EVOLUTIONARY ECOLOGY

Evolving nature-based solutions for urban resilience

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Despite growing investments in nature-based solutions for urban resilience, their design often overlooks a fundamental biological process: evolution. Populations of organisms that sustain nature-based solutions are dynamic and can evolve over time. Rapid evolutionary changes, driven by urban environmental stressors, such as pollution, climate extremes, and habitat fragmentation, can reshape species' traits, alter interactions, and shift ecosystem functions. We synthesize evidence of evolutionary change across systems that serve as nature-based solutions in urban contexts and show how evolutionary processes can enhance or undermine their performance. We propose four testable hypotheses linking evolutionary dynamics to nature-based solutions and outline design strategies to maintain adaptive potential. Integrating evolution into nature-based solutions is essential to ensure long-term and efficient functionality under accelerating environmental change.

Cities are at the forefront of rapid environmental change (*1*). Rising sea level, intensifying heat waves, and other extreme events increasingly threaten urban infrastructure, public health, and social stability (*2*). Nature-based solutions—actions that protect, restore, or sustainably manage ecosystems to address societal challenges (*3*)—are gaining momentum as strategies to enhance urban social-ecological resilience, the capacity of cities to absorb, reorganize, and adapt to disturbances while maintaining ecosystem functions and human well-being (*4*–*6*). By harnessing ecological processes, such as flood mitigation by wetlands, cooling by urban forests, and shoreline stabilization by coastal vegetation, nature-based solutions can reduce risks while delivering cobenefits, including biodiversity conservation, improved public health, and economic efficiency (*7*–*9*).

Investment in nature-based solutions reached an estimated $200 billion globally in 2022 (*10*), with annual needs projected to rise to meet climate and biodiversity targets (*11*). Although only a fraction targets urban systems, cities act as laboratories for nature-based solutions implementation, monitoring, and evaluation. Yet rapid scaling of these approaches exposes a critical tension: Deployment is outpacing the evidence needed to assess long-term effectiveness (*4*, *12*), especially in rapidly urbanizing regions, where limited ecological data and constrained monitoring capacity heighten risks of underperformance (*13*, *14*).

Despite widespread enthusiasm, nature-based solutions can underperform (*15*) or fail because of oversimplified designs, inadequate management, weak governance (*16*–*18*), and mismatches with local conditions (*14*, *19*) or the pace of environmental change (*20*). Current evaluations emphasize short-term outcomes—reductions in flood risk, heat, or pollution (*15*, *16*)—with limited attention to performance under changing environmental conditions (*21*). Nature-based solutions design often assumes ecological stability, yet underlying populations are dynamic and can shift, reshaping ecosystems.

A key gap in the design of nature-based solutions is the neglect of evolution (*21*). Populations can undergo rapid genetic and phenotypic change in response to urban stressors, such as pollution, altered hydrology, temperature extremes, and habitat fragmentation, altering species traits that support ecosystem function (*22*–*25*). Evidence shows that evolutionary change can measurably influence ecosystem resilience (*26*–*29*). These eco-evolutionary dynamics—feedbacks between ecological processes and evolutionary change (*30*, *31*)—can influence the functions that nature-based solutions provide, affecting long-term performance and cost-effectiveness (*23*, *32*, *33*). Because natural selection acts on traits that increase organismal fitness in specific environments, adaptive evolutionary responses may enhance population fitness while constraining the human-valued functions underpinning nature-based solutions (*21*, *34*, *35*).

We bridge evolutionary science and urban resilience planning by synthesizing empirical evidence on how eco-evolutionary dynamics shape nature-based solutions. We focus on urban environments, where selective pressures are intense, newly created, and spatially heterogeneous, making evolutionary responses especially relevant. Because this review spans biological and social-ecological processes, we distinguish biological adaptive evolution—heritable genetic change driven by natural selection—from nonevolutionary forms of climate adaptation, including ecological, social, institutional, and technological changes that reduce vulnerability and enhance resilience.

We introduce a conceptual framework and four hypotheses that link evolutionary processes to nature-based solutions outcomes: context-specific selection, adaptive potential, historical adaptation, and functional traps. We aim to provide a foundation for designing systems capable of sustaining function under accelerating environmental change.

An overlooked dimension: Evolution in nature-based solutions

Nature-based solutions rely on populations, traits, and interactions that can evolve over contemporary timescales, particularly in urban environments. Understanding how evolutionary responses shape nature-based systems is essential for evaluating their long-term performance (*15*, *36*). Evolutionary resilience—defined as an ecosystem's capacity to maintain or reorganize key ecological functions through evolutionary processes in response to changing conditions—provides a robust framework for understanding the long-term performance of nature-based solutions (*21*, *37*, *38*). Evolution can occur within a few generations, producing trait shifts that alter ecological dynamics (*39*, *40*). In urban environments, strong and previously unencountered selection pressures

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increase the likelihood of such change when additive genetic variance is present (*25*, *41*–*44*). Selection for traits such as drought tolerance, altered phenology, or pollutant resistance can modify species interactions and biogeochemical processes, affecting ecosystem functions (*45*–*47*). These dynamics are evident in such cases as pesticide resistance in pest populations (*48*) and heritable variation in belowground traits of marsh plants that affect sediment accretion and carbon storage, key processes for shoreline protection and climate resilience (*33*).

Eco-evolutionary interactions often operate at the community level, where species might evolve through mutualistic or competitive feedbacks (*49*). In urban systems, cross-species dynamics, such as pollinator-plant networks, rhizosphere symbioses that enhance nutrient cycling, or oyster-microbe partnerships that stabilize sediments, strongly influence ecosystem functions. Because nature-based solutions depend on multispecies assemblages, functional and genetic diversity must be maintained across multiple biological levels.

Despite mounting evidence of rapid evolutionary change in populations (*23*, *30*, *39*) and communities (*30*, *50*), evolutionary considerations remain largely overlooked in designing nature-based solutions (*21*). Interventions often rely on genetically uniform or nonlocal populations, such as clonal nursery stocks, without accounting for adaptive potential or local fitness, which can constrain the capacity of populations to evolve under changing conditions. Even when standing variation is present, the potential for elevated mutation rates in urban environments to contribute to adaptive responses remains poorly understood (*51*). Assessing these evolutionary capacities is therefore critical for ensuring long-term resilience.

Distinguishing between fitness-enhancing adaptations and their functional consequences is critical to understanding long-term resilience. Because natural selection favors traits that increase individual fitness, not those that maximize human-valued outcomes, evolutionary change may strengthen, constrain, or redirect the ecological processes underpinning nature-based solutions. Under environmental stress, evolution can enable population persistence through evolutionary rescue (*52*), but the adaptive trait changes that enable persistence will not necessarily align with desired functional outcomes.

Empirical evidence linking eco-evolutionary dynamics to nature-based solutions

Empirical studies show that evolutionary change is central to ecosystem function for nature-based solutions. These effects operate through a set of dominant biological pathways, which we discuss through several illustrative examples (Fig. 1).

Structural ecosystem engineers

Foundation species that physically structure ecosystems play a central role in nature-based solutions by stabilizing sediments, attenuating waves and storm surge, and supporting carbon storage and habitat complexity in coastal and estuarine environments. Because these functions depend on organismal traits that influence belowground structure, growth form, and persistence, evolutionary change in foundation species can shape long-term performance.

Coastal marsh grasses, such as *Spartina alterniflora*, support nature-based solutions by buffering storm surge and reducing erosion, protecting urban coastal regions (*53*). Their dense root systems stabilize sediment and promote carbon storage. Yet these traits can be evolutionarily labile; under altered nutrient or hydrologic regimes, population shifts may weaken ecosystem functions and resilience to sea level rise. *Spartina alterniflora* populations exhibit heritable differentiation in root-to-shoot ratio and nutrient uptake efficiency, reflecting adaptation to local tidal and nutrient regimes (*54*, *55*). Along tidal and nutrient gradients, *Spartina* populations exposed to nutrient enrichment and reduced tidal flushing allocate more biomass aboveground at the expense of roots, weakening marshes' capacity to stabilize sediment and maintain elevation (*33*). Genomic analyses indicate adaptive divergence across environmental gradients, including nutrient availability (*26*, *56*).

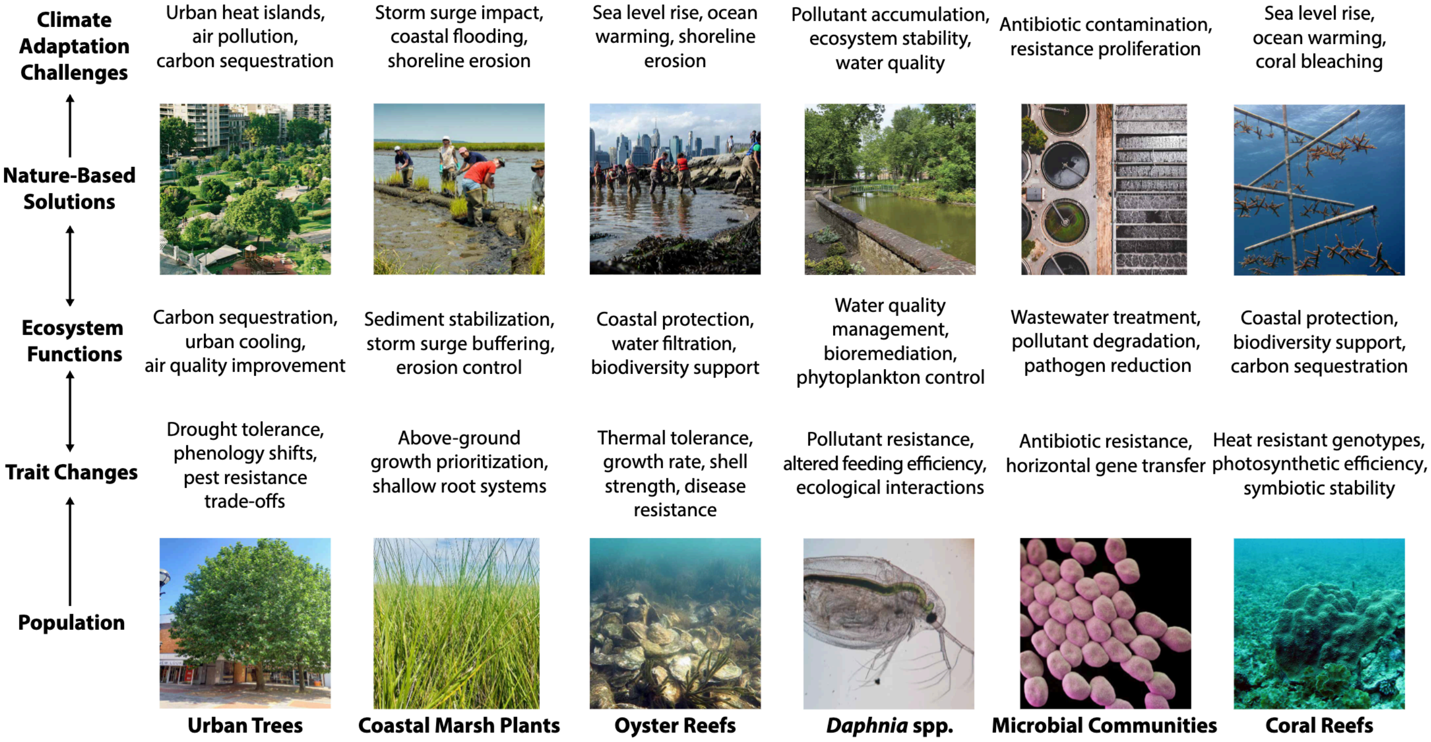

Fig. 1. Examples of eco-evolutionary dynamics in nature-based solutions. Examples of urban-driven evolutionary trait changes that alter organisms' ability to perform key ecosystem functions.

PHOTO CREDITS: URBAN TREES, PLAZA WITH URBAN TREES (AERIAL VIEW), UNSPLASH, NEREA MARTÍ SESARINO. LONDON PLANE TREE (*PLATANUS* × *ACERIFOLIA*), INATURALIST, HELEN FROST, PUBLIC DOMAIN (CC0). CHAIRMAKER'S BULRUSH, (*SCHOENOPLECTUS* SPP.), WIKIMEDIA, GORDON LEPPIG AND ANDREA J. PICKART, PUBLIC DOMAIN (CC0). OYSTER REEF (*CRASSOSTREA* SPP.), BILLION OYSTER PROJECT, © STEVEN DEWITT/WITNESS TREE MEDIA. OYSTER REEF (*CRASSOSTREA* SPP.), WEEKAPAUG BREACHWAY, WIKIMEDIA, NRCS RHODE ISLAND, PUBLIC DOMAIN (CC0). *DAPHNIA* SPP., PUBLIC PARK POND
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Although these evolutionary responses demonstrate a potential decoupling between population performance and ecosystem function in *Spartina*, evidence from the marsh species *Schoenoplectus americanus* shows that evolution can enhance nature-based solutions. Combining resurrection ecology—reconstructing historical phenotypes or genotypes from dormant propagules—with common-garden experiments reveals evolutionary increases in root biomass and associated trait shifts over time. These changes improve soil accretion and carbon accumulation, key indicators of marsh resilience to sea level rise (*33*).

Oyster reefs exemplify structural biota functioning as adaptive natural infrastructure. Reefs formed by the eastern oyster, *Crassostrea virginica*, buffer shorelines, improve water quality, and create habitat for diverse marine species in urbanized coastal systems, such as New York Harbor (*57*, *58*). However, these benefits are increasingly threatened by warming, eutrophication, human disturbance, and disease.

To enhance restoration, evolutionarily informed strategies are being used to increase resilience to thermal tolerance and disease resistance in native *C. virginica*. Selective breeding programs have produced oyster lines with improved resistance to pathogens, such as multinucleate sphere unknown (MSX) and the harmful protozoan parasite that causes dermo disease, showing higher survival than wild stocks (*59*, *60*). Advances in genomic tools enable genomic selection and monitoring of genetic diversity in restoration efforts (*61*). Because oysters exhibit high genetic diversity and fine-scale population structure (*62*), restoration outcomes vary across geographic contexts (*63*). Population genomic studies indicate that effective population size and standing genetic variation influence the adaptive potential of restored oyster populations (*64*).

Selected oyster lines show increased thermal tolerance and growth rates, with heritability of adaptive traits. Genome-wide association studies have identified specific loci correlated with resilience to thermal and pathogenic stress, offering tools for trait-based restoration. Maintenance or enhancement of adaptive genetic variation allows restored oyster populations to evolve in situ, sustaining structural integrity and ecological function under changing conditions (*65*, *66*). Thus, restoration success might depend on how genetic variation and selection shape resilience traits over time.

Coral reefs are a distinctive case where evolutionary principles have been harnessed to enhance nature-based solutions' resilience under climate change (*67*, *68*). As foundation species, corals stabilize shorelines (*69*), maintain biodiversity, and sequester carbon (*70*). However, rising sea temperatures are driving widespread bleaching and functional decline (*71*). To increase thermal tolerance and sustain ecosystem function, researchers use assisted evolution: selective breeding or transplanting heat-tolerant coral genotypes. In the Great Barrier Reef, corals exposed to simulated warming are selected for traits such as higher photosynthetic efficiency and stable symbiotic relationships under heat stress (*72*). Similar efforts are underway in Pacific Island projects, where evolutionarily informed restoration strategies are gaining traction. However, assisted evolution carries risks, including potential reductions in genetic diversity and uncertain responses to future conditions. As practices expand, monitoring evolutionary trajectories will clarify how assisted evolution influences long-term protection and ecological function under warming.

Long-lived woody vegetation

Urban forests are nature-based solutions that contribute to temperature regulation, shading, and carbon storage and that can intercept airborne particulates through deposition on foliage (*73*, *74*). Their performance can be shaped by eco-evolutionary dynamics (*75*). Because of elevated temperatures, pollution, compacted soil, and, often, increased drought stress, urban environments impose strong selection pressures on tree populations (*32*, *55*). In cities such as Phoenix, AZ, and Los Angeles, CA, shifts in photosynthetic efficiency and water-use strategies have been observed in tree populations (*76*). These trait changes may enhance stress tolerance but can involve physiological trade-offs, such as reduced canopy cover or slower biomass accumulation (*77*). Urban forests also influence air quality through biogenic volatile organic compound emissions and pollutant dispersion; whether these traits can evolve under urban selection pressures remains poorly understood.

Although evolutionary changes in trees are difficult to observe owing to long generation times and human planting, evidence suggests that trait filtering and adaptation may be occurring (*75*). Traits that enhance survival such as pest resistance or increased root allocation often reduce growth or photosynthesis (*78*, *79*). Such trade-offs may limit carbon sequestration, shading, and other ecosystem services. Evolutionary trade-offs can decouple short-term stress tolerance from long-term ecosystem function, especially when genetic diversity, plasticity, or coadapted traits differentially shape ecosystem processes under changing conditions. The long-term functionality of urban forests under intensifying environmental stress depends on how resilience traits, service delivery, and evolutionary capacity are distributed within and among planted populations.

Aquatic consumers

Aquatic consumers, such as *Daphnia* spp., play a central role in freshwater nature-based solutions by regulating algal blooms, enhancing water clarity, and contributing to nutrient cycling and bioremediation in urban lakes, ponds, and constructed wetlands (*80*, *81*). Their effectiveness can be shaped by rapid evolutionary responses to temperature increase and chemical contamination.

In urbanized watersheds and constructed wetlands, *Daphnia* populations have evolved resistance to pollutants such as heavy metals, pesticides, and pharmaceuticals, enabling their persistence in environments where more sensitive species would disappear (*82*, *83*). These evolutionary responses can occur rapidly with standing genetic variation and intense selection in urban systems. Functional outcomes are mixed. Resistant *Daphnia* populations actively graze algae and thereby control nutrient cycling under degraded conditions. However, reduced sensitivity to contamination can limit their effectiveness as sentinel species for water quality, even when they remain as functional nature-based solutions in targeting eutrophication.

Adaptations often involve physiological trade-offs. Resistance traits have been associated with reduced feeding efficiency, slower growth, and lower reproductive output (*84*). For example, populations that evolve to tolerate contaminants could exhibit weakened control of algal populations, undermining water-purification services (*85*) and thus reducing long-term ecosystem function, particularly under accelerating environmental change. Given their ecological role and evolutionary responsiveness, shifts in *Daphnia* population traits can provide early indicators of eco-evolutionary change affecting the performance and stability of freshwater nature-based solutions.

Microbial communities

Microbial communities underpin many nature-based solutions, particularly those designed for water treatment and contaminant degradation. Systems such as constructed wetlands, bioswales, and green stormwater infrastructure rely on microbial processes to remove nutrients, break down organic and inorganic pollutants, and reduce pathogens through well-characterized biogeochemical pathways (*86*). Evidence shows microbial populations evolve rapidly under selective pressures imposed by urban wastewater and stormwater systems (*87*, *88*). In constructed wetlands used for treating municipal and industrial wastewater, microbial populations can acquire resistance traits through horizontal gene transfer (*89*, *90*). For example, the genera *Pseudomonas* and *Acinetobacter* maintain antibiotic resistance phenotypes through intrinsic mechanisms and acquired genes, persisting even after reductions in antibiotic exposure (*90*, *91*). Microbial communities in urban green infrastructure also show elevated tolerance thresholds in heavy metal-contaminated soils, indicating selection-driven shifts in functional traits (*92*).

AND FOOTBRIDGE, MEMORIAL MUSEUM PASSCHENDAELE 1917, ZONNEBEKE, BELGIUM, FLICKR, EDK7. *DAPHNIA PULEX*, INATURALIST, DAVID BIRD, PUBLIC DOMAIN (CC0). WASTEWATER TREATMENT PLANT (AERIAL VIEW), UNSPLASH, IVANA BANDURA. *ACINETOBACTER* SP., CDC/PHIL, PUBLIC DOMAIN (PD).

Evolutionary and ecological microbial responses present both potential benefits and risks. Microbial community dynamics can support pollutant removal and treatment performance in constructed wetlands through well-characterized biogeochemical processes (*93*). However, selective conditions can undermine performance or increase environmental risks, for example, by increasing nitrous oxide emissions under specific nutrient loads (*94*) or through pathways promoting antibiotic resistance gene transfer (*95*). Thus, microbial evolutionary and community-assembly dynamics influence both treatment performance and environmental risk. Patterns of frequencies of resistance alleles, functional trait composition, hydraulic and nutrient loading regimes, and microbial diversity determine wetlands response to selective pressures over time, making these dynamics central to the long-term stability and biological safety of microbially mediated nature-based solutions.

Linking eco-evolutionary dynamics to the resilience of nature-based solutions

Integrating eco-evolutionary dynamics into the design of nature-based solutions provides a mechanistic basis for enhancing long-term functional performance under rapid environmental change. Rather than treating species' traits as fixed attributes, an eco-evolutionary perspective recognizes that traits emerge from interacting populations and communities that respond to environmental drivers through selection, genetic change, and phenotypic plasticity.

We identify three interrelated mechanisms—selection on heritable traits (M1), eco-evolutionary feedbacks (M2), and adaptive potential (M3)—through which evolutionary processes influence the performance of nature-based solutions (Fig. 2). Urban environments impose strong and emerging selective pressures that alter genetic and phenotypic distributions within populations, shifting traits such as drought tolerance, nutrient uptake efficiency, thermal performance, or pollutant resistance. These trait changes do not operate in isolation: Reciprocal feedbacks among evolving traits, population abundances, community compositions, and ecosystem processes can amplify or dampen the ecological functions for which nature-based solutions are designed (*96*). The capacity of these systems to sustain performance over time depends on their ability to respond to continued and intensifying environmental change through evolutionary adaptation within populations and trait-based filtering at the community level.

Building on these mechanisms, we propose four hypotheses that link evolutionary processes to ecosystem function and the design and evaluation of nature-based solutions. Figure 3 describes study designs and potential measurements (e.g., species' traits, genetic diversity) to test these hypotheses. Each hypothesis specifies how evolutionary dynamics influence functional outcomes and identifies conditions under which evolution enhances or constrains performance, laying the foundation for eco-evolutionary design principles. The hypotheses identify mechanisms and suggest empirical approaches and design implications that form an integrated eco-evolutionary framework for nature-based solutions.

H1. Context-specific selection hypothesis

The performance of nature-based solutions depends on eco-evolutionary dynamics shaped by the fine-scale spatial and temporal heterogeneity of urban environments.

Mechanism

Cities create fine-scale spatial and temporal heterogeneity in temperature, pollutants, hydrological regimes, and disturbance that impose distinct selective pressures driving local trait differentiation. Variation in these selective agents both within and among cities leads to context-specific adaptive responses that can alter ecological processes underpinning nature-based solutions, such as canopy cooling, sediment stabilization, nutrient uptake, and contaminant processing, influencing functional performance. In some cases, locally evolved traits enhance functional performance under prevailing stressors. For example, mosses exposed to hotter and drier urban microclimates evolved drought-tolerant traits that improved roof function (*97*). Similarly, urban red maple (*Acer rubrum*) populations exhibit greater physiological acclimation, such as increased stress metabolite accumulation and nutrient reallocation, relative to nonurban populations, enhancing canopy performance under urban stresses (*98*).

Trait shifts that enhance survival under local stressors may reduce other functional attributes, generating trade-offs between persistence and service delivery. Management interventions, such as irrigation or soil amendments, can modify selective regimes, altering evolutionary trajectories and functional outcomes. Functional performance therefore depends on the correspondence between evolved trait distributions and the selective environments in which nature-based solutions are implemented.

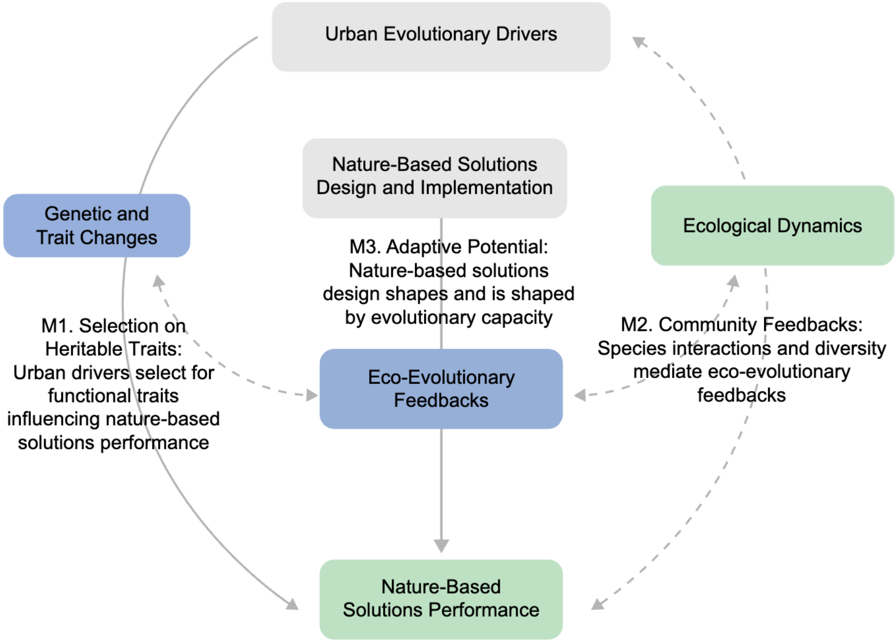

Fig. 2. Framework linking evolution and nature-based solutions performance. Conceptual schematic showing the interactions between urban evolutionary drivers, evolutionary trait changes, ecological dynamics, eco-evolutionary feedbacks, and nature-based solution performance.

Testing approach

Common garden and reciprocal transplant experiments across urban gradients allow comparison of local and nonlocal genotypes under current and projected stressors, including heat, drought, salinity, and pollution. Replicated studies across dense urban cores, peri-urban zones, and microhabitats can quantify how variable selective regimes shape trait divergence and associated ecosystem processes. These approaches determine whether adaptive trait differentiation translates into sustained functional performance. Comparative assessments across cities experiencing similar selection regimes can identify consistent trait-function relationships.

Design implications

Design strategies grounded in these mechanisms will prioritize populations with traits adapted to urban conditions. Populations may be matched to environments with similar selective regimes, experimentally screened for advantageous traits, or initialized with diverse genotypes while allowing

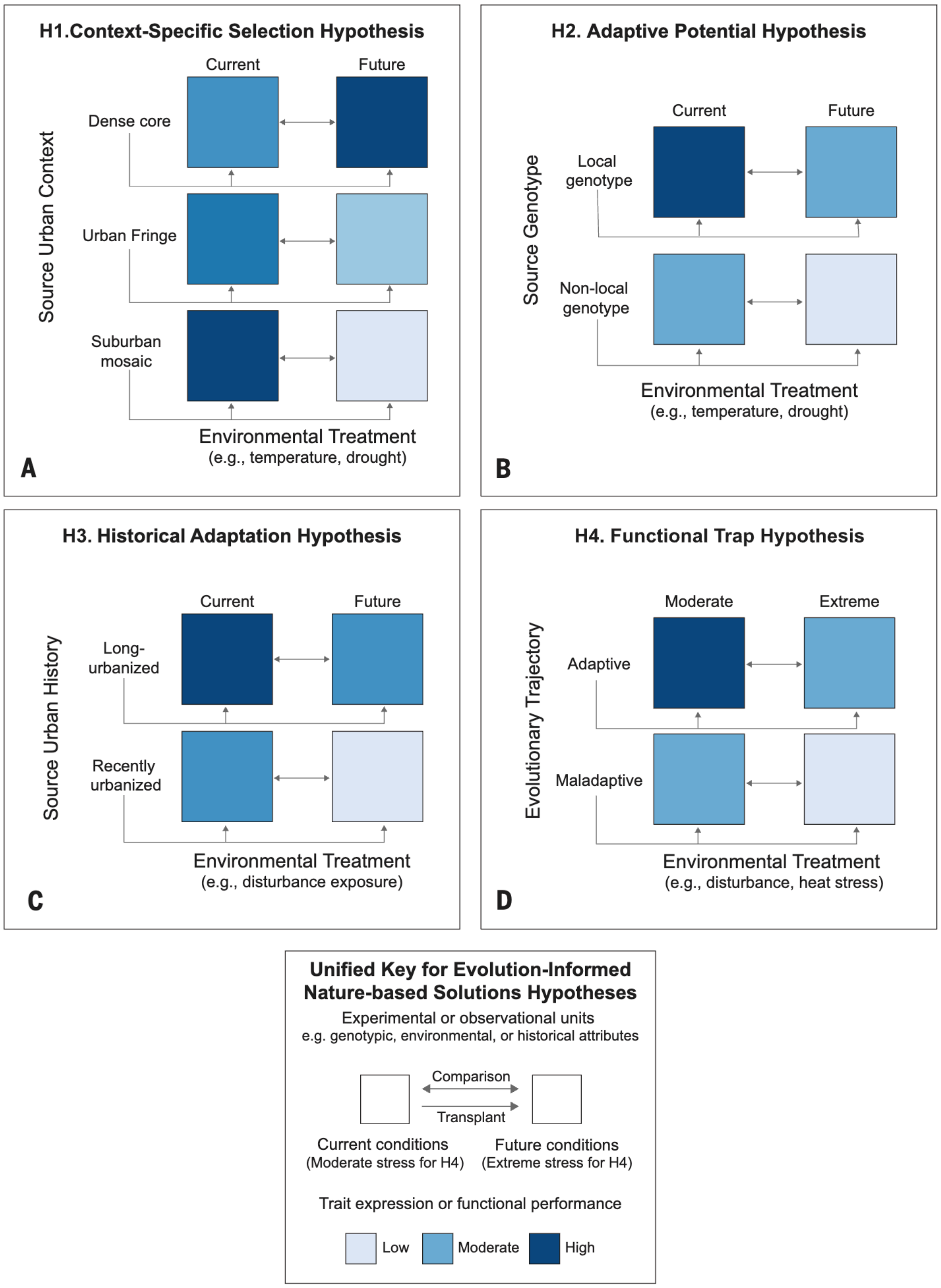

Fig. 3. Schematic representation of study designs to test the four hypotheses. The four panels illustrate how experimental and comparative approaches can be used to evaluate when and how evolutionary processes influence the performance and resilience of nature-based solutions. The unified key indicates how changes in trait expression or functional performance are compared across current and future environmental conditions. (**A**) H1: Context-specific selection hypothesis: Replicated studies across urban gradients (dense core, urban fringe, suburban mosaic) test how context-specific selection shapes trait divergence and functional outcomes. (**B**) H2: Adaptive potential hypothesis: Common garden or reciprocal transplant experiments compare local and nonlocal genotypes under current and projected future stress to assess the persistence and functional effects of adaptive traits. (**C**) H3: Historical adaptation hypothesis: Longitudinal or space-for-time comparisons evaluate how populations with longer urban histories differ in stability and recovery relative to recently urbanized populations. (**D**) H4: Functional trap hypothesis: Stress response experiments expose organisms or communities with different evolutionary trajectories to acute disturbances (e.g., heat waves or salinity pulses) to detect thresholds beyond which previously advantageous traits reduce performance.

selection to operate. The appropriate strategy depends on life history, management intensity, and social context. Species selection should balance functional performance with ecological compatibility. Native species are preferred because they sustain regional biodiversity and coevolved interactions; however, non-native or selectively bred taxa can enhance specific functions where structural stability or stress tolerance is prioritized (*99*). Hybrid *Spartina* lineages that strengthen sediment stabilization and selectively bred oysters that enhance shoreline protection and water filtration under urban stressors demonstrate such cases. Nevertheless, the ecological risks associated with introducing non-native species or lineages must be weighed against functional gains. Suitability should be guided by empirical evidence of performance, adaptability, and minimal ecological risk under defined selective regimes.

H2. Adaptive potential hypothesis

Nature-based solutions that include populations with high adaptive potential are more likely to sustain functional performance and resilience under environmental change.

Mechanism

Adaptive potential depends on genetic variation within and among populations that buffer environmental stress. Local adaptation can enhance present-day performance (e.g., canopy cooling or flood mitigation under current drought or pollution regimes), but when driven by strong directional selection that reduces genetic diversity, it may constrain future evolutionary responses. For example, urban tree populations matched to local precipitation regimes can maintain canopy growth and cooling during heatwaves better than nonmatched source populations (*100*). However, reliance on genetically uniform planting stock may reduce genetic variance and evolvability in ecologically important traits and increase vulnerability to future shifts in precipitation or more extreme thermal regimes. Thus, natural selection or genetic bottlenecks may compromise long-term resilience even when short-term performance is maintained.

Intraspecific genetic variation can directly influence ecosystem processes (*101*, *102*). Genetic diversity increases a population's capacity to adapt to emerging or intensifying stressors and provides functional potential against environmental variability, making it essential for managing nature-based solutions under uncertain future conditions (*103*). For example, stonecrop (*Sedum* spp.) shows strong intraspecific variation in drought response and stormwater retention on green roofs, suggesting that genetically diverse plantings can buffer performance under variable climates (*104*). Evidence from urban plant populations further indicates that stress-response variation persists under urban conditions; thus, preserving such diversity may support future adaptations (*105*).

Testing approach

Genetic diversity can be quantified in representative species deployed in nature-based solutions. Performance assays across stress gradients can determine whether populations with greater genetic variation or plasticity can sustain ecosystem functions under projected future conditions. Longitudinal monitoring further allows assessment of whether genetically diverse populations maintain functional stability across time.

Design implications

Incorporating diverse genotypes in planting designs can stabilize ecosystem functions while preserving evolutionary capacity. Beyond species selection, eco-evolutionary design must sustain processes that enable continued adaptation. Urban fragmentation can reduce population size and increase genetic drift, eroding genetic variation. Maintaining large, connected populations through corridors, greenways, and park systems can facilitate gene flow, the movement of alleles among populations, thereby supporting adaptive potential (*106–108*). However, excessive connectivity may homogenize populations and limit local adaptation. Studies across taxa show that urban green infrastructure can maintain gene flow in fragmented landscapes, challenging assumptions that urban fragmentation necessarily constrains evolutionary processes (*109*, *110*).

Habitats such as wetlands, stormwater basins, or green roofs can act as evolutionary refugia by buffering extreme stress, promoting persistence, and preserving genetic variation. For example, common frog (*Rana temporaria*) populations in Scottish drainage ponds maintain genetic diversity and connectivity comparable to those of populations in rural sites, demonstrating evolutionary potential despite urban fragmentation (*111*). When integrated into nature-based solutions, these habitats can sustain adaptive potential and increase the likelihood that ecosystem functions persist under accelerating environmental change (*110*).

H3. Historical adaptation hypothesis

Nature-based solutions embedded in long-urbanized systems may benefit from historical adaptation to cumulative stressors, yet their future success depends on the correspondence between past selective regimes and emerging environmental conditions.

Mechanism

Historical adaptation can reinforce functional stability or constrain performance under emerging stress trajectories. Urban ecosystems with extended histories of anthropogenic modification have exposed populations to persistent selection to urban stressors, which has likely shaped genetic composition, trait distributions, and species interactions. Such historical adaptation may confer higher fitness and functional stability under current urban conditions, but its impact under future conditions may vary.

Adaptation to past or chronic stressors does not guarantee resilience under rapid environmental change. When selective environments shift beyond the historical range of variation through intensifying heatwaves, altered precipitation, or new contaminants, previously advantageous traits may become maladaptive. The degree of correspondence between historical and emerging selective regimes therefore determines whether adapted populations continue to sustain ecosystem function. This hypothesis emphasizes that evolutionary history can both enhance and constrain the long-term performance of nature-based solutions.

Testing approaches

Empirical evaluation can use comparative approaches across long-urbanized and recently urbanized systems to identify trait-function relationships under chronic stress. Space-for-time substitutions assess cumulative adaptation by contrasting populations along urbanization gradients. Longitudinal studies track trait distributions and ecosystem processes through time. Where feasible, resurrection approaches comparing ancestral and contemporary genotypes can provide direct evidence of evolutionary shifts and their functional consequences under current and projected conditions.

Design implications

Cities with a long urban development history serve as empirical reservoirs for identifying taxa, genotypes, and traits associated with sustained function under chronic urban stressors. Such systems may reveal interaction networks and community configurations that maintain stability despite prolonged press disturbances. These insights can inform species and population selection for new interventions, particularly where similar stress regimes are anticipated (*42*). However, implementation should not rely solely on historical performance. Experimental evaluation under projected future conditions remains critical to identify thresholds beyond which historical adaptation no longer supports ecosystem function. By integrating evidence of past adaptation with environmental projections, nature-based solutions can better align evolutionary history with anticipated trajectories of change.

H4. Functional trap hypothesis

When environmental change exceeds adaptive capacity or when management interventions alter selective pressures, adaptive evolution may favor traits that enhance organismal fitness but undermine the ecosystem functions that nature-based solutions are designed to sustain, thereby reducing functional resilience.

Mechanism

Natural selection acts on traits that increase organismal fitness within specific environments, not necessarily on traits that maximize human-valued ecosystem services. Thus, evolutionary responses can decouple population persistence from the ecological processes that nature-based solutions are designed to sustain. Functional traps arise when adaptive evolution maintains population persistence under chronic or intensifying stress but weakens the intended nature-based solution processes, such as sediment stabilization, nutrient removal, carbon storage, or canopy cooling.

Trade-offs may arise through shifts in allocation, physiology, or species interactions. Wetland plants evolving tolerance to salinity or nutrient enrichment may reduce belowground biomass allocation, decreasing sediment stabilization and carbon sequestration. Similarly, resistance traits in aquatic consumers or microbial communities may enhance survival under pollution or temperature stress but reduce nutrient or pollutant removal efficiency. At the community level, simplified assemblages may favor opportunistic species that persist under disturbance yet provide reduced multifunctionality. In these cases, demographic persistence does not guarantee maintenance of ecosystem function.

Testing approaches

Stress-response experiments exposing populations to acute or new disturbances help identify thresholds beyond which evolutionary responses fail to sustain ecosystem processes. Monitoring frameworks should distinguish between demographic metrics, such as survival, abundance, or recruitment, and rates of ecological processes. Detecting divergence between persistence and function provides early evidence of emerging functional traps.

Design implications

Design can buffer against such decoupling by incorporating functional redundancy within genetically and functionally diverse assemblages, including coevolving mutualistic systems, such as tree-microbe or pollinator-plant networks. Community-level diversity stabilizes multifunctionality under disturbance and reduces dependence on single trait combinations (*112, 113*). Where environmental change outpaces adaptive capacity, assisted evolution can direct trait change toward sustaining ecosystem processes. For example, selective breeding programs producing oysters with increased tolerance to elevated temperatures and disease for urban estuarine restoration show how assisted adaptation can support shoreline protection and water filtration under intensifying stress (*114*). Such interventions require careful evaluation to avoid unintended ecological consequences.

The path forward: Research and policy priorities

The four hypotheses outlined above provide a framework for understanding how selection, adaptive potential, historical contingency, and functional traps shape the long-term performance of nature-based solutions. Translating this framework into practice now requires coordinated empirical testing, monitoring, and policy integration. Evolution should be framed not as a background process but as a contemporary and forward-looking determinant of ecological resilience and functional stability under accelerating environmental change.

Empirical evidence: Testing eco-evolutionary effects on nature-based solutions

The feasibility of applying an eco-evolutionary framework to nature-based solutions depends on linking population-level adaptations with community dynamics, local ecological contexts, and management goals. Urban assemblages often include species of native and introduced origin whose interactions can amplify or constrain adaptive responses. Understanding how these dynamics influence the persistence and function of nature-based solutions requires empirical studies that integrate genetic change; trait dynamics; multispecies processes, such as competition, facilitation, trophic feedbacks; and direct measurements of ecosystem processes. Distinguishing demographic persistence from maintenance of ecological function is particularly important to detect cases in which adaptive responses stabilize populations but erode ecosystem performance.

Trait databases and monitoring frameworks

Current monitoring of nature-based solutions focuses largely on structural and ecological attributes, with limited attention to evolutionary dynamics (*115*). There is a growing need for integrated frameworks and tools tracking functional trait variation, genetic diversity, and adaptive change over time (*116*). Linking genomic metrics, such as allele frequency change or population genetic diversity, with trait variation and ecosystem processes is essential for monitoring evolutionary dynamics in nature-based solutions. Tools such as trait assays and genomic surveillance can support early detection of traits evolving counter to intended nature-based solutions and inform management strategies (*117*). Making trait- and gene-based information accessible to planners, practitioners, and community groups will support collaborative implementation and long-term stewardship of nature-based solutions.

Measuring eco-evolutionary resilience of nature-based solutions

Measuring the eco-evolutionary resilience of nature-based solutions requires indicators that capture both ecological function and the capacity for adaptive change. Metrics should reflect the evolutionary potential of key species and the environmental conditions enabling adaptation. Practical indicators include population genetic diversity from genomic data (e.g., heterozygosity, allele frequencies), genetic variation in functional traits, strength of selection, and fitness outcomes. Equally important are ecosystem-level metrics, such as canopy cooling, nutrient removal, sediment accretion, or carbon storage, that can be evaluated alongside evolutionary parameters. Composite indicators linking ecological function with evolutionary parameters can help early detection of functional decline. Emerging tools, including population-genomic screening and community-science monitoring, make these approaches increasingly feasible at the city scale.

Anticipating evolutionary resilience through scenario planning

Urbanization and climate change reshape selective environments by altering the strength and direction of selection. Scenario modeling linking evolutionary processes to projected environmental change can help anticipate adaptive thresholds and ecosystem tipping points (*21*, *118*). Such approaches allow planners to identify where adaptive capacity may be exceeded and where interventions, such as genetic rescue or assisted adaptation, may be warranted.

Predicting evolutionary trajectories remains inherently uncertain under complex urban and climatic drivers. This uncertainty underscores the importance of adaptive monitoring and experimental design as mechanisms for iterative learning from observed evolutionary responses. Scenario-based modeling, population-genomic tools, and repeated genetic sampling can reveal trait shifts or adaptive thresholds in near real time, enabling management to evolve with changing selective environments rather than relying on long-term forecasts.

Building an evolutionary ethic into urban practice

An evolutionary ethic in urban practice centers on maintaining the capacity of nature-based solutions to sustain ecological function under uncertain futures. Because evolutionary processes determine whether populations and communities can adapt to changing conditions, design decisions made today shape future options. Embedding evolutionary principles in urban planning requires prioritizing adaptive capacity by maintaining genetic variation, viable populations, ecological connectivity, and functional redundancy so ecosystem processes persist as conditions shift.

Maintaining adaptive capacity is especially important where human communities face disproportionate exposure to climate risk. In neighborhoods with histories of environmental neglect, failure of nature-based solutions would compound vulnerability. An evolutionary ethic requires safeguarding long-term ecological function and adaptive potential across urban landscapes, including in frontline communities. This framing links intergenerational ecological resilience with access, stewardship, and environmental justice as practical considerations for sustaining ecosystem services under accelerating change.

Operationalizing this ethic must account for financial and governance constraints. Funding for implementation, research, and long-term monitoring competes with other priorities, yet investing in adaptive capacity can reduce project failure and future costs. Designing nature-based solutions that maintain genetic diversity, population viability, and ecological connectivity preserves function under shifting conditions. The evolutionary ethic frames them as dynamic systems whose performance depends on the capacity to adapt.

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