as originally designed and publicly documented.[68] By adding intertidal plantings in Alt 1, this project could increase its carbon drawdown potential.

68 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

COMPARATIVE ANALYSIS

Nature-based Solutions

The business-as-usual designs for the primary De-Pave Park adaptation typology has the lowest cost at $18 per square foot (sf) of adapted coastline, while Pier 6—also an NbS—costs $21 per sf. Findings indicate that including NbS in project strategies yield a more cost-effective adaptation approach to balance upfront financial investment with long-term resilience and environmental impact.

Hybrid Projects

Mid-cost projects designed with a business-as-usual approach, like the Peninsula Perimeter Protection typology ($47 per sf) and Resilient Norfolk Coastal Storm Risk Management (CSRM) ($61 per sf), combine gray infrastructure (e.g., concrete floodwalls and seawalls) with ecological enhancements like riprap or habitat features.

Projects with mid- to high costs, including the Resilient Norfolk CSRM, Peninsula Perimeter Protection Project, and Moakley Park, typically use a hybrid strategy combining gray and ecological defenses. These designs integrate NbS elements, like marine restoration, into traditional infrastructure, creating resilient adaptations that support biodiversity. However, high costs stem from complex engineered elements in dense urban settings.

Gray Infrastructure Projects

Higher-cost projects with substantial concrete use, such as Eastside Coastal Resilience Park ($173 per sf) and Elliott Bay Seawall Project ($157 per sf), feature large-scale flood defenses like cantilevered bulkheads and extended seawalls. Contrary to the study findings, mega-projects like the Elliott Bay Seawall and Eastside Coastal Resilience Park report that extensive NbS incorporation in urban spaces raises costs but offers notable ecological and social benefits. This study finds that prioritizing NbS and expanding space for NbS or re-prioritizing spatial distribution in such designs would reduce reliance on gray infrastructure and reduce costs.

PROJECT OPTIMIZATION RELATIONSHIP BETWEEN CARBON IMPROVEMENTS AND COST

The case study project data analysis methodology concludes the following:

Carbon net impacts possible: 64% improvement from BAU to Alt 1 and 91% from BAU to Alt 2

Cost improvements possible: 2.33% improvement from BAU to Alt 1 and 21% from BAU to Alt 2

While a significant net carbon impact improvement of 64% can be achieved with relatively straightforward optimizations from Business-as-Usual to Optimized Alternative 1, the cost performance is less so at 2.33% improvement. While costs vary significantly based on geographic location or availability, the primary finding from this analysis is that the “low-hanging fruit” improvements to each project will be a relatively zero sum increase to costs.

However, when making more intentional and potentially structurally significant shifts towards a nature-based approach, the study concludes a potential 91% net carbon improvement from Business-as-Usual to Optimized Alternative 2 also gains an average of 21% total cost reduction. While this cost performance may seem lower than other studies,9 this is likely the outcome of comparing more feasible urban adaptations alternatives to one another rather than comparing widely different approaches and contexts. For example, comparing urban seawall performance to that of a rural or fully natural mangrove forest ecosystem restoration.

These findings indicate that the incorporation of nature-based coastal adaptations perform much higher from a carbon than a cost performance standpoint, the former of which has been significantly overlooked, undocumented, and unregulated in North America, if not globally.

Table 27: Carbon and cost improvements summary

Projects	Improvements						
	Net Intensity % Reduction from BAU to Opt Alt 1	**Emissions Intensity % Reduction from BAU to Opt Alt 1**	**Net Intensity % Reduction from BAU to Opt Alt 2**	**Total Cost Reduction from BAU to Alt 1**	**Total Cost Reduction from BAU to Alt 2**	**Cost per SF Reduction from BAU to Alt 1**	**Cost per SF Reduction from BAU to Alt 2**
Eastside Coastal Resilience Park	74%	70%	87%	0.39%	49%	0.39%	54%
Elliott Bay Seawall	13%	13%	32%	2.25%	19%	2.25%	19%
Eastside Coastal Resilience Park - Cantilever	76%	72%	80%	0.30%	45%	0.30%	31%
Mission Rock / China Basin Park	74%	71%	82%	3.20%	19%	3.20%	19%
Resilient Norfolk CSRM	28%	23%	95%	8.57%	6%	8.57%	30%
Hunters Point Park South	104%	74%	N/A	-0.71%	N/A	-0.71%	N/A
Peninsula Perimeter Protection	46%	37%	96%	1.63%	17%	1.63%	32%
East Boston Waterfront	27%	27%	79%	14.13%	20%	14.13%	67%
Moakley Park Resilience Plan	82%	47%	103%	13.35%	29%	13.35%	29%
Morningside Park Resilient Shoreline	102%	36%	N/A	0.00%	N/A	0.00%	N/A
Pier 6	89%	66%	104%	-7.48%	-10%	-7.48%	4%
TI Cityside Park	21%	11%	149%	2.66%	19%	2.66%	19%
De-Pave Park	95%	5%	N/A	-8.00%	N/A	-8.00%	N/A
Summary							
Average Improvements	64%	42%	91%	**2.33%**	**21%**	**2.33%**	**30%**
Median Improvements	74%	37%	91%	1.63%	19%	1.63%	29%
Avg. Improvements for Typ. Projects (removing lower than 10%, already optimized)	**64%**	**45%**	**91%**	N/A2	N/A2	N/A2	N/A2
Median Improvements for Typ. Projects (removing lower than 10%, already optimized)	74%	42%	91%	N/A2	N/A2	N/A2	N/A2

N/A = not included as maximum performance was achieved through alternative 1

N/A2 = Excluded as all projects were deemed suitable for use in cost performance analysis

(-) Negative sign indicates carbon sequestration (or net positive drawdown) beyond project emissions

STRUCTURAL EMISSIONS CAP

Several architecture, engineering, and construction industry organizations and municipalities have set recommended or even required maximum upper emissions limits per m² for building certifications and/or city approvals. The cap established for LETI 2030 building benchmarks, the City of Toronto Green Standard for buildings, International Living Future Institute, Structural Engineering Institute SE2050 Program, Carbon Leadership Forum have aligned around a maximum upper limit of 350 kgCO2e/m2 for embodied carbon.[69]

Findings from the study conclude that 64% of business-as-usual coastal adaptations exceed the current recommended cap for buildings and structures (identified with an (*) asterisk in the charts), even after factoring in site sequestration. This underscores that site infrastructure designs can be just as carbon intensive as the surrounding buildings.

However, by including alternative optimized strategies, the projects previously exceeding the carbon emissions cap drops to 20%-31%. With more nature and sequestration potential included, only 10%-23% of projects exceed the requirement. Despite the potential improvements, these projects generate significant embodied carbon emissions per area for sites and infrastructure, which are typically overlooked and currently have no global emissions limitations on their implementation.

CARBON OFFSET POTENTIAL

While the typical adaptation typology of only one project, De-Pave Park, has the potential to offset its own embodied carbon emissions within its sixty-year lifespan as per business-as-usual, by incorporating the optimization strategies five additional project adaptations have/had the potential to become “carbon positive” within their lifespans. Those projects are identified by a (-) negative symbol.

N/A = not included as maximum performance was achieved through alternative 1

* Emissions exceeding recommended carbon upper limit for buildings (350kgCO2e/m2)

(-) Negative sign indicates carbon sequestration (or net positive drawdown) beyond project emissions

69 LETI et al, ““Embodied Carbon Target Alignment.”; City of Toronto, “Toronto Green Standard (TGS),” 2024; ILFI, “Zero Carbon Certification,” 2025; SE2050 et al, “Commitment Program 2023 Data Analysis,” 2024; Carbon Leadership Forum, “The Embodied Carbon Benchmark Report,” 2025.

Table 28: Carbon impacts summary

Performance and Optimization	BAU		Optimized Alternative 1		Optimized Alternative 2	
	Net Impact Intensity (kgCO2e/m2)	Emission Intensity (kgCO2e/m2)	Net Impact Intensity (kgCO2e/m2)	Emission Intensity (kgCO2e/m2)	Net Impact Intensity (kgCO2e/m2)	Emission Intensity (kgCO2e/m2)
Eastside Coastal Resilience Park	2,216*	2,304*	573*	690*	289	354*
Elliott Bay Seawall	1,869*	1,869*	1,631*	1,631*	1,274*	1,274*
Eastside Coastal Resilience Park - Cantilever	1,361*	1,420*	326	404*	265	335
Mission Rock / China Basin Park	1,084*	1,112*	281	322	195	236
Resilient Norfolk CSRM	679*	694*	490*	535*	31	134
Hunters Point Park South	506*	615*	-22	159	N/A	N/A
Peninsula Perimeter Protection	409*	431*	220	272	18	130
East Boston Waterfront	376*	376*	275	275	186	171
Moakley Park Resilience Plan	207	282	37	150	-6	128
Morningside Park Resilient Shoreline	62	175	-1	112	N/A	N/A
Pier 6	153	182	18	62	-6	51
TI Cityside Park	46	89	37	79	-23	84
De-Pave Park	-14	30	-27	28	N/A	N/A
% of projects exceeding cap (350 kgCO2e/m2)	**62%**	**62%**	**23%**	**31%**	**10%**	**20%**
Number of projects above cap	8	8	3	4	1	2
Total Number of Projects	13	13	13	13	10	10

NET CARBON IMPACTS | BAU

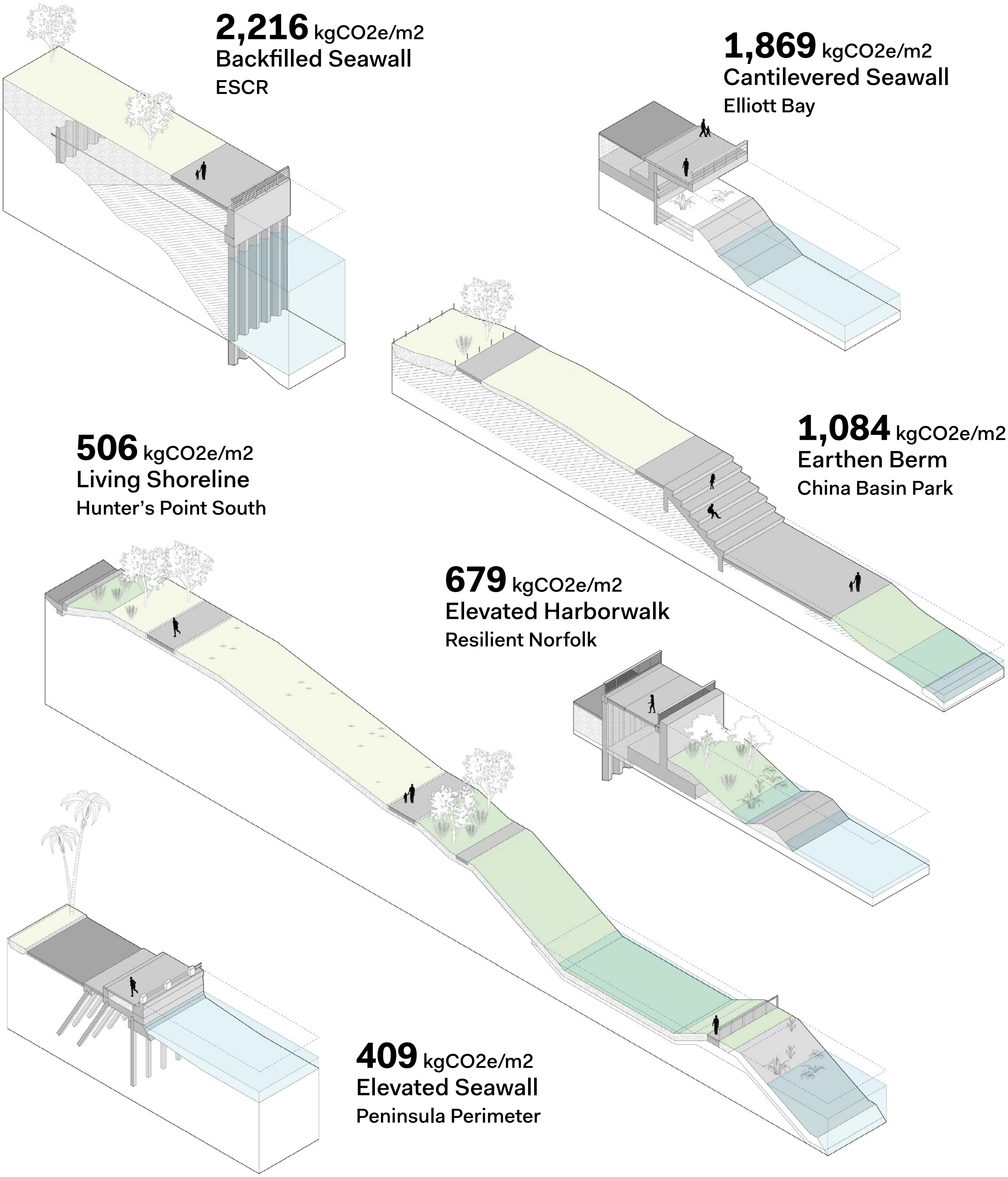
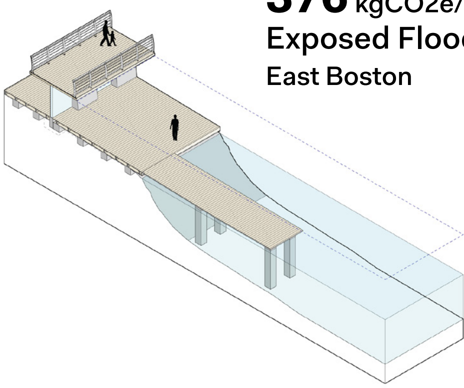
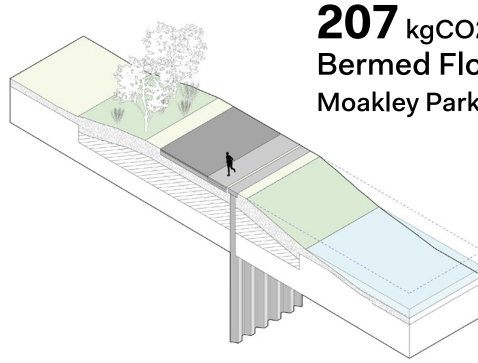


Figure 37: BAU Net Carbon Impacts Summary

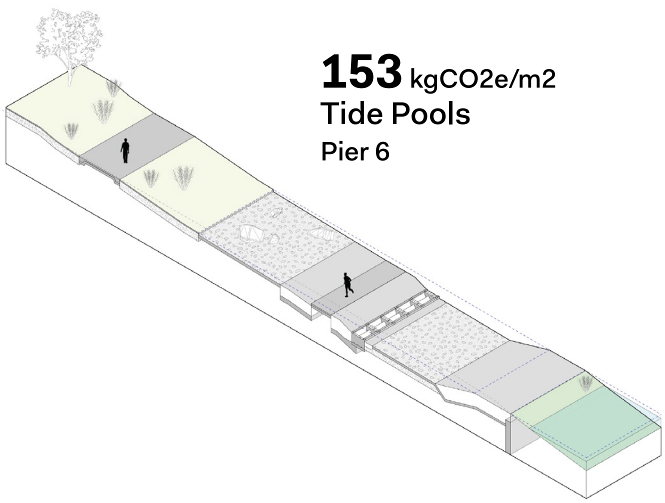
376 kgCO2e/m2
Exposed Floodwall
East Boston



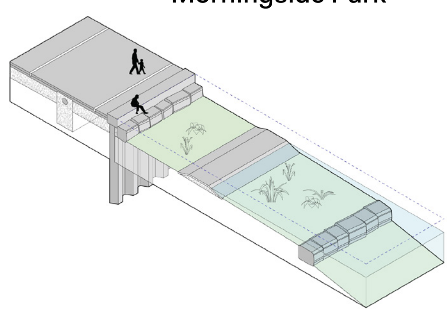
207 kgCO2e/m2
Bermed Floodwall
Moakley Park



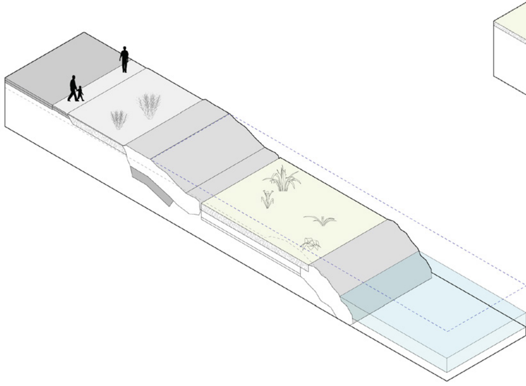
153 kgCO2e/m2
Tide Pools
Pier 6



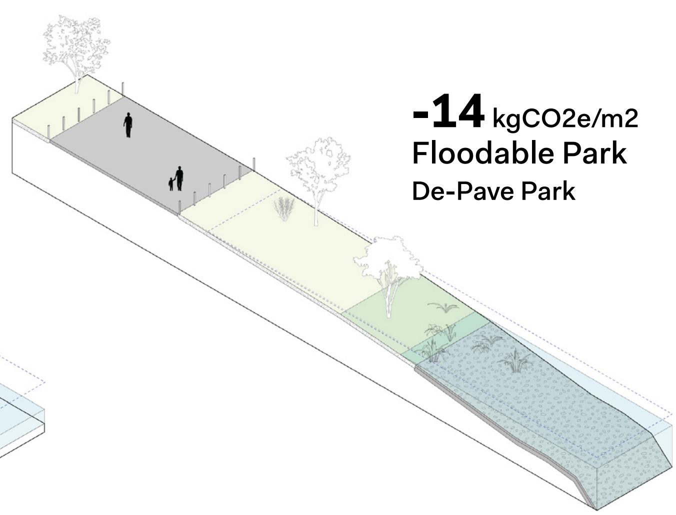
62 kgCO2e/m2
Multi-Purpose Levee
Morningside Park



46 kgCO2e/m2
Terraced Shoreline
TI Cityside Park



-14 kgCO2e/m2
Floodable Park
De-Pave Park



NET CARBON IMPACTS | ALT 1

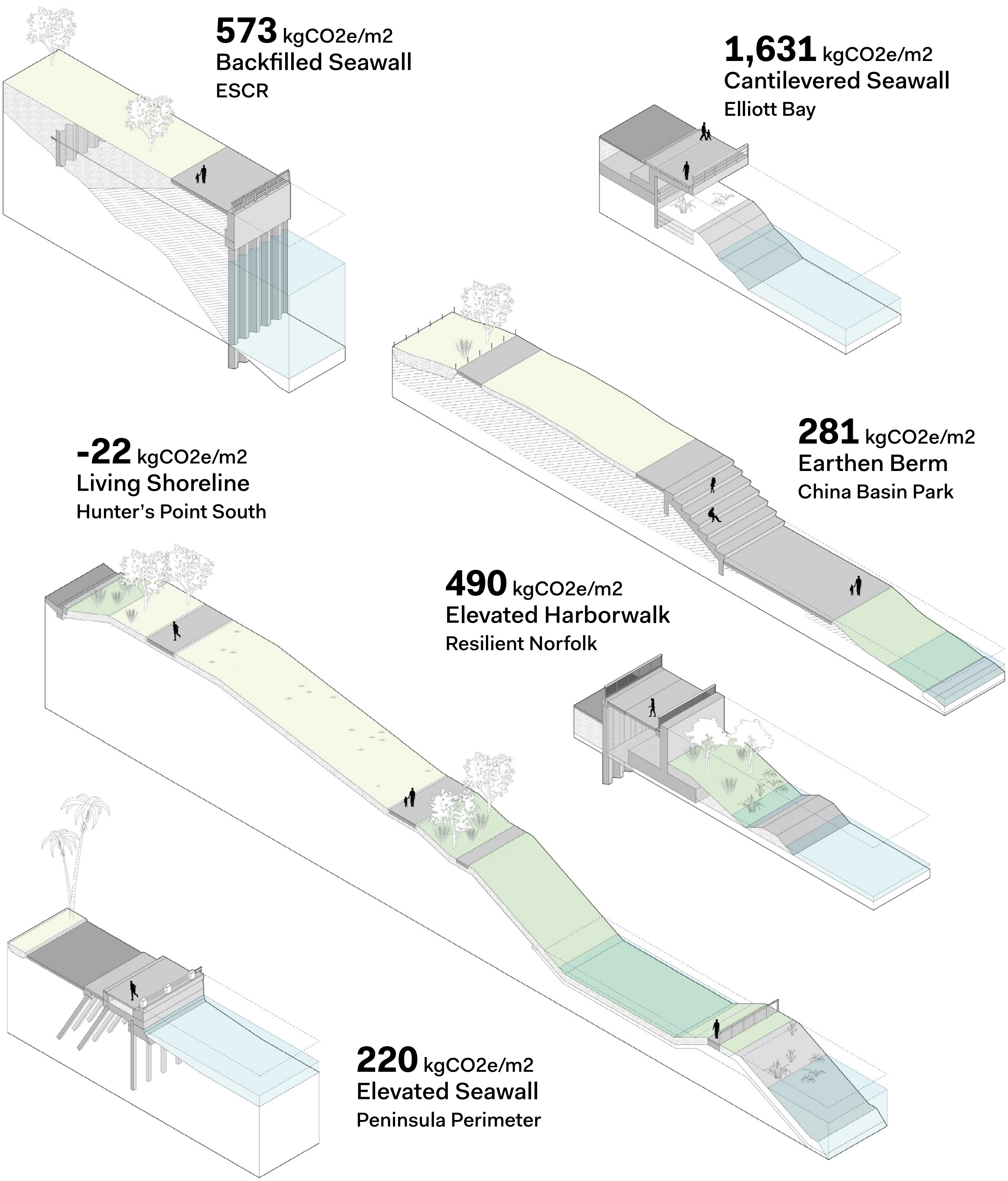
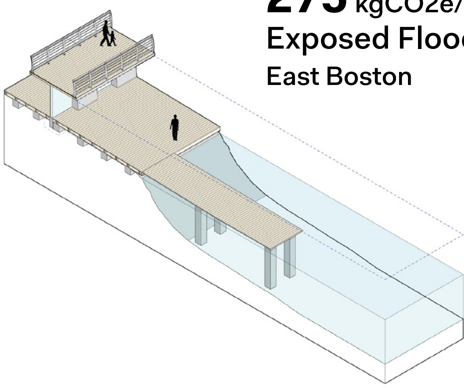


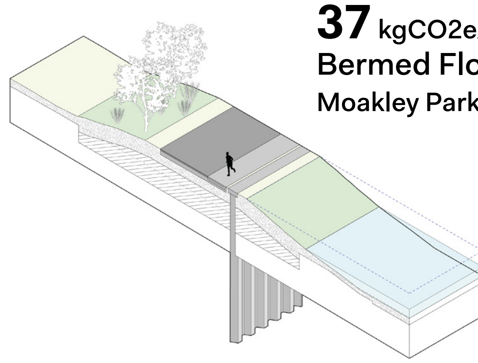
Figure 38: Alt 1 Net Carbon Impacts Summary

64% Average Improvements from BAU

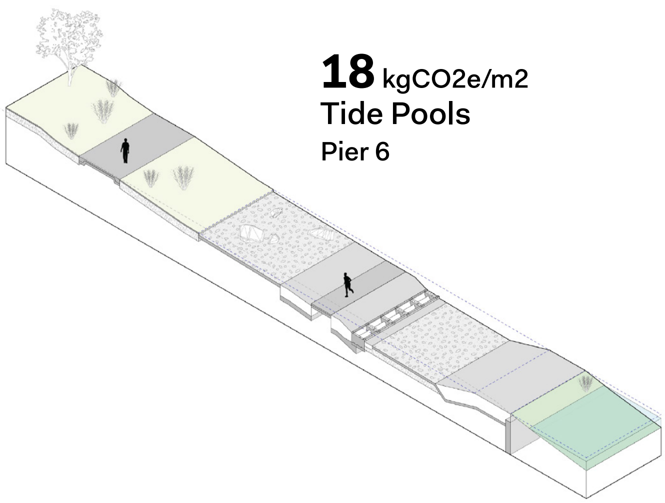
275 kgCO2e/m2
Exposed Floodwall
East Boston



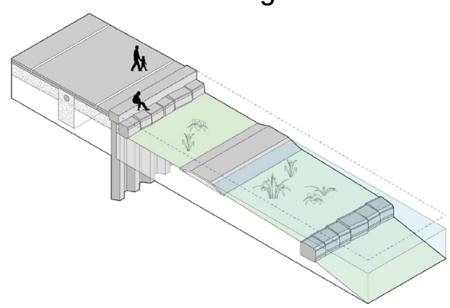
37 kgCO2e/m2
Bermed Floodwall
Moakley Park



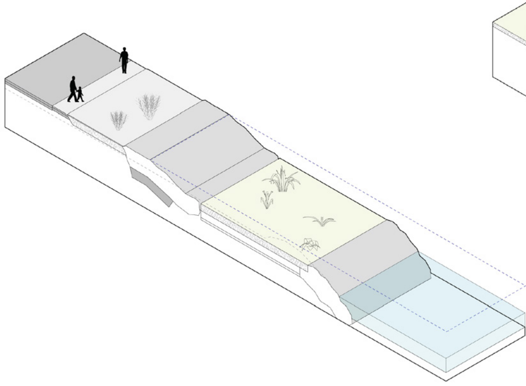
18 kgCO2e/m2
Tide Pools
Pier 6



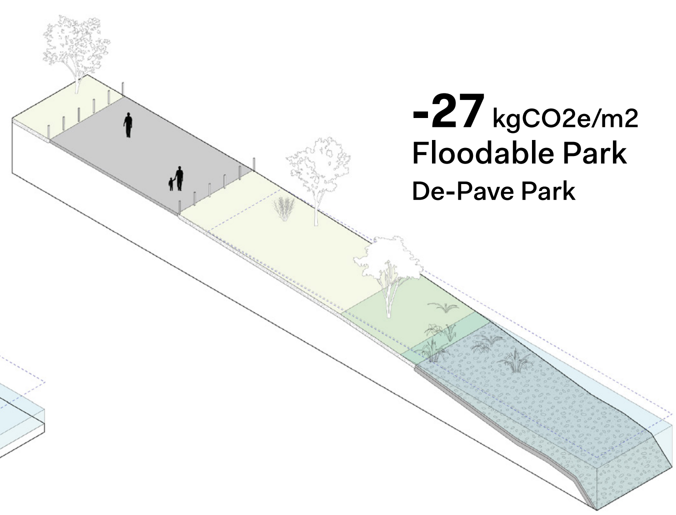
-1 kgCO2e/m2
Multi-Purpose Levee
Morningside Park



37 kgCO2e/m2
Terraced Shoreline
TI Cityside Park



-27 kgCO2e/m2
Floodable Park
De-Pave Park



NET CARBON IMPACTS | ALT 2

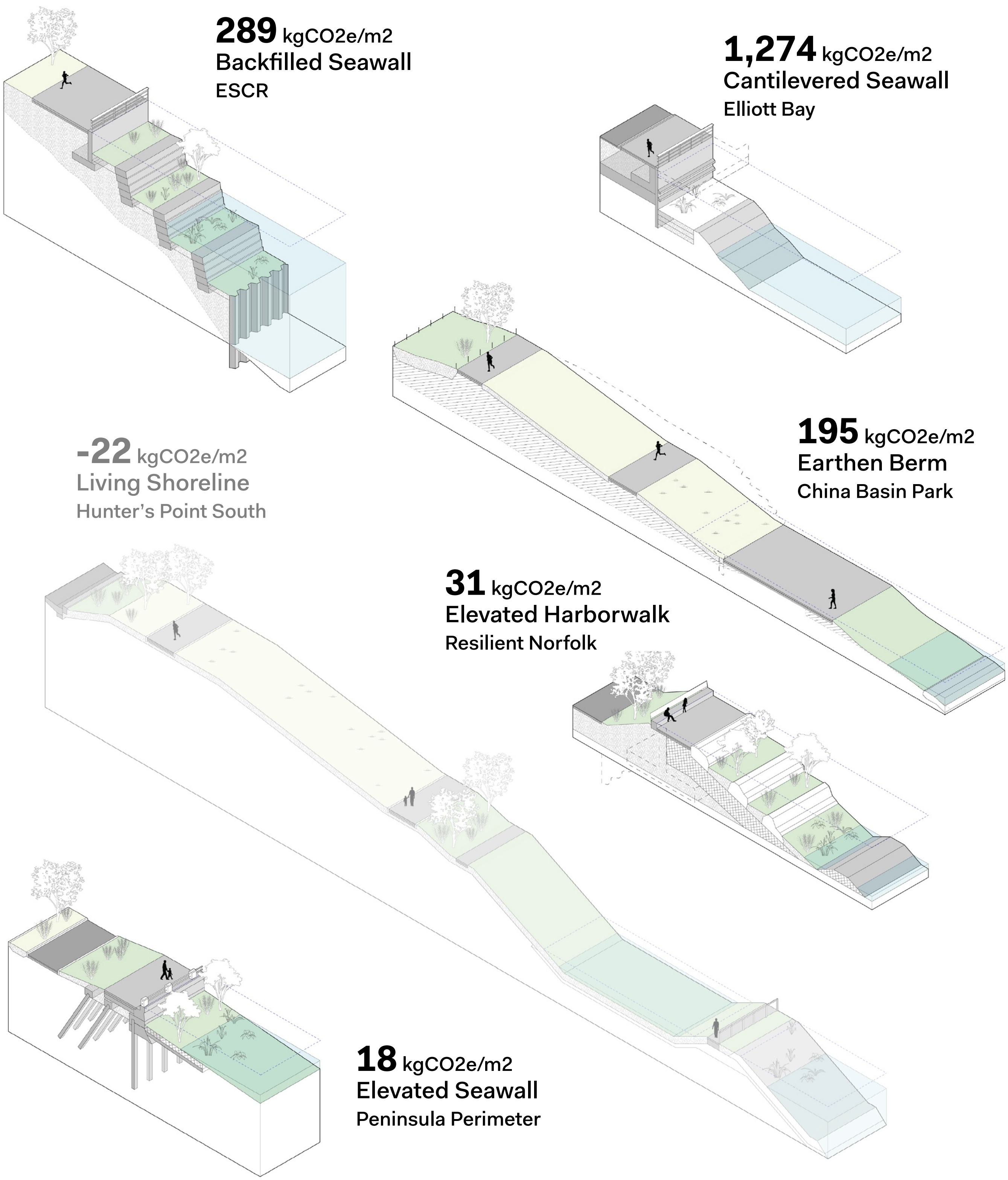
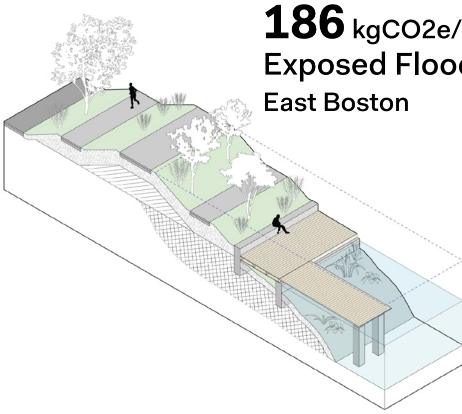


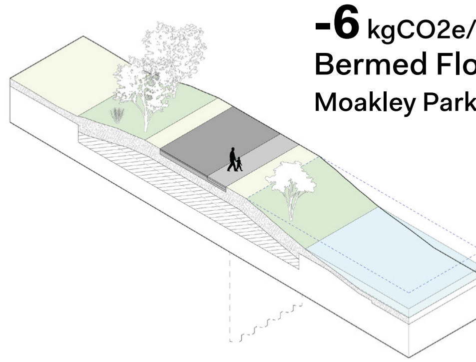
Figure 39: Alt 2 Net Carbon Impacts Summary

91% Average Improvements from BAU

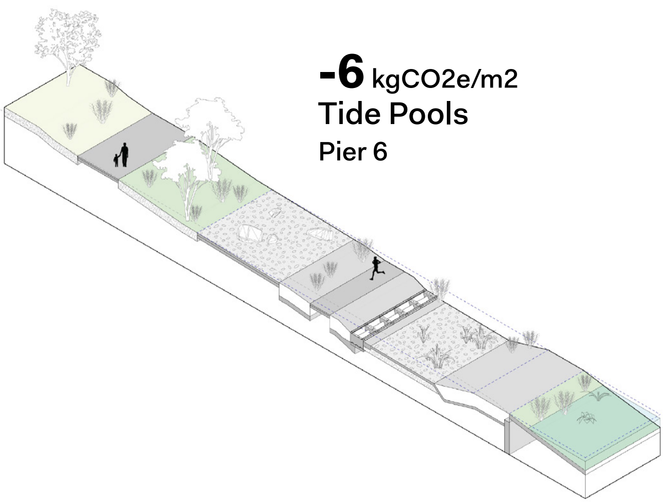
186 kgCO2e/m2
Exposed Floodwall
East Boston



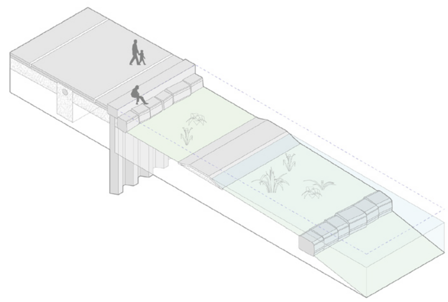
-6 kgCO2e/m2
Bermed Floodwall
Moakley Park



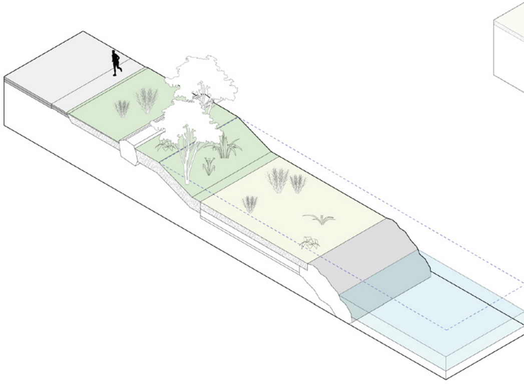
-6 kgCO2e/m2
Tide Pools
Pier 6



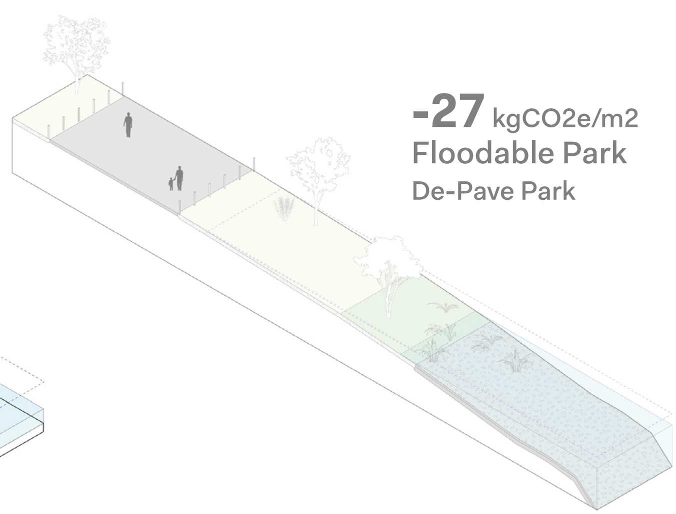
-1 kgCO2e/m2
Multi-Purpose Levee
Morningside Park



-23 kgCO2e/m2
Terraced Shoreline
TI Cityside Park



-27 kgCO2e/m2
Floodable Park
De-Pave Park



IMPACT ANALYSIS

For each of the adaptation typologies, the width required for the adaptation was recorded for BAU, Alt 1, and Alt 2. If adjustments to width were required, the delta between the two is also calculated and noted.

The findings show a correlation between lower emissions and more cost-effective strategies utilizing between 98-107 feet when compared to the higher emitting, gray infrastructure requiring between 91-93 feet in width.

Five out of the thirteen project typologies that were optimized to achieve lower carbon and increased nature-based benefits were widened by an average of 12.7 feet by either adding shoreline fill or reducing the width of wide transit corridors.

Table 29: Adaptation width and changes summary

Projects	**BAU**	**ALT 1**	**ALT 2**		
	Width (ft)	**Width (ft)**	**Width (ft)**	**Delta between BAU and Alt 2 (width')**	**% Change in width between BAU and Alt 2**
Eastside Coastal Resilience Park	73.5	73.5	82.0	8.5	11.56%
Elliott Bay Seawall	42.5	42.5	42.5	0.0	0.00%
Eastside Coastal Resilience Park - Cantilever	N/A	N/A	N/A	N/A	N/A
Mission Rock / China Basin Park	183.8	183.8	183.8	0.0	0.00%
Resilient Norfolk CSRM	77.0	77.0	103.3	26.3	34.16%
Hunters Point Park South	125.1	125.1	N/A	N/A	N/A
Peninsula Perimeter Protection	45.5	45.5	55.5	10.0	21.98%
East Boston Waterfront	35.3	35.3	85.0	49.7	140.79%
Moakley Park Resilience Plan	108.1	108.1	108.1	0.0	0.00%
Morningside Park Resilient Shoreline	78.0	78.0	N/A	N/A	N/A
Pier 6	135.0	135.0	155.0	20.0	14.81%
TI Cityside Park	79.0	79.0	79.0	0.0	0.00%
De-Pave Park	155.5	155.5	N/A	N/A	N/A
Overall Average	**94.9**	**94.9**	**99.4**	**12.7**	**4.74%**
Overall Median	**78.5**	**78.5**	**85.0**	**8.5**	**8.28%**
Avg for Projects above median	**91.2**	**91.23**	**93.42**	**8.96**	**2.40%**
Avg for Projects at or below median	**98.5**	**98**	**107**	**17**	**8.42%**

GLOBAL IMPACT POTENTIAL

While difficult to ascertain the actual impacts of widespread global adaptation of more nature-based adaptations, this study explores a potential methodology to calculate such impacts. The extrapolation first seeks to identify the areas at highest risk (Low Elevation Coastal Zones (LECZs)[70] that also correlate to developed or quasi-developed areas that have a higher likelihood of being adapted.

To further understand the potential impact areas, the Intergovernmental Panel on Climate Change (IPCC)[71] Representative Concentration Pathway (RCP) 8.5 scenario, is utilized. This projection is nearly identical across all emissions scenarios (even low-emissions ones) for 2050, because sea level rise in the first half of the century is largely locked in by past emissions.

Whereas the impacted area and population has the potential to equal:

By 2050:

32,500 coastal miles of shoreline and 173 million[72] people are at risk.

[See the Appendix for full calculations.]

Though implementation would be highly uneven, based on the projected and somewhat speculative risks, the following potential global carbon emissions impacts of adaptation with a Business-as-Usual approach may lead to the following outcomes:

70 B. Neumann, A.T. Vafeidis, J. Zimmermann, and R.J. Nicholls, "Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding – A Global Assessment", PLOS ONE, 10(3) (2015): e0118571, https://doi.org/10.1371/journal.pone.0118571.

71 Intergovernmental Panel on Climate Change (IPCC), "Climate Change 2021: The Physical Science Basis", Contribution of Working Group I to the Sixth Assessment Report of the IPCC, Cambridge University Press, (2021). https://www.ipcc.ch/report/ar6/wg1/.

72 E. Kirezci et al, "Projections of global-scale extreme sea levels," 2020.

Table 30: Case study averages for informing global impacts

							BAU	ALT 1	ALT 2	
	Business-as-Usual (BAU)		**Alt 1**		**Alt 2**		11.960	4.633	2.117	*Avg for Projects above median*
	Net Impact (tCO2e)	**Net Impact per Linear Foot (tCO2e/LF)**	**Net Impact (tCO2e)**	**Net Impact per Linear Foot (tCO2e/LF)**	**Net Impact (tCO2e)**	**Net Impact per Linear Foot (tCO2e/LF)**	13.900	4.350	2.200	*Median for Projects above median*
Eastside Coastal Resilience Park	151	15.1	39	3.9	22	2.2	15.100	5.625	3.025	*75% Quartile above median*
Elliott Bay Seawall	74	7.4	64	6.4	50	5.0	18.500	6.400	5.000	*Max above median*
Eastside Coastal Resilience Park - Cantilever	139	13.9	33	3.3	22	2.2	1.440	0.429	-0.015	*Avg for Projects at or below median*
Mission Rock / China Basin Park	185	18.5	48	4.8	33	3.3				
Resilient Norfolk CSRM	49	4.9	35	3.5	3	0.3	**12.275**	3.900	2.200	*High Quartile (75% Percentile)*
Hunters Point Park South	N/A	N/A	59	5.9	-3	-0.3	3.500	0.900	0.100	*Median*
Peninsula Perimeter Protection	17	1.7	9	0.9	1	0.1	1.750	0.400	**-0.100**	*Low Quartile (25th Percentile)*
East Boston Waterfront	12	1.2	9	0.9	6	0.6				
Moakley Park Resilience Plan	21	2.1	4	0.4	-1	-0.1				
Morningside Park Resilient Shoreline	N/A	N/A	5	0.5	-0.07	-0.01	18.500	6.400	5.000	*Max*
Pier 6	19	1.9	2	0.2	-1	-0.1	0.300	-0.200	-0.400	*Min*
TI Cityside Park	3	0.3	3	0.3	-2	-0.2				
De-Pave Park	N/A	N/A	-2	-0.200	-4	-0.400	6.700	**2.369**	0.969	*Average (all)*

Table 31: Global impact findings

BAU					
Year	**Shoreline Miles**	**ft**	**tCO2e**	**Thousand tCO2e**	**Gigatons (gCO2e)**
2050	32,500	171,600,000	2,106,390,000	2,106,390	2.106
2100	40,000	211,200,000	2,592,480,000	2,592,480	2.592
Impact Value	**12.275**				
ALT 1					
Year	**Shoreline Miles**	**ft**	**tCO2e**	**Thousand tCO2e**	**Gigatons (gCO2e)**
2050	32,500	171,600,000	406,560,000	406,560	0.407
2100	40,000	211,200,000	500,381,538	500,382	0.500
Impact Value	**2.369**				
ALT 2					
Year	**Shoreline Miles**	**ft**	**tCO2e**	**Thousand tCO2e**	**Gigatons (gCO2e)**
2050	32,500	171,600,000	-17,160,000	-17,160	-0.017
2100	40,000	211,200,000	-21,120,000	-21,120	-0.021
Impact Value	**-0.100**				

FINDINGS SUMMARY

If BAU adaptations continue as the norm and set the standard as a global precedent for adapting developed and quasi-developed areas, upwards of 2.1 gigatons of CO2e will be emitted from their construction by 2050. This is the equivalent of adding the emissions of New York City (approximately 50 million metric tons CO2per year) every year for the next 40 years.[73]

If minor, non-structural shifts occur in design, specification, and sourcing and Alt 1 approaches are instead implemented, 80% less emissions will be emitted by the coastal adaptation deployment, approximately 0.4 gigatons by 2050.

If Nature-based Solutions are fully embraced and shifting how designs, procurement, and policies are prioritized, the adaptations identified by Alt 2 become the new standard, not only will 2.1 gigatons of CO2e be avoided, but those solutions would become net positive by taking over 17 million tCO2e out of the atmosphere by 2050. It is only with large-scale global deployment of coastal adaptations that they have the potential to emerge from being a climate change contributor to a solution for both the climate and biodiversity crises.

73 NYC Mayor’s Office of Sustainability, “NYC Greenhouse Gas Emissions,” 2017.

CONCLUSIONS

1. The Emissions from Global Coastal Adaptations will be a Significant Contributor to Climate Change if Left Unchecked

It is estimated that approximately 32,500 miles of coastal shoreline globally will require adaptation by 2050 and by 2100, this figure could increase up to 40,000 miles.[74]

Based on business-as-usual emissions from gray infrastructure coastal adaptations of 12.28 tCO2e/LF, by 2050 emissions will exceed 2.1 gigatons of CO2e, equivalent to adding the annual New York City emissions every year for the next 40 years.[75]

Non-structural optimizations could improve that impact by 80%, reducing emissions to 2.37 tCO2e/LF, and emitting 0.4 gigatons.

By fully embracing NbS, those adaptation projects would instead sequester over 17 million tCO2e by 2050 beyond offsetting their own emissions (and avoiding 2.1 gCO2e emissions total), shifting from a climate change contributor to a carbon drawdown solution.

2. Meeting Global Emissions Reductions Goals for Site Infrastructure is Feasible Now and by 2030

From a business-as-usual approach, the study shows that a 45% emissions reduction alone and a 64% net improvement when including sequestration is possible without significant design changes, structural modifications, or policy changes. The findings indicate that largely meeting the global 50% emissions reductions targets now and by 2030 is possible. In addition, the case study results indicate this can be met on average with a net zero cost increase.

The measurement tools and alternative strategies that align with policies are available and well documented. To accomplish this potential, design education, commitment to change, and collaborative implementation is critical.

74 E. Kirezci et al, “Projections of global-scale extreme sea levels,” 2020.
75 NYC Mayor’s Office of Sustainability, “NYC Greenhouse Gas Emissions,” 2017.

3. Incorporating Nature-based Solutions into Coastal Adaptations can Achieve Significant Carbon and Cost Savings

The case study methodology concludes that by including true "Nature-based Solutions" in coastal adaptations a 91% net performance increase is possible from both reduced emissions and increased sequestration while saving an average cost savings of 30%.

However, the larger carbon and cost savings for true nature-based adaptations can be achieved with increased commitment and charge from clients, coordination (between engineers, landscape architects, ecologists etc.), design advocacy, policy considerations, and design evolution for coastal adaptations to meet their full potential.

4. Reducing the Emissions from Site Infrastructure is of Equal Importance to that of Buildings

From the study, 62% of business-as-usual coastal adaptations exceed the current recommended cap for buildings and structures (350 kgCO2e/m2) even after factoring in site sequestration.[76]

However, the study suggests there is room for improvement. By incorporating the "easy win" strategies, the percentage of projects exceeding the carbon cap drops to 23%, and with more nature incorporated, less than 10% of study projects exceed the carbon cap.

5. While Coastal Adaptations are Carbon Intensive, they can become Net-Positive with a Nature-based Approach

Given the industry standard sixty-year useful lifespan of structures, only one of the business-as-usual project adaptations will offset its own carbon footprint. This is due to existing material salvage and reuse while prioritizing native planting wherever possible.

For all other case studies, minor material and transportation distance improvements would shift two others to net-positive, and three more could accomplish this goal with more structural shifts or designing a more nature-based

76 LETI et al, ""Embodied Carbon Target Alignment."; City of Toronto, "Toronto Green Standard (TGS)," 2024; ILFI, "Zero Carbon Certification," 2025; SE2050 et al, "Commitment Program 2023 Data Analysis," 2024.

approach. By incorporating these low-carbon, nature-based approaches at least 46% of the coastal adaptations could become net-positive.

6. Most Embodied Carbon Sources are Unseen

The study illuminated that oftentimes the biggest carbon offenders are hidden below a green veil. Examples include deep steel sheet pile walls buried below berms or promenades, extensive use of lightweight fill materials (such as cellular concrete or geofoam), concrete foundations, and walls.

Despite little to no visual distinctions in the project outcomes, the following business-as-usual approaches are typical for material sourcing and specifying:

- Materials with little to no recycled content are still widely used even if alternatives are available.
- The majority of cast-in-place or precast concrete mix designs were lacking consequential amounts of supplementary cementitious materials (SCMs).
- Heavy materials are transported over long distances to reach the project site.

7. Six Key Approaches Achieve the Greatest Carbon Improvement Impacts

- **Lightweight Fill:** Lightweight fill is commonly needed in coastal adaptations to raise the shoreline elevation without adding significant load against retaining structures or creating geotechnical uplift. However, traditional materials such as cellular concrete or high-density foam are significant carbon emitters. The use of glass foam aggregate can serve as a lower carbon alternative, but better yet, expanded clay aggregates (such as LECA) can serve as a source for significant carbon reductions.

- **Hyperlocal Sourcing:** Adaptation projects often require large volumes of heavy materials, aggregates or soils. Sourcing these materials closer to the project site can significantly reduce overall emissions by minimizing transportation impacts.

- **Recycled Material Content:** Recycled aggregates can be used in hot mix asphalt or as a base material. Onsite crushing operations may be considered for creating the recycled aggregate base material needed for paving. On site existing materials, such as concrete, can also be broken up and used as shoreline armor or riprap, which can significantly reduce the emissions from sourcing virgin materials.

Using recycled content steel from electric arc furnaces (EAF), for example, can also move the dial on site emissions, which is largely a specification and sourcing effort.

- **Supplementary Cementitious Substitutions (SCMs):** The use of LC3 in lieu of ordinary Portland Cement (OPC) can yield significant carbon reductions. Other cement substitution options include slag, fly ash, glass pozzolan, and many other emerging alternatives.

- **Plant More:** Not only does increasing site vegetation increase site sequestration it also means less embodied carbon paving or hardscape materials. Planting strategies that sequester the most carbon include preserving and restoring ecosystems, in particular blue carbon ecosystems such as intertidal wetlands, that can sequester large amounts of carbon for extended durations. Plant species should be selected that do not require extensive resources such as irrigation, maintenance or fertilizers, which most often include native or adaptive plants. Plants with more biomass also have a direct correlation to larger amounts of carbon sequestered.

- **Use Less:** As found in the optimization strategies, simply modifying the design to reduce the overall material quantity has a direct relationship to reducing emissions. This can be accomplished by terracing a shoreline edge rather than installing a vertical wall with backfill or lightweight fill. Using less of the highest emitting materials can have a direct reduction without significant structural change, for example using weathering steel versus stainless steel has approximately 50% less embodied carbon emissions.

8. Nature-based Coastal Adaptations Benefit from a Modest Amount of Additional Space

The study found that while a width increase was helpful to fully maximize the nature-based adaptation, the spatial increase requirement was not substantial. The findings show a correlation between lower emissions and more cost-effective strategies utilizing between 98-107 feet for their adaptations when compared to higher emitting, gray infrastructure requiring between 91-93 feet in width.

Five out of the thirteen project typologies optimized to achieve a lower carbon and nature-based benefits widened by an average of 12.7 feet by either adding shoreline fill or reducing the width of wide transit corridors.

While both changes will likely require additional review and approvals, and even potential permitting changes and programmatic shifts, these choices may determine the potential of implementing more carbon and cost-effective shorelines in the future. Any alteration decisions should be holistically made with the property owner, stakeholders, and community members to ensure there is broad agreement on any trade-offs.

9. Nature-based Coastal Adaptations have National Significance and Global Scalability

The application of NbS is not only needed to course-correct the trajectory of future adaptations, but also to set a positive global precedent for those that require lower cost adaptations to secure their future.

National Adaptation Plans (NAPs) are actively being developed and deployed globally.[77] However, per the United Nations, increased sharing of lessons-learned between countries, in both directions between developed and developing countries, is needed to advance the implementation of more cost and carbon effective nature-based adaptations.[78]

This study demonstrates that lower cost and higher benefit adaptations are possible. While focused on projects based in the United States, the findings can be applied globally and benefit everyone.

10. Further Study and Support is Needed to Widely Implement these Key Findings

If the benefits of NbS are truly a priority, we must make the shift collectively towards a new business-as-usual.

Starting now, designers, engineers, and contractors can adopt and integrate these approaches into projects through interdisciplinary collaboration. They can also measure and communicate performance impacts from project inception.

For sourcing, design teams can collaborate with product manufacturers to discover new low-carbon materials and then coordinate with contractors for support.

77 United Nations Framework Convention on Climate Change (UNFCCC), “National Adaptation Plans”, accessed July 28, 2025, https://unfccc.int/national-adaptation-plans.
78 Climate Positive Design, LLC, Pamela Conrad, and Kotchakorn Voraakhom, “WORKS with Nature: Low Carbon Adaptation Techniques for a Changing World”, 2024, https://climatepositivedesign.org/design/works-with-nature/.

FUTURE POTENTIAL EFFORTS

This research can be utilized to inform further study working with municipalities to set upper carbon limits for site infrastructure, evolving existing codes and standards.

In addition, as the sea level rise (SLR) planning horizon and emissions scenario varied for each project, further study is needed to develop low-carbon adaptation techniques with a consistent SLR approach to create more standardized design adaptation toolkits for use throughout the AEC industry.

APPENDIX

METHODOLOGY LITERATURE REVIEW

This review considered twelve studies on Nature-based Solutions for climate adaptation in coastal urban settings. Using diverse methodologies—such as field data analysis, cost-benefit analysis (CBA), and scenario planning—these studies highlight NbS effectiveness, cost-efficiency, and additional ecological and social benefits over traditional gray infrastructure.

Cost-benefit analysis (CBA) as a Core Evaluation Tool

CBA consistently appears as a primary method to assess NbS relative to gray infrastructure, capturing direct and indirect benefits like avoided damages and biodiversity gains. Sensitivity analyses, which account for variables like discount rates and climate scenarios, strengthen CBA's role by factoring in future uncertainties, offering a robust measure of economic viability across conditions.

Effectiveness of NbS in Coastal Defense

Field studies indicate that NbS effectively reduce wave energy during storms with habitats, like salt marshes and coral reefs, acting as natural buffers. Compared to engineered solutions, NbS often provide long-term resilience and co-benefits like biodiversity enhancement and carbon sequestration, typically absent in gray infrastructure.

Broader Ecosystem and Socioeconomic Benefits

NbS projects provide broader ecosystem services beyond flood protection, including biodiversity support, improved water quality, and carbon storage. Many studies assess these non-market benefits—such as recreation and aesthetic value—through models like stated preference and travel cost approaches to reflect NbS's full socioeconomic impact.

Integration of NbS with Gray Infrastructure

Most NbS projects in coastal adaptation utilize hybrid approaches, layering

NbS onto conventional gray infrastructure. This strategy balances the structural reliability of gray infrastructure with ecological benefits but may limit NbS as a standalone defense. Additionally, few studies included carbon accounting, suggesting a need for lifecycle assessments to guide sustainable adaptation.

Challenges and Uncertainties in NbS Implementation

The studies also reveal uncertainties about NbS's long-term performance, especially regarding lifespan, maintenance, and response to extreme weather. One scenario planning case study shows NbS adaptability in urban contexts with changing climate conditions, suggesting that broader resilience strategies could benefit from similar planning approaches to address variability and enhance urban coastal adaptation.[79]

79 Fred Pearce, "Nature-Based Solutions," 2022.

ASSUMPTIONS AND EXCLUSIONS

General Assumptions and Exclusions

Exclusions:
1. Concrete reinforcement
2. Geotechnical improvements
3. Any paver setting material, grout etc.
4. All hardware and attachments
5. Operations and maintenance

LCA Assumptions and Exclusion

Element standardization is required across projects to ensure fair comparison.

1. For example: Unless noted otherwise specifically by design team or in drawings, any project with cast-in-place (CIP) concrete gets the same mix, same distance, same transportation option and same replacement number.
2. See default element settings below.

Default Element Settings.

These are applied unless noted otherwise in the provided drawings:

1. Distances[80]

    a. On-site
    b. Hyperlocal (within 16 km or 10 mi radius from the site)
    c. Intermediate Local (within 80 km or 50 mi radius from the site)
    d. Local (within 160 km or 100 mi radius from the site)
    e. Subregional (within 400 km or 250 mi radius from the site)
    f. Regional (within 800 km or 500 mi radius from the site)
    g. Long Distance (within 4800 km or 3000 mi radius from the site)

2. Cast-in-Place Concrete (Includes all variations)
    a. Transportation Type: Assume 100% Truck
    b. Distance: Intermediate Local
    c. Mix: Typical
    d. Replacements: 0

80 Climate Positive Design, Inc. “Pathfinder 3.1 Methodology Report,” 2025; Sasaki, Chris Hardy, and Michael Frechette, “Carbon Conscience V2,” 2025.

3. Precast Concrete (includes all variations)
    a. Transportation Type: Assume 100% Truck
    b. Distance: local
    c. Mix: Typical
    d. Replacements: 0

4. Precast Unit Pavers
    a. Transportation Type: Assume 100% Truck
    b. Distance: Subregional
    c. Mix: Typical
    d. Replacements: 1

5. Steel
    a. Standard Primary Steel from USA = Blast Furnace - Basic Oxygen Furnace (BF-BOF), 30% recycled content
    b. “Recycled” Steel from USA = Electric Arc Furnace (EAF), 90-95% recycled content

6. Metal Posts
    a. Transportation Type: Assume 100% Truck
    b. Distance: Regional
    c. Material: SS
    d. Replacements: 0

7. Guardrails (sim for Handrails)
    a. Material: Stainless Steel
    b. Transportation Type: Assume 100% Truck
    c. Distance: Regional
    d. Replacements: 0
    e. Post Diameter: 2.5”
    f. Post Ht: 4’
    g. Post Spacing: 5’ OC ((3) per 10’ section depth)
    h. Picket Diameter: 1”
    i. Wall Thickness: 0.125”

8. Wood Guardrails or Handrails
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Material: PT Pine
    d. Replacements: 2
    e. Post Spacing: 5’ OC ((3) per 10’ section depth)

f. Post Ht: 4’
g. Post size: 6x6
h. Top/Bottom Roil 2x4
i. For Guardrails, add cladding for the length of fence 1” thick
9. Geotextile (woven, non-woven, mat)
a. Transportation Type: Assume 100% Truck
b. Distance: Regional
c. Replacements: 0

10. Erosion Control Blanket (natural fibers)
    a. Transportation Type: Assume 100% Truck
    b. Distance: Long Distance
    c. Material: Jute Fiber
    d. Replacements: 2

11. Crushed Stone Paving (loose)
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Replacements: 1

12. Drain Rock
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Replacements: 0

13. Gravel
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Material: Gravel (Crushed)
    d. Replacements: 0

14. Riprap (Armor Rock)
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Material: Riprap (Typical)
    d. Replacements: 0

15. Asphalt
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Material: Asphaltic Concrete (HMA)

    d. Replacements: 2

16. Compacted Aggregate Base
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Material: Aggregate Base (Crushed) (Typical)
    d. Replacements: 0

17. Lightweight Structural Fill
    a. Transportation Type: Assume 100% Truck
    b. Distance: Intermediate Local
    c. Material: Cellular Concrete
    d. Replacements: 0

18. Sheet Pile Wall
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Type: Hat type 900x300
    d. Material: Steel (World Avg BOH & EAF)
    e. Replacements: 0

19. Organic Mulch
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Replacements: 2

20. Planting Soil
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Replacements: 0

21. Planting - General
    a. Growing Season: Moderate

22. Planting - Perennials
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Material: Low-intensity Container Planting (#1gal)
    d. Percent of Cover: 100%

23. Planting - Trees - Large Deciduous

a. Transportation Type: Assume 100% Truck
b. Distance: Local
c. Nursery: 2” caliper

24. Planting - Lawn - Moderate
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Material: Sod

25. Planting - No-mow Lawn / Meadow
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Nursery: Hydroseed
    d. Percent of Cover: 100%

26. Planting - Ecosystem Restoration
    a. Transportation Type: Assume 100% Truck
    b. Distance: Local
    c. Nursery: Plug & Tree Combination
    d. Target Condition: Good

Costing Assumptions and Exclusions

Estimated costs are derived from national RSMeans data, available project-specific details, and historical data from comparable projects.[81] All costs have been standardized to ensure consistency and enable accurate comparisons. Estimates account for both structural and material changes where relevant data was available.

1.	General planting cost:	$10 per SF
2.	Tree planting:	$1000 each
3.	Lightweight fill:	$150 CY
4.	CIP Concrete Cap:	$250 CY
5.	Sheet Pile:	$50 per SF
6.	Sheet Pile Tieback:	$2400 per ton
7.	Sod:	$2 per SF
8.	Concrete Curb:	$12 per LF
9.	Boulders or Rocks:	$500 ea
10.	Earthwork - moderate:	$0.75 per SF

81 CHUBB, Environment: “Protecting Miami’s vulnerable coast,” 2025.

11.	Earthwork - heavy:	$1.50 per SF
12.	Stabilized DG:	$10 per sf
13.	AC Paving:	$5 per sf
14.	Concrete Paving	$15 per sf
15.	Concrete subslab	$12 per sf
16.	CIP structural slab	$350 per cy
17.	Backfill:	$55 per cy
18.	Hydroseed:	$2 per sf
19.	Geotextile	$2 per sf
20.	Base courses:	$50 per cy
21.	Import Amended Soil:	$50 per cy
22.	Amended Onsite Soil:	$0.5 per sf
23.	Unit Pavers:	$25 per sf
24.	Stone Paving	$50 per sf
25.	Gabions:	$300 per cy
26.	Gabion Ret Walls:	$250 per lf
27.	Riprap:	$350 per cy
28.	Handrail/Guardrail-Steel:	$250 per lf
29.	Handrail/Guardrail-Welded:	$100 per lf
30.	CIP Ret Wall - 6’:	$500 per lf
31.	CIP Flood Wall 12’+	$850 per lf
32.	Precast Beams:	$500 per lf
33.	Demo - Wall:	$25 per lf
34.	Stl Pipe - Galv:	$55 per lf
35.	Wood Rails 4x:	$10 per lf
36.	Perf Pipe Subdrainage:	$20 per lf
37.	Drainage Trench w/Geo:	$30 per cy
38.	Oystershells:	$100 per cy
39.	Econcrete:	$500 per cy
40.	CIP Seatwall:	$250 per lf
41.	Precast Seawall	$50 per sf
42.	Precast Seawall Structure:	$450 per cy
43.	Precast LPS Paving:	$50 per sf
44.	HDPE Drainpipe 15”:	$55 per lf
45.	Oolite Local Stone:	$500 per tn
46.	Rock embedded CIP paving:	$10 per sf
47.	Loose DG Path:	$5 per sf
48.	Jute Mesh:	$1 per sf
49.	Wood deck:	$75 per sf
50.	Elevated Walk:	$150 per sf

GLOBAL IMPACT POTENTIAL CALCULATIONS

Total Low Elevation Coastal Zones (LECZ) and Buffer Depth[82]

To determine the potential global impacts, the total LECZ, or areas < ten meters from mean sea level, were identified as ~ 2.6 million km.[83]

Neumann et al. models of urban LECZ areas were often confined to ten to fifteen kilometers from the coast in most regions.

Therefore, the calculation is as follows:

2.6 million km2 / 10 - 15 km buffer = 170,000 to 260,000 km of LECZ shoreline

Total Coastal Impact[84]

Next, the areas of impact were determined by selecting an emissions scenario and population exposed to future impact (ie, only including developed or quasi-developed LECZs, which is approximately 25% of the total LECZ shoreline length).

Per the Intergovernmental Panel on Climate Change (IPCC):[85]

RCP8.5 is a Representative Concentration Pathway (RCP) scenario, specifically a high-emissions scenario, that projects significant increases in global temperatures and radiative forcing by the end of the 21st century. This projection is nearly identical across all emissions scenarios (even low-emissions ones) for 2050, because sea level rise in the first half of the century is largely locked in by past emissions. By contrast, post-2050 divergence increases sharply based on emissions trajectories. The IPCC characterizes the projected sea level rise by 2050 as “virtually certain” (high confidence).

SSP5-8.5 is a Shared Socioeconomic Pathway (SSP) scenario that incorporates the GHG baseline used in RCP8.5 but also applies economic growth, population, education, etc.

82 B. Neumann et al, “Future Coastal Population Growth,” 2015.
83 IPCC, “We can halve emissions by 2030,” 2022; E. Kirezci et al, “Projections of global-scale extreme sea levels,” 2020.
84 E. Kirezci et al, “Projections of global-scale extreme sea levels,” 2020.
85 IPCC, “Climate Change 2021,” 2021.

By 2050:
Global mean sea level is projected to rise by approximately 0.32 to 0.38 meters across various emission scenarios (RCP8.5/SSP5-8.5).

By 2100:
Under high emission scenarios (RCP8.5/SSP5-8.5), projections indicate a rise of approximately 0.63 to 1.01 meters.

Calculations

Using RCP8.5/SSP5-8.5:8
- 2050 mean inundated area = 640,000 km2
- 2100 mean inundated area = 819,000 km2

Apply buffer:[86]
- 2050 = 640000 / 10 - 15 km buffer = 42,500 - 64,000 km
- 2100 = 819000 / 10 - 15 km buffer = 54,600 - 81,900 km

Area
- 2050
- 640,000 km2 / 10 - 15 km buffer = 42,500 - 64,000 km
- Conversion (km>mi) = 25,000 - 40,000 mi
- Median Result = 32,500 mi

- 2100
- 819,000 km2 / 10 - 15 km buffer = 54,600 - 81,900 km
- Conversion (km>mi) = 30,000 - 50,000 mi
- Median Result = 40,000 mi

Population Exposed[87]
- 2050 = 173 million (mean)
- 2100 = 225 million (mean)

86 B. Neumann et al, “Future Coastal Population Growth,” 2015.
87 E. Kirezci et al, “Projections of global-scale extreme sea levels,” 2020.

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