NVF Climate and Environment

Circular economy and sustainable materials for biodiversity regeneration in bridge projects

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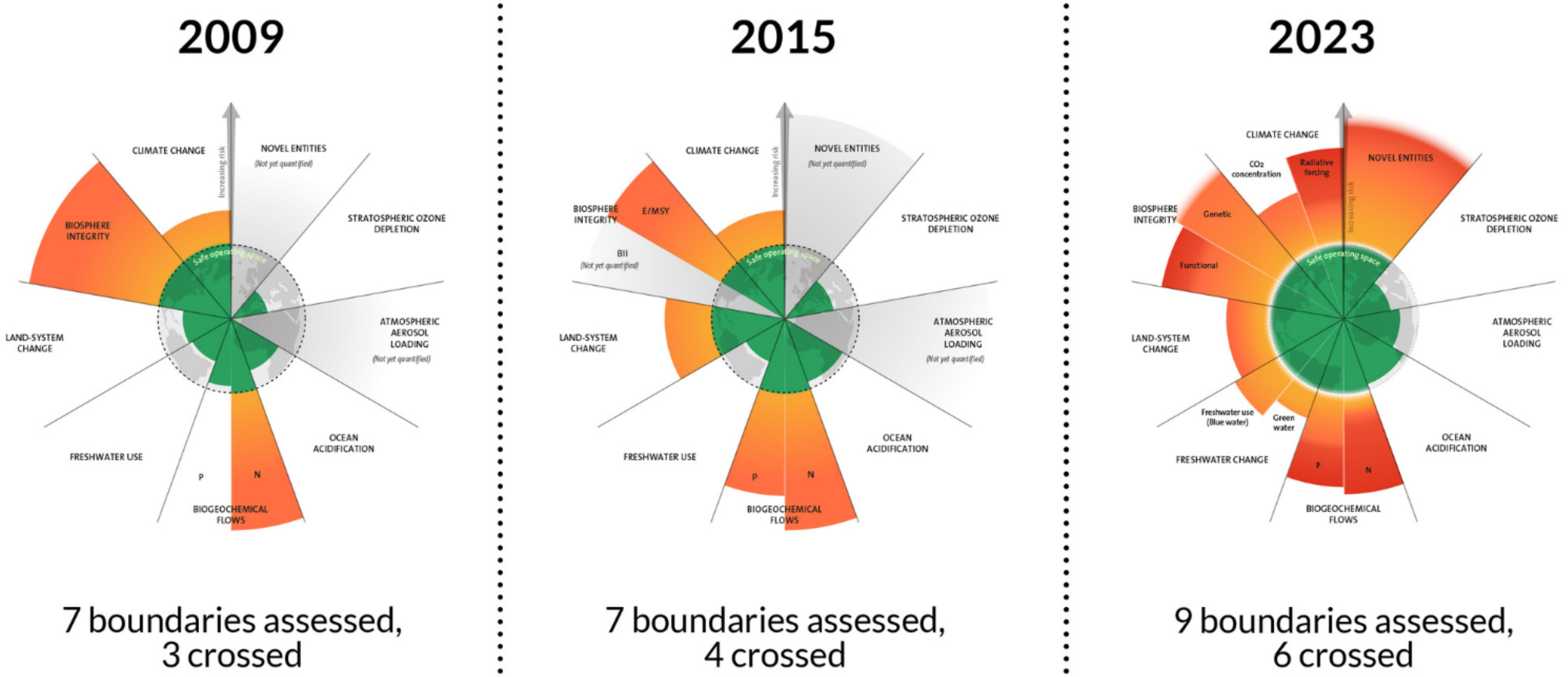
RAMBOLL Bright ideas. Sustainable change.

Planetary boundaries

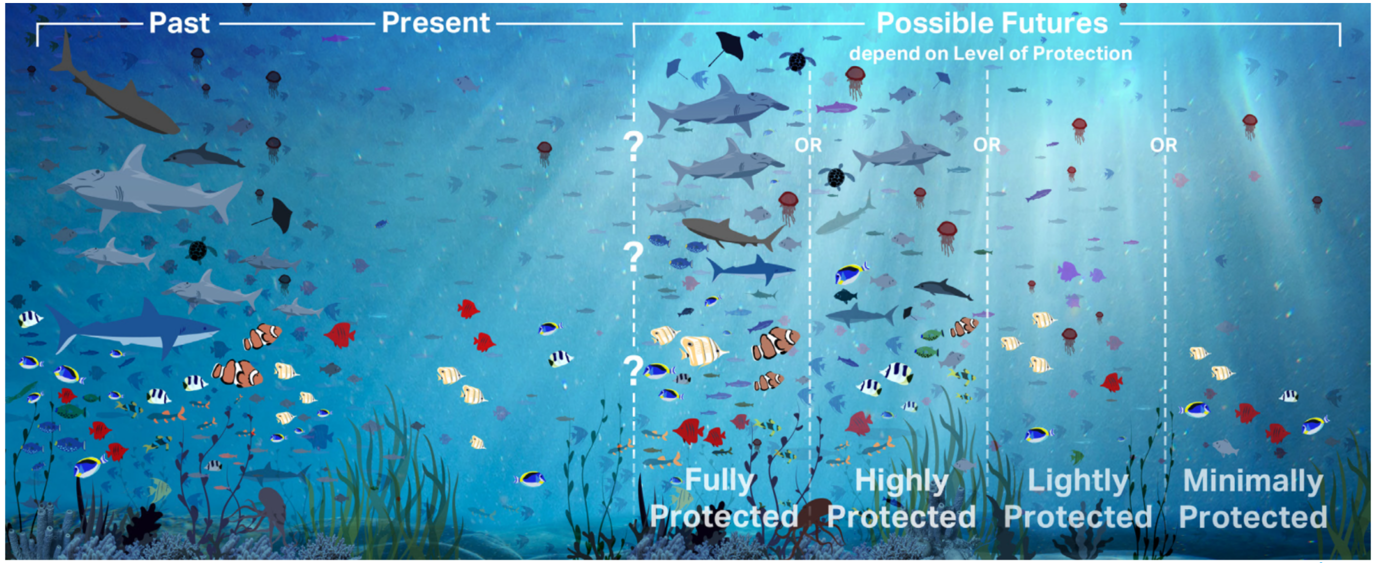


The evolution of the planetary boundaries framework. Licenced under CC BY-NC-ND 3.0 (Credit: Azote for Stockholm Resilience Centre, Stockholm University. Based on Richardson et al. 2023, Steffen et al. 2015, and Rockström et al. 2009)

- **9 natural processes** that **regulate Earth's biosphere and keep it stable** (Stockholm Resilience Centre)

- As one boundary shifts □ the impact ripples outwards, affecting others.
- The **most important interaction is between climate and biodiversity**.
- World Meteorological Organisation (WMO 2025)and the EU's Copernicus Climate Change Service (Copernicus 2025) confirm 2024 as warmest year on record with global average mean temperature at about 1.55°C above pre-industrial level.

- Focus on the ocean, because:
  - multiple boundaries that all end up in the ocean.
  - the ocean is like the end station of most of our waste, of our eutrophication and of the carbon dioxide.



The level of protection, and therefore the effectiveness of MPAs greatly influences the future state of the ocean. Past ocean ecosystems were abundant and diverse in species and habitats. (Oregon State University 2023)

Biodiversity crisis

- Biodiversity on land and in the ocean is the variety of life on Earth.
- The biodiversity holds the resilience of the entire living biosphere both in the ocean and on land.
- Since 1970 there has been a 70 % loss in abundance of animal species
- The built environment is a significant contributor to this crisis: globally, the sector is responsible for 30% of biodiversity loss.

We load nature roughly in 2 ways:

We unsustainably consume natural resources (land use change, overexploitation of natural resources)

1. Our waste is a burden on the environment (air, water and soil pollution)

The most significant threats over the next 10 years:

Failure to deliver on climate action

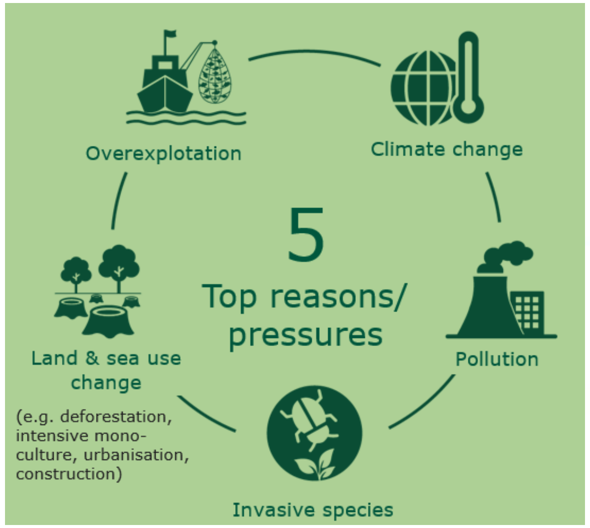
Extreme weather events

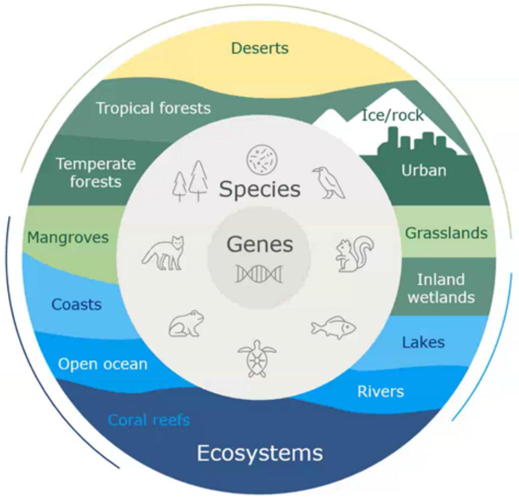
2. Biodiversity loss

- Climate change alters our environment dramatically
  - Need for new desing practices that emphasize on resilience and adaptability
  - Need for material innovations aimed at maximising durability
  - Every facet of bridge engineering must evolve accordingly.

In the EU

81%	18% of land	30 % of land and sea
of habitats are in poor status	is part of a Natura 2000 protected area	to be protected by 2030 (EU target)



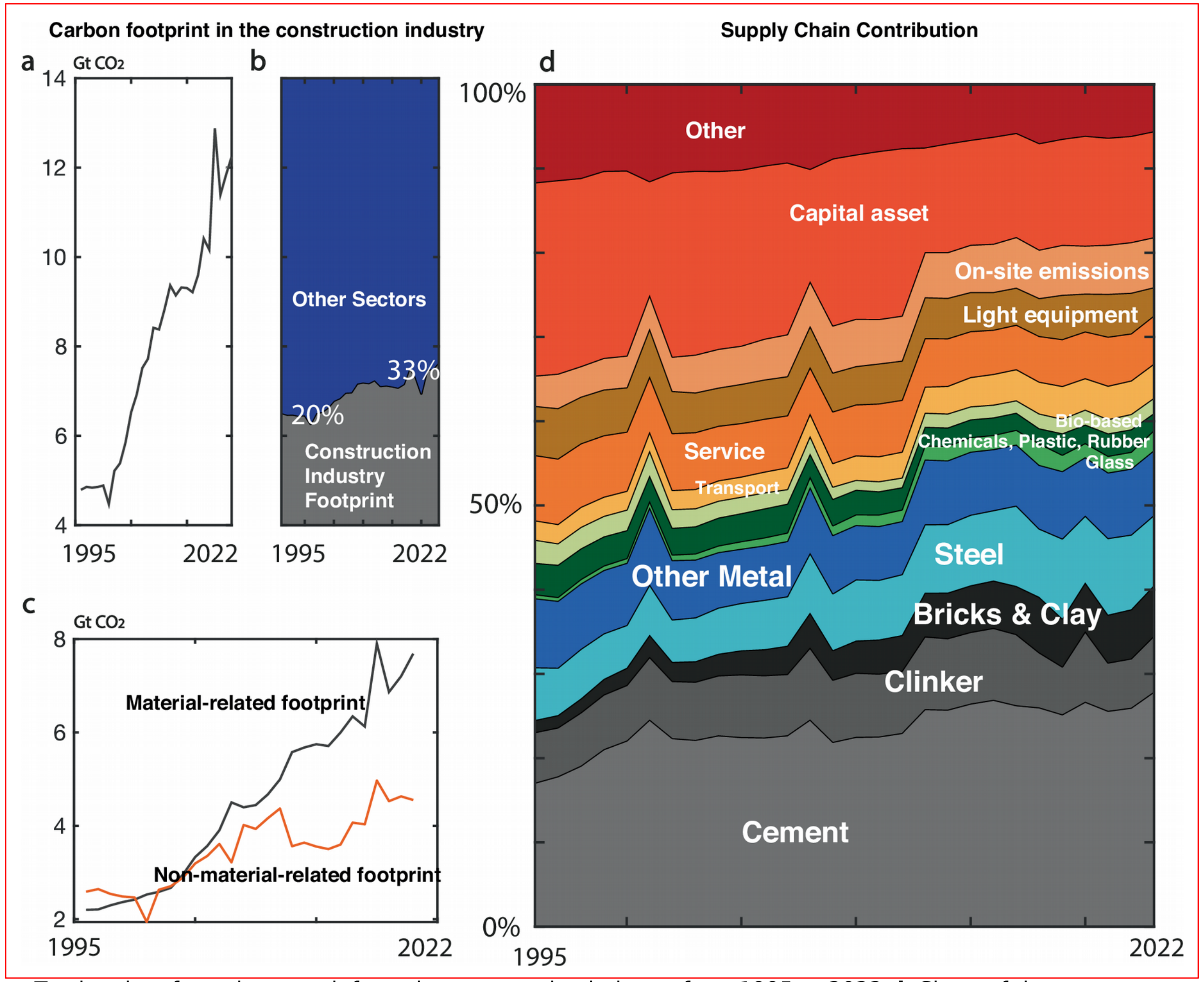


“ $44 trillion - more than half of global GDP - is potentially under threat of dependence of business on nature and its services. (WEF, 2020) ”

- The ocean needs protection urgently and by all means and in every project.
- The global effort is to protect 30 % of ocean by 2030 to achieve this marine protected areas need to increase
- Currently, only 3 % of ocean is fully or highly protected.

Carbon footprint of the construction sector is projected to double by 2050 globally

- The construction industry has grown more than twice within less than three decades.
- The construction industry footprint took around one-fifth of total carbon emissions in 1995, and this percentage grew to 33% in 2022.
- The construction industry has grown more material-based, driven by the increasing use of materials such as cement and steel.

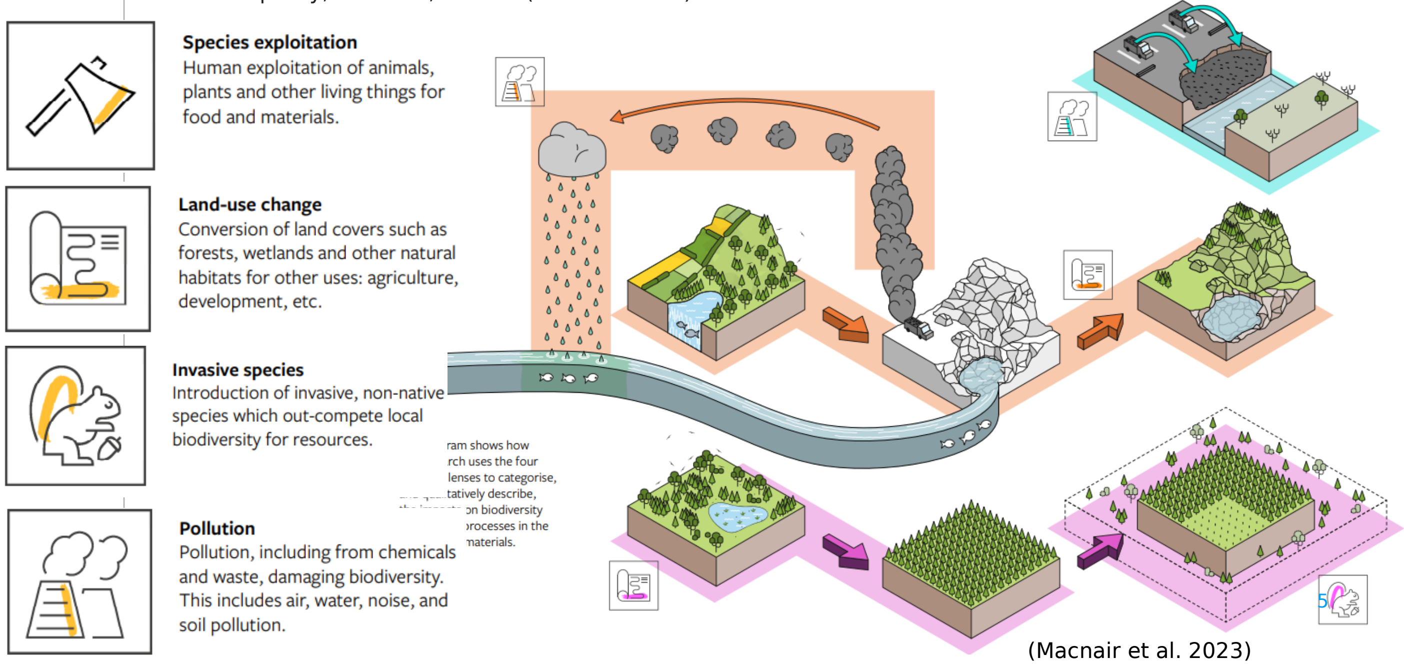


a Total carbon footprint growth from the construction industry from 1995 to 2022. **b** Share of the construction industry's carbon footprint in total carbon emissions. **c** Material and non-material related footprints in the construction industry. **d** Evolution of components of carbon footprints from the construction industry from 1995 to 2022. (Li et. al 2025)

Embodied biodiversity impact of construction materials

- Construction industry uses significant amounts of materials.
  - The construction sector is responsible for 21% of global emissions, 50% of extracted materials, and 30% of global waste.
- Material extraction processes for construction comes with various ecological impacts on biodiversity:
    - Limestone habitats are destroyed by quarrying of cement material
    - Biodiversity-poor monocultures are introduced in management of forests for timber
    - Wildlife is affected by noise generated when transporting materials
- Embodied biodiversity impacts = Embodied Ecological Impact (EEI)
  - Analogous to embodied carbon.
  - However, Embodied ecological impact (EEI): the impacts on biodiversity due to all of the processes that take place throughout a material’s lifecycle.
  - Climate change is not addressed since contribution of studied materials to climate change would be accounted for in embodied carbon consideration
- Embodied biodiversity impacts of materials:
    - are not covered by other metrics such as Biodiversity Net Gain.
    - depend on local factor (local habitats, species and environmental receptors) to a greater extent than the embodied carbon.

Limestone quarry, Parainen, Finland (Vasileva 2024)



(Macnair et al. 2023)

Ecological Impacts of Conventional Bridge-Building Materials (beyond CO_2)

MATERIAL	MAIN NON-CARBON PRESSURES	TYPICAL ECOSYSTEM CONSEQUENCES	KEY MITIGATION / CIRCULAR ACTIONS
Concrete (cement + sand + gravel)	• Quarrying of limestone, sand and aggregates - habitat loss, river-bed incision • High water use and kiln NO_x/SO_2 emissions • Alkaline wash-out raising pH of receiving waters	• Loss of riparian / karst biodiversity • Sediment plumes that smother spawning beds • Air-borne dust affecting nearby vegetation	• Use recycled aggregates and industrial SCMs (GGBS, calcined clay) to cut virgin extraction • Source manufactured or dredged sand from certified low-impact sites • Capture and recycle wash-water on site
Steel	• Iron-ore mining → deforestation, tailings leakage of heavy-metals • Coke-oven dust, slag and dioxins • Run-off of Zn/Cu from galvanised or painted surfaces	• Acidification, metal toxicity to aquatic invertebrates and fish • Landscape fragmentation at mine sites	• Specify scrap-based EAF or H_2-DRI steel; design for reuse (bolted splices) • Low-zinc duplex coatings, paint systems with <5 % VOC • End-of-life take-back schemes
Timber / engineered wood	• Expansion of monoculture plantations, soil compaction by harvesting machinery • Potential loss of old-growth habitat when sourcing is poor • Resin, preservative and adhesive leachates	• Reduced species richness and altered hydrology in catchments • Localised aquatic toxicity from biocides	• FSC/PEFC certified sourcing; favour mixed-species or agro-forestry supply • Use borate-free, low-VOC adhesives; design details that keep timber dry and uncoated • Plan for deconstruction and second-life use
Earth materials (sand, gravel, rock fill)	• River and coastal sand extraction → erosion, delta retreat • Dust and noise from crushing / haulage • Alien-species introduction via dredging equipment	• Wetland loss, turbidity spikes; declines in benthic fauna • Disturbance of nesting birds and riparian mammals	• Prioritise site-won or recycled fill; adopt circular "urban quarry" models • Enforce extraction limits based on watershed sediment budgets • Wash and quarantine dredging gear to prevent invasives
Asphalt (bitumen + aggregates)	• Oil-derived bitumen – PAH leaching under UV & heat • Run-off laden with micro-plastics and heavy metals • High night-time surface temps ("heat-island" effect)	• Chronic toxicity to aquatic species, especially after first-flush rain • Elevated stream temperatures impairing salmonids	• Warm-mix or bio-bitumen alternatives; high RAP (reclaimed asphalt) content • Permeable or "cool" pavements; integrate edge bioswales to trap fines • Sealcoats free from coal-tar pitch

Cross-Cutting Take-aways for Bridge Projects

- **Embodied ecological impact (EEI) ≠ embodied carbon** – add land-use, water use, toxicity and biodiversity metrics to material selection.
- **Circular material loops** (reuse steel girders, recycled concrete aggregate, high-RAP asphalt) simultaneously cut extraction pressure and disposal impacts.
- **Design for disassembly** and material passports keep future demolition waste – and its contaminants – out of ecosystems.
- **Pair lean material use with nature-based measures** (bioswales, living shorelines) to intercept any remaining pollutants before they reach the river.

Most common climate-related threats that can jeopardise a bridge’s safety, serviceability, durability, or whole-life cost

- **Why these risks matter**
  - Safety and reliability:
    - Extreme events can trigger sudden failures or require emergency closures.
  - Lifecycle costs:
    - Accelerated deterioration increases inspection, maintenance and rehabilitation budgets.
  - Network resilience:
    - Bridge outages often sever critical transport links, magnifying socio-economic disruption.

Key climate hazards for bridges

HAZARD / DRIVER	TYPICAL BRIDGE IMPACTS
1. River flooding & extreme precipitation	• Scour and undermining of foundations • Deck/substructure inundation leading to debris impacts • Loss of approach embankments and access roads
2. Sea-level rise & storm surge (coastal bridges)	• Overtopping and salt-water intrusion • Accelerated corrosion of steel and reinforced concrete • Increased wave and current forces on piers and abutments
3. Heatwaves & high average temperatures	• Thermal expansion causing joint distress, bearing failure or excessive deck movements • Asphalt surfacing rutting or softening • Reduced strength of some materials at high temperatures
4. Freeze–thaw cycles & ice loading	• Concrete cracking and spalling • Ice accretion on cables, hangers or trusses adding dead load • River-ice breakup collisions with piers
5. Drought & soil desiccation	• Differential settlement of foundations in expansive clays • Lower river stages exposing piles to air-induced corrosion
6. High-intensity wind & tropical cyclones	• Uplift and lateral loads on long-span decks • Vortex-shedding–induced vibrations • Wind-borne debris impacts
7. Wildfire (in fire-prone regions)	• Heat damage to steel girders or cable sheathing • Loss of protective coatings, leading to long-term corrosion
8. Lightning & more frequent severe storms	• Direct strikes damaging expansion joints, bearings or monitoring equipment
9. Increased humidity & salinity	• Accelerated corrosion of reinforcement and post-tensioning ducts • Shortened maintenance intervals
10. Permafrost thaw (high-latitude bridges)	• Loss of bearing capacity in frozen soils, causing pile or pier settlement

Heavier and more erratic rainfall undermines bridge reliability

RAIN-RELATED CLIMATE HAZARD	TYPICAL BRIDGE CONSEQUENCES	RESULT FOR RELIABILITY
1. Peak flood discharge & higher water levels	• Scour around piers/abutments removes supporting soil. • Uplift on decks of low-clearance bridges. • Bank or approach-road wash-outs.	Loss of bearing capacity; risk of sudden collapse or prolonged closures.
2. Longer wet seasons / saturated soils	• Reduced shear strength of embankments and foundation soils. • Increased pore-water pressures in pile caps and retaining walls.	Progressive settlement, tilting or rotation of sub-structures.
3. More intense cloudbursts (flash floods)	• Debris rafts (trees, cars) slam into piers, generating impact loads well above code assumptions. • Hydrodynamic forces excite vibrations in long, slender piers.	Exceedance of ultimate or fatigue limits; faster deterioration of joints and bearings.
4. Sediment-laden flows	• Abrasive action erodes concrete surfaces and protective coatings on steel. • Blocked drainage systems on decks, causing standing water.	Accelerated material degradation; higher maintenance frequency.
5. Increased humidity & longer wet-dry cycles	• More freeze–thaw or wet-dry cracking of concrete. • Chloride ingress (if floodwaters are saline or brackish).	Shortened service life of reinforcing steel and post-tensioning ducts.
6. Compound hazards (rain + wind or landslide)	• Concurrent high winds drive floating debris and wave run-up. • Rain-induced landslides undermine abutments or approach cuttings.	Multiple failure modes activate simultaneously, reducing residual safety margins.

- **Knock-on impacts for network performance**
  - Higher probability of emergency closures → loss of redundancy in transport corridors.
  - Increased inspection, dive-survey and scour-countermeasure costs.
- **Mitigation & adaptation actions**
  - Update hydraulic models with regional climate-change rainfall projections; re-check scour design depths.
  - Use deep foundations or sleeve piles that tolerate 1–in-100/1–in-500-year scour depths.
  - Install real-time scour and water-level sensors linked to early-warning systems.
  - Strengthen piers against debris impact (steel collars, fenders).
  - Improve deck drainage and apply water-resistant membranes to expansion joints.
  - Elevate or armour approach embankments; add relief culverts to reduce upstream ponding.

Pathways through which a bridge and its approaches can degrade nature

❑**Habitat loss and fragmentation of ecological corridors**

• The permanent footprint of abutments, embankments, approach roads and construction lay-down areas **removes riparian or flood-plain habitat**.

• By spanning a watercourse or valley with piers and causeways a **bridge can interrupt the continuous "green corridor**" many species depend on, forcing wildlife to cross traffic lanes or enter culverts. Linear transport infrastructure is widely documented to be a catalyst for habitat fragmentation and biodiversity loss

❑**Barrier and filter effects for aquatic organisms**

• Closely-spaced piers, debris screens or altered flow regimes (scour holes, turbulence) can make longitudinal migration for fish, otter or beaver more difficult.

• Shading from a wide deck changes light and temperature conditions, altering in-stream primary production and benthic communities.

❑**Hydromorphological alteration**

• Pier noses and abutments modify local hydraulics, often increasing erosion (scour) immediately downstream while trapping sediment upstream.

• Hard bank protection upstream of the bridge can disconnect the flood-plain, reducing natural overbank deposition and leading to channel incision – a form of land degradation.

❑**Construction-phase soil disturbance and land degradation**

• Vegetation clearance, heavy equipment, borrow-pits and spoil heaps compact soil, increase runoff and raise the risk of slope failure or gully erosion, especially on steeper river valleys.

• Fine sediment from disturbed surfaces is a major carrier of phosphorus and heavy metals.

❑**Storm-water and de-icing pollutants**

• Road-salt, tyre-wear particles, brake-dust and spilled fuels wash off decks and approaches, enter the river via scuppers or roadside ditches and reduce water quality (raised chloride, zinc, copper).

• In cold climates the first spring melt often delivers the single largest annual concentration of contaminants.

❑**Introduction of invasive species**

• Construction equipment, fill material and altered light / temperature niches around abutments provide entry

Ecology & circular economy into the earliest phase of a bridge project

- Dual baseline
  - Map living systems before any line is drawn
    - survey habitats, species corridors, flood-plain dynamics, water quality and cultural values
  - Scan the material stock
    - catalogue nearby decommissioned spans, surplus girders, recycled-aggregate depots and low-carbon mix plants that could be utilized in the project.
- Set regenerative objectives in the brief
  - Go beyond "no net loss" → require **Biodiversity Net Gain** and "minimal-virgin-material" targets alongside cost and programme.
  - Link success fees for designers/contractors to verified performance on both metrics (e.g., m^2 of habitat restored **and** % of reused steel).

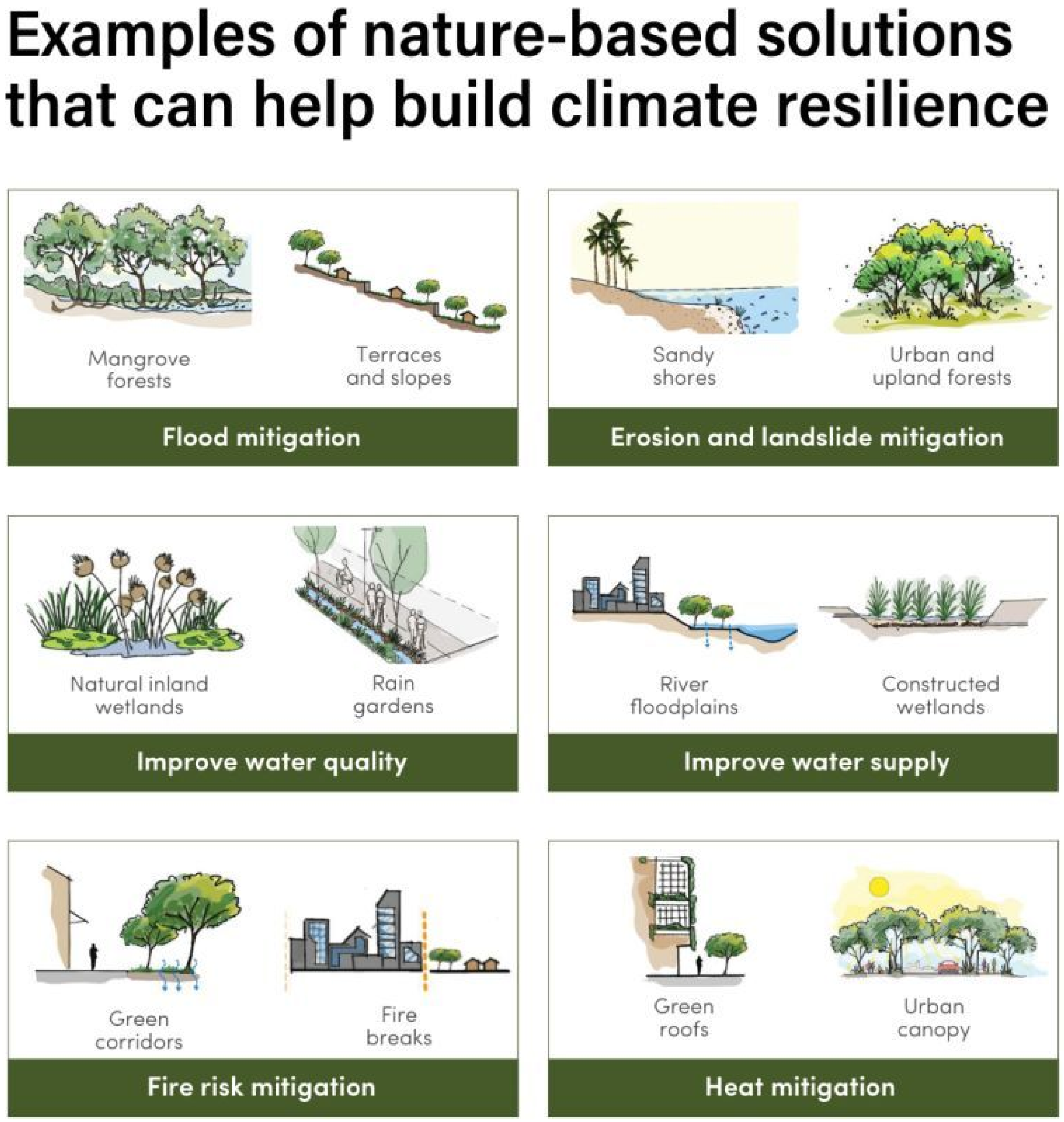
- Apply the mitigation & circularity hierarchy in concept design
  - **Avoid** impacts – choose clear-span alignments that keep riverbeds intact; repurpose an existing crossing if possible.
  - **Minimise** – optimise structural grids, use high-strength or hybrid sections to cut tonne-kilometres of concrete and steel.
  - **Reuse / urban-mine** – specify reclaimed girders, recycled aggregates, RAP asphalt; design bolted connections for future disassembly.
  - **Regenerate / offset** – embed nature-based scour protection, riparian planting, fish passages and pollinator

- Embed ecology in the geometry & drainage DNA
  - Size soffit-to-water clearances and pier spacing to maintain wildlife and sediment continuity.
  - Route deck runoff through integrated bio-retention planters or vegetated swales before discharge.

- Material passports and digital twin from day one
  - Each beam, bearing or slab gets a digital ID with grade, coatings

Nature-based Solutions (NBSs)

- Nature-based solutions refer to set of approaches that aim to protect, manage and restore natural systems — such as forests or wetlands — to benefit people, nature and the climate simultaneously.
- **Nature-based solutions** can also be integrated with traditional built infrastructure, such as roads or dams, to **enhance resilience and cost-effectiveness**.
- These natural systems can build resilience against hazards like flooding, heat or drought.
  - planting trees on hillsides can stabilize soils, reduce erosion and enhance water quality for downstream communities by controlling sediment and filtering pollutants, helping to protect crop yields and safeguard rural livelihoods
- **Nature-Based Solutions Do More Than Enhance Climate Resilience**
  - water quality improvements, water supply enhancements, flood mitigation, erosion and landslide control.
  - these solutions also result in co-benefits like job creation and biodiversity protection.
  - NBS can reduce the impact of natural hazards in cities, such as flooding, erosion, landslides, drought, and extreme heat.



Source: Illustration by John Wamagata Nduru/World Resources Institute (WRI), adapted from World Bank 2021

Nature-Based Solutions Are on the Rise in Africa | World Resources Institute

NBS in bridge project: Room for the River in Netherlands

Instead of building higher and higher levees, the Netherlands adopted a “Room for the River” strategy, founded on the principles of water safety and spatial quality. The idea is to live with the water instead of fighting it: The strategy gives water more space to spread out when floods occur, reducing damage and loss of life. The country moved dikes inland, widened rivers, raised bridges, dug flood channels, and added river catchment areas. New parks, public infrastructure, and recreational spaces were also created. Now the Rhine River can safely carry 1,000 cubic meters of water per second more than it could before.

CREDIT: ROBERTO MALDENO/FLICKR

Nijmegen River Park in the Netherlands, part of the country’s Room for the River project.

GSA (2019). Adapt now: a global call for leadership on climate resilience. Global Commission on Adaptation (GSA), Report, available at:
Adapt now: a global call for leadership on climate resilience - Global Center on Adaptation

- Cold climates can support Nature-Based Solutions, but low temperatures, snow, ice and short growing seasons change how those solutions behave and how they must be designed, built and maintained.

Biophysical performance shifts of NBS in cold regions

1.Short growing season
• Vegetation establishes and matures more slowly, so bank-stabilisation, dune-building or wetland attenuation benefits can lag several years behind those seen in warmer regions.
• Root–soil reinforcement peaks later in the life cycle; scour protection is therefore weaker in the early years.

2.Freeze–thaw and frost heave
• Repeated freezing breaks up soil aggregates and reduces shear strength; roots can be loosened or broken, lowering slope stability.
• Frost heave can uplift geotextiles or displace rock toe–protection that anchors bio-engineered riverbanks.

3.Snowpack dynamics
• Deep seasonal snow stores large volumes of water that are released rapidly during spring freshet. Peak runoff can occur before vegetation leaf-out, so flow-attenuation wetlands or floodplain forests are less effective at the moment of greatest need.
• Drifting snow can bury young plants or clog swales and bioswale inlets, reducing infiltration until meltwater clears the blockage.

4.Ice processes
• Ice jams and frazil ice increase hydraulic forces on vegetation and can scour restored riverbanks or floodplains.
• Floating ice rubs against living shorelines or log-jam deflectors, demanding stronger, more abrasion-resistant species or hybrid green–grey details (e.g., sacrificial hardwood piles in front of willow brush mattresses).

5.Permafrost and seasonally frozen ground
• In continuous or discontinuous permafrost zones, roots cannot penetrate deeply; waterlogged active layers may limit species choice and delay peatland or wetland development.
• Thaw settlement around embedded structures (e.g., root wads) can create unwanted surface ponding or erosion gullies.

Nature-Based Solutions (NBS) and Blue–Green Infrastructure (BGI) add value to bridge projects

- **Strengthening climate-resilience of the asset**
  - Flood-peak shaping – re-meandered channels, flood-plain reconnection and “room-for-the-river” set-backs slow water, lowering design flow velocities and local-scour depth at piers (-10 … -40 % recorded on Dutch Room-for-the-River sites).
  - Wave & surge damping – living shorelines that pair oyster-/mussel reefs with planted salt-marsh reduced storm-wave pressure on the US-90 Biloxi Bay bridge piles by c. 30–50 % and cut scour to near-zero two years after installation.
  - Bank-stabilisation – bio-engineered vetiver or willow geogrids on approaches lower erosion rates 30–50 % compared with rip-rap alone and extend resurfacing intervals.
  - Temperature & drought buffering – riparian tree belts shade deck runoff pipes, keep water cooler for salmonids and lengthen bearing-seal service life.

- **Restoring or upgrading already-degraded sites**
  - Sediment & nutrient traps – bioswales, two-stage ditches and vegetated retention ponds on bridge embankments capture 70–90 % of suspended solids and tyre-wear metals documented in Finnish Ahti-programme pilots, improving downstream water quality.
  - Re-vegetation of channelised reaches
    - clear-span retrofits remove obsolete culvert concrete
    - riparian planting and large-wood structures rebuild habitat complexity and natural hydraulic roughness.
  - Culvert daylighting or fish-pass “nature ramps” re-open migration routes that may have been blocked for decades, helping recover upstream spawning grounds.

Nature-Based Solutions (NBS) and Blue–Green Infrastructure (BGI) add value to bridge projects

- **Embedding biodiversity regeneration in day-one design**
  - Habitat continuity – specifying open-bottom arches or long-span girders avoids bed concrete and lets river substrate, insects, mammals and amphibians move freely.
  - Multi-layer planting palette on abutments (native grasses, shrubs, climbing plants) creates vertical habitat, pollinator forage and bat feeding corridors while filtering deck runoff.
  - "Green parapets" or planter-boxes integrated into the edge-girder collect runoff, provide nectar strips and visually soften the structure for surrounding residents.
  - Nature-inclusive details such as bat ledges, swift-bricks and otter shelves are inexpensive (< 0.1 % of bridge CAPEX) yet deliver measurable Biodiversity-Net-Gain units.
  - Flood-tolerant bridges and elevated causeways that allow for future sea-level rise or 1-in-100-year storm surges.
  - Permeable or "cool" pavements on roads to reduce surface runoff and urban-heat build-up, in line with the document's call to mainstream climate considerations into transport plans .
  - Micro-grids with rooftop solar and battery storage

- **Circular-economy synergies**
  - Vegetated scour protection uses locally won soil and brush instead of imported rock armour, reducing quarry extraction and haulage.
  - Living shorelines constructed from oyster-shell waste or decommissioned timber piles valorise by-products that would otherwise be land-filled.
  - NBS often allow lighter super-structures (lower design flood/scour loads) → less virgin steel and concrete → smaller embodied-ecological footprint.

- **Governance, metrics & monitoring**
  - Begin with a baseline habitat survey and apply the Biodiversity Net Gain metric (or local equivalent) to set uplift targets.
  - Link contractor payments to survival rate of plantings, scour-depth reduction and species-richness indicators collected by low-cost sensors and annual ecologist walk-overs.
  - Digital twins can host both structural-health and ecological-health layers, enabling adaptive management: if flow paths change or invasive species appear, planting mixes and flow-deflectors are updated rather than replaced.

Development

- Long-term goals and policies for bridge stormwater management are needed.
- All bridge projects must take into account stormwater source management BMPs that are appropriate for local conditions.
- A new design paradigm that minimizes negative impacts and maximizes positive impacts on planetary well-being.

A bridge is resilient when its environment is resilient.

- Leaching of hazardous substances from bridge structural components and elements into stormwater and the environment
  - Reducing stormwater load from bridge deck by draining stormwater safely away from the bridge deck without risk to water bodies and soil
  - Ensures that pollutants in stormwater do not end up in nearby ditches and rivers with rainwater.
  - Consider suitable treatment for stormwater at bridge embankments or near them
  - Consider functionality of current solutions
  - Cleanliness and anti-freeze protection of current solutions
  - Suitable diameter of the bridge stormwater pipe

- Transformation of the approach for infrastructure development with Nature-based solutions integrated in bridge projects

1. Considering ecological impacts from the earliest design stages.
   - Both at a site level and where your materials will be coming from **within the whole supply chain**.
   - Material choices have far-reaching consequences beyond just carbon emissions.
   - Material innovation: Working with suppliers to source materials with lower ecological impacts.
2. Implementing better monitoring and measurement of biodiversity impacts.
   - Biodiversity-sensitive design: Incorporating green corridors and native species into infrastructure projects.
   - Can BNG be applied to supply chains?
3. Developing innovative solutions that protect and enhance local ecosystems.
   - Even minor solutions on a broad scale would have an impact.
4. Collaborating across the industry to share best practices.
   - Circular economy principles: Maximising the reuse of materials and minimising waste.

Key Take-Aways

- **Nature-based solutions can transform a bridge** from a mono-functional structure into a climate-resilient, biodiversity-supporting, people-friendly public space—provided that **structural, hydraulic and operational necessities are integrated from day one**.
  - **Plan early**: allocate load allowance, maintenance access and right-of-way for green elements in concept design.
  - **Think hybrid**: combine vegetation with discreet hard details (rock toe, stainless wear plates) to survive ice, snowploughs and vandalism.
  - **Monitor smartly**: embed low-cost sensors for both structural and ecological performance—data justify the approach and trigger timely maintenance.
  - **Engage users**: interpretive signs, community planting days and cafés on ramps turn the bridge into a destination, not just infrastructure.

- Nature-based and blue–green measures turn storm-water management from a compliance cost into a multifunctional system that
  - protects the bridge against climate-driven extremes, especially for reducing landslide risk and managing stormwater
  - repairs legacy ecological damage, and
  - delivers net-positive biodiversity—while often **reducing** whole-life material, maintenance and carbon costs compared with all-grey solutions.

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Thank you!