ARUP

Designing for planetary boundary cities

Contact

For more information about our services at Arup or any information presented in this report, please contact:

e: sustainable.development@arup.com
e: foresight@arup.com

#PlanetaryBoundaryCities
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Please consider the planet when printing this document.

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Foreword

Johan Rockström
Director of the Potsdam Institute for Climate Impact Research and Professor in Earth system Science, University of Potsdam

Today, the scientific community is being forced to investigate a research question that we have managed to avoid until now: are we at risk of destabilising the entire planet?

Our task master is the unfettered pressures we humans are putting on the Earth system and the growing evidence that we are approaching points of no return. Crossing these 'tipping points' could irreversibly push our global commons, that bestow Earth with its resilience and thereby its capacity to remain in a Holocene-like inter-glacial state, out of the sweet-spot of planetary conditions.

These scientific insights have emerged in the ten years since the original 2009 publication of the planetary boundaries framework. Sure, the planetary boundaries framework was inspired by the advent of the Anthropocene and a deeper understanding of tipping elements in the Earth system, but it was clearly a pro-active attempt to provide humanity with scientifically-defined, quantitative targets for a safe operating space for humanity on Earth.

Since its first publication, and the 2015 scientific update, the framework has grown increasingly scientifically robust; not through academic tinkering, but through real-world observations. The ten year update of tipping elements in the Earth system, published at the end of 2019, showed that nine of the 15 known major biophysical tipping elements that contribute to regulating the state of the Earth system are on the move: They are showing signs of rapid change. Here are just two examples:

A very recent study showed how the Antarctic ice sheet – resting place of half the fresh water on the entire planet – has built in trigger points, beyond which ever-more melting would be 'locked in' for the future.[1] Letting global warming reach 2°C would trigger enough melting to raise sea levels by around 2.5m in the long term – that would put some the world's largest cities under water, not to mention large parts of densely-populated South East Asia, and low-lying island nations like Kiribati and the Maldives would be completely submerged.[2]

Scientists are also honing their understanding of how the natural defences of the Amazon rainforest will be whittled away by rising temperatures. In fact, latest results suggest that almost 1.5 million square kilometres (about the area of Spain, France and Germany combined) may cross a tipping point within the current century, beyond which tropical rainforest is replaced with less thickly-vegetated savannah.[3] The Amazon is integral to more than one of these life support systems: it's not just a 'big player' in the global water and carbon cycles, it also hosts one quarter of our planet's land-based species.

Whilst each of these examples paints a frightening picture on its own, the interconnectedness of these systems could trigger a cascade of such tipping episodes. In other words, we could be on the verge of pushing our entire Earth system – including the climate, natural ecosystems and biodiversity, and air and water quality – along a one-way track to a 'Hothouse Earth' state not seen in the past three million years, and definitely not since humans have walked the Earth.[4] It is truly beyond our current scientific knowledge if such a planet is habitable for humankind.

With such a dire prognosis, we need to place the planetary boundaries framework right at the centre of operationalising sustainable development in the depths of the Anthropocene. I sincerely welcome Arup's contribution with this report to this task, highlighting a heartening trend towards science-based decision making. Even more noteworthy is Arup's exemplary efforts to heed the planetary boundaries in their own projects, whether in the form of wood-based high-rise constructions or implementation of sustainable food systems. For me, the kinds of activities described here are a logical extension of the scientific work we started now over 10 years ago, without which the planetary boundaries framework would remain an academic concept, rather than a blueprint for turbulent times to come.

> "We need to place the planetary boundaries framework right at the centre of operationalising sustainable development in the depths of the Anthropocene."

Introduction

Humans are just one chapter in Earth's long history, part of an ever-evolving and complex system that has seen many life forms emerge and disappear. While the planet will continue to exist with or without us, our urgent challenge is to find a planetary balance that allows future generations to not only survive but thrive.

Over the past 10,000 years, in the geological epoch termed the Holocene, Earth's relatively stable climate allowed civilizations to flourish.[5] This relatively recent, narrow chapter of stability in the Earth's 4.5 billion-year climatic history allowed our ancestors to transition from nomadic tribes into stable, permanent settlements which have evolved into the cities and complex global economies of today.[6] Human behaviour is now threatening this balance, bringing about a new era with less climatic predictability which has been referred to as the Anthropocene: the period since the Industrial Revolution during which humans have had a significant impact on the Earth's geology, ecosystems and climatic stability.

If the Earth is to remain habitable for future generations, the critical Earth systems that support life must remain within healthy limits. The Planetary Boundary Framework (PBF) proposes science-based targets to define the limits of acceptable alteration to nine key Earth systems - encompassing Earth's physical, chemical, and biological processes. including biodiversity and climate change - effectively creating a 'planetary playing field' for future human development.

The form and function of urban development is fundamental to rebalancing the Earth system: while cities physically occupy just 3% of the Earth's surface, they are home to more than half the global population meaning they play an outsized role in environmental degradation and are responsible for 70% of carbon emissions.[7] Cities rely heavily on Earth's systems within and beyond their boundaries to support urban life: fertile soils enable food production; rivers, lakes and oceans enable transport and provide core resources; forests regulate and purify water supplies while protecting against flooding; and nature broadly provides a space for leisure and wonderment fundamental to human wellbeing.

As the primary resource sink and emissions source, transitioning toward regenerative practices in cities can have cascading benefits locally, regionally, and globally.

We believe there are opportunities to foster change. By understanding the thresholds set out in the PBF, and how the built environment contributes to them, we can implement actions that drive meaningful change. The planetary boundaries provide us with 'guard rails,' creating an opportunity to transform the way we design cities, so that future urban development works with nature rather than against it. This means improving air quality and soil health, creating carbon sinks and circular resource flows, fostering biodiversity and conserving water. Only then can we secure the lasting health of the habitat we all depend on, our planet Earth.

This report introduces the nine Earth system processes of the PBF, describing their importance; the drivers of degradation; the enablers of regeneration; and the actions that cities can take to bring us back into a safe operating space.

3%

of Earth's surface is occupied by cities.[8]

70%

of global CO_2 emissions are produced by cities.[9]

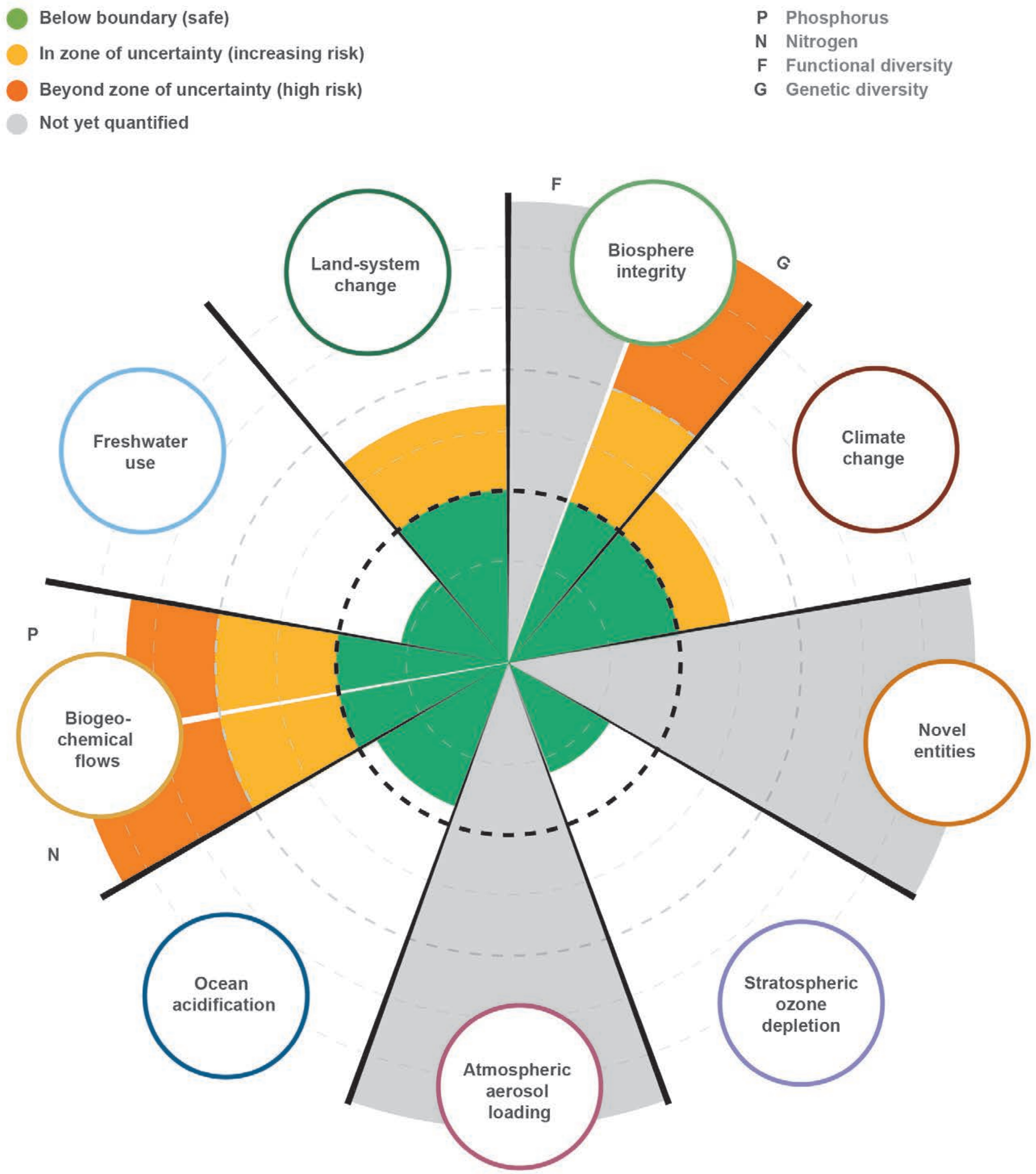


Figure 1
Planetary boundary framework

This diagram represents the status of seven Earth system processes relative to their planetary boundary (black dotted line). Processes for which global boundaries cannot yet be quantified do not display a status.[11]

What are the planetary boundaries?

The science based targets that humanity must respect to avoid the risk of catastrophic environmental change at the global scale.

An Earth system describes the planet's interacting biological, physical and chemical processes. It shows how the planet's natural cycles are deeply intertwined. Changes to one part of the system have a cascading impact on the others.

The planetary boundaries Framework was developed by a team of Earth systems scientists at the Stockholm Resilience Centre to characterise the limits of acceptable alteration to nine key Earth systems: biosphere integrity, climate change, ocean acidification, freshwater use, atmospheric aerosol loading, the introduction of novel entities, biogeochemical flows, land-system change, and stratospheric ozone depletion.

Each Earth system process has a threshold – the point at which the functioning of the system crosses a specific boundary and 'transitions.' Traversing this threshold will set in motion larger, possibly catastrophic effects through system collapse or compounding feedbacks. The complexities of these systems and intrinsic uncertainties can make thresholds difficult to identify. Consequently, the PBF as illustrated in figure 1, identifies a safe operating space (green), a zone of uncertainty (yellow), and a danger zone (red), representing the high, or low, risk of impact. To date, we have surpassed the thresholds or are operating in the zone of uncertainty for four of the nine planetary boundaries: climate change, loss of biosphere integrity, land-system change ad biogeochemical flows. Two of the planetary boundaries, introduction to novel entities and atmospheric aerosol loading do not have set boundaries.

The nine boundaries are not of equal standing; climate change and biosphere integrity are recognised as 'core' boundaries through which all others operate, meaning each, individually, has the potential to drive the Earth system into a new state should they be substantially and persistently transgressed.[10] The proposed boundaries are rough first order estimates about the nature of the biophysical thresholds; current estimates are conservative and may underestimate some of the systemic risks.

We are the first generation with sufficient data and computing power to begin to understand and articulate what has been happening to our planet as a result of our collective behaviour. These insights are key in determining how we start to modify those actions to ensure a healthy and liveable planet for future generations.

How do the boundaries interact?

A holistic understanding of the PBF and the interactions between boundaries is important to ensure that regeneration occurs across the entirety of the Earth system.

The PBF considers these nine Earth system processes in unison, recognising and highlighting their interdependencies as seen in figure 2; crossing one boundary may cause other boundaries to be transgressed, or set positive and feedback loops in motion. For example, the warming effects of climate change cause land-system changes that reduce CO_2 sequestration, further exacerbating climate change impacts. Other changes can improve the state of boundaries; for example, an increase in certain types of atmospheric aerosols causes more of the sun's energy to be reflected, thus mitigating warming effects associated with climate change.

Understanding the interactions is important to highlight the synergies that exist between boundaries and to determine which areas might act as leverage points for action, where one intervention will positively impact multiple parts of the Earth system. This systemic understanding also allows us to acknowledge the trade-offs that exist.

Individually the planetary boundaries are defined and quantified, yet they are highly interdependent and together form a complex system of systems.

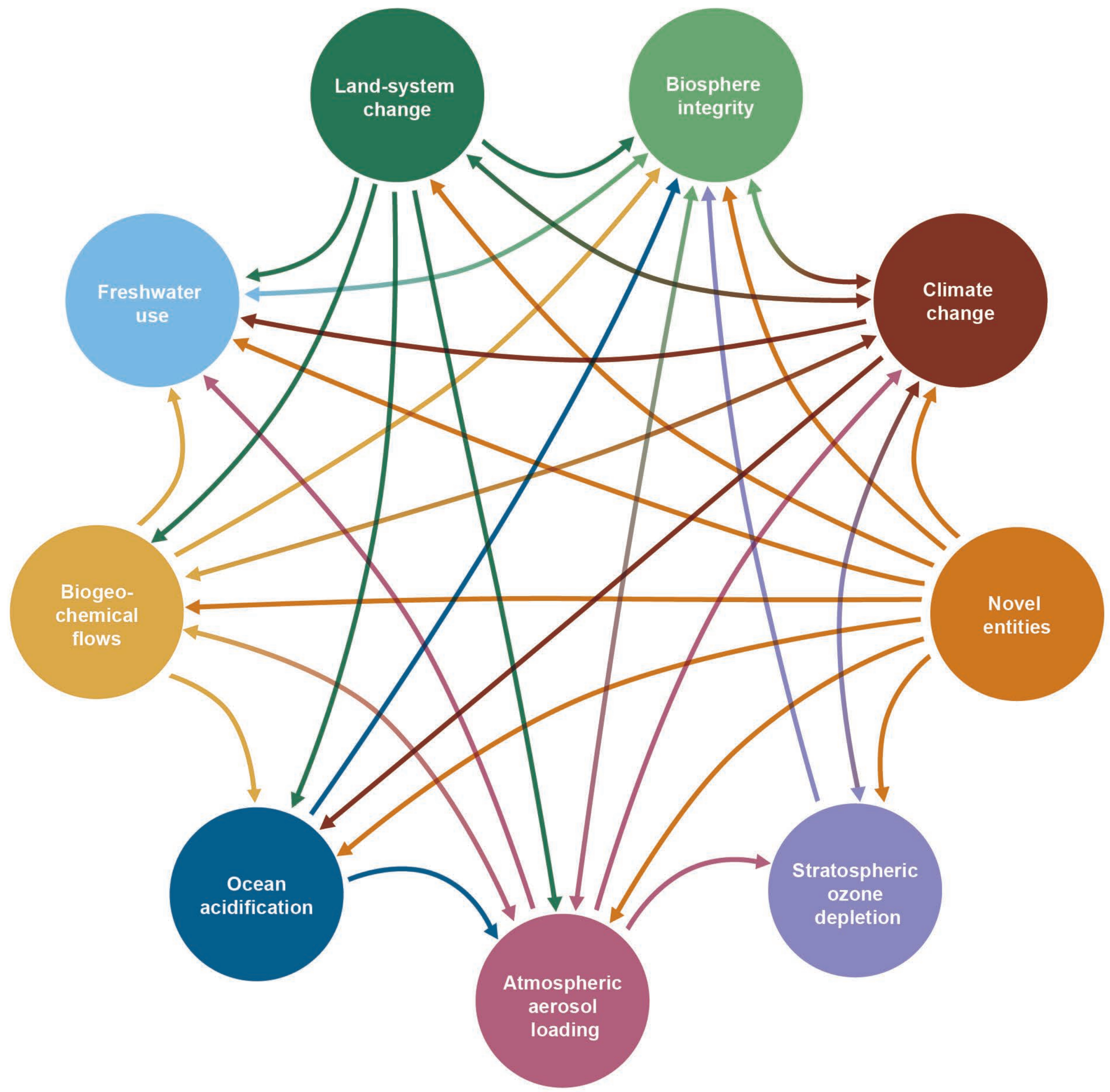


Figure 2
Planetary boundary interactions

This diagram represents the interactions between each of the nine planetary boundaries.

Loss of Biosphere Integrity

The Earth's biosphere is home to all living organisms; it regulates the climate, filters pollution, and acts as a sink for CO_2. It is the original source of services and materials that our civilisation depends on, including oxygen, fresh water, soil, food, raw materials, and medicinal resources. Biosphere integrity refers to the Earth's biodiversity (the variety of life at genetic, species and ecosystem levels) and the functioning of the Earth system in its entirety. Excessive biodiversity loss can cause ecosystems to degrade and undergo abrupt changes to their structure and functioning.[1] This boundary has two sub-boundaries: functional and genetic diversity. We have exceeded the boundary for genetic diversity and are in the zone of uncertainty for functional diversity.

Biosphere integrity

Why is this boundary important?

The biosphere regulates material and energy flows in the Earth system and increases its resilience to abrupt and gradual change, underpinning environmental conditions for all flora and fauna.

Change in the biosphere is accelerating

Species interactions have driven a continual yet gradual co-evolution over millions of years, leading to increasingly complex life forms and relationships within the interconnected system – a diversification that underpins stability.[2] Changes in biodiversity due to our activities have been more rapid in the past 50 years than any time in our history.[3]

Functional diversity is integral to ecosystem service provision

Functional diversity refers to an ecosystem's capacity to provide life-supporting functions such as water cycling, soil formation, carbon capture, nutrient cycling and crop pollination based on a variety of species traits. Higher functional diversity has been linked to greater plant growth, drought resilience, crop yields, control of agricultural pests by natural enemies, and resistance to invasion from non-native species.[4]

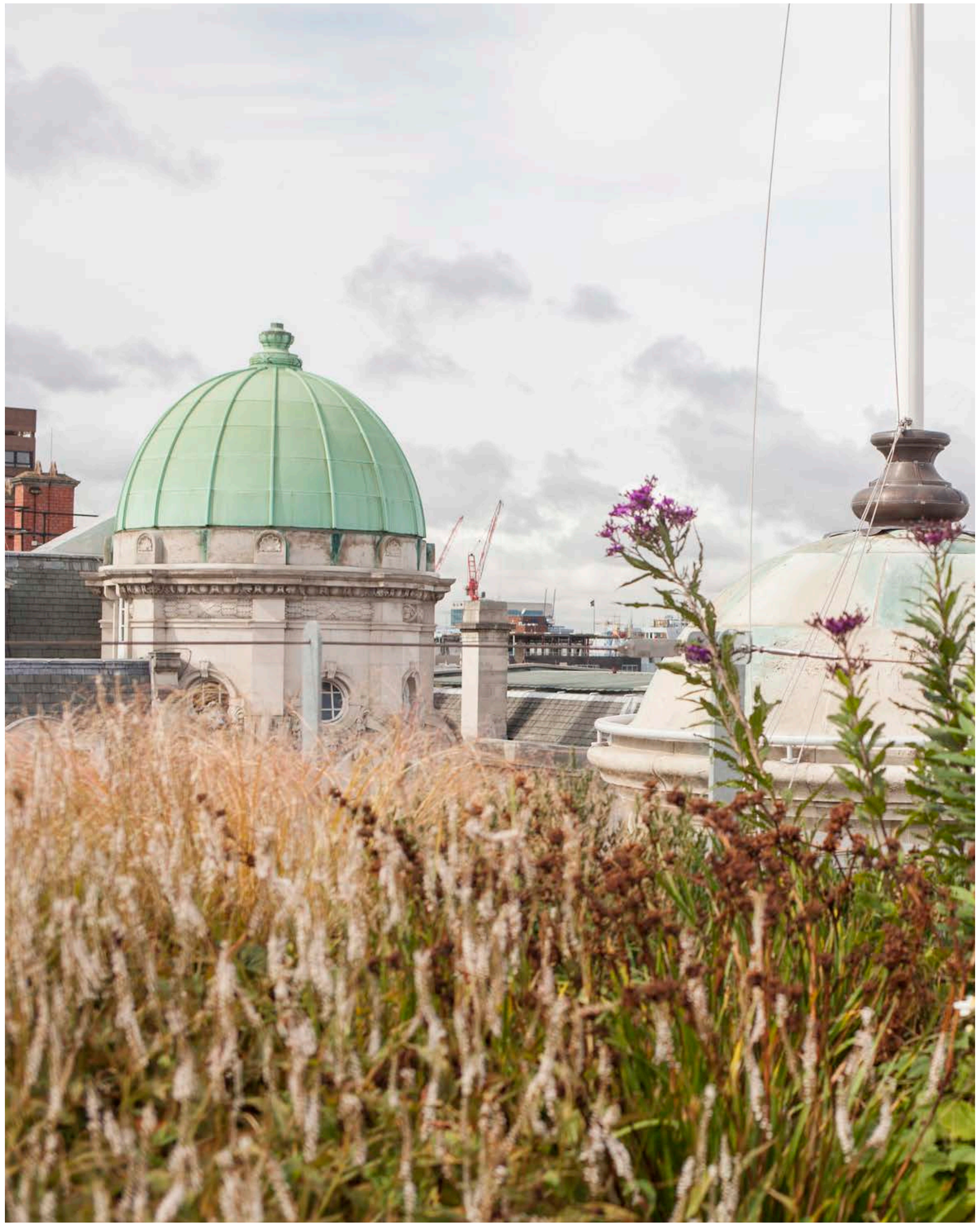
Genetic diversity improves resilience to change

The variety of genetic characteristics within a population contributes to an ecosystem's long-term capacity to cope with shocks and to adapt to change.[5] This is of particular concern with increased extreme weather events linked to longer-term systematic changes in the climate.[6]

3.6 million
hectares of old growth rainforest were lost in 2018, an area the size of Belgium.[7]

1 million
animal and plant species are currently threatened with extinction.[8]

75%
of the world's food comes from just twelve plant and five animal species.[9]



+ Exemplar
The Crown Estate's London Ecological Corridor, Arup

The Crown Estate's central London Ecology Masterplan was launched in 2015, with a goal of increasing green space, biodiversity and people's interactions with nature in London's West End. The masterplan recommends a mix of native, non-native and drought-tolerant species that support increased biodiversity, for example by providing nectar, seeds or berries. The developments also deliver a range of ecosystem services including slowing stormwater runoff and reducing the urban heat island effect.[10] The project has resulted in an increase in green space in the study area of over 7,000% from the 2012/13 baseline.

What is driving degradation?

- Visible impact
Water Hyacinth invasion
in South Africa

The water hyacinth, native to the Amazon basin, was first introduced to South Africa in the 1900s and has wreaked havoc on ecosystems in the region due to its invasive nature.[11] It grows in thick mats on water bodies, supressing aquatic biodiversity, aggravating flooding through the obstruction of river flows, and interfering with water navigation, irrigation, and hydropower.[12] It uses a significant amount of water, further straining South Africa's limited supply.

Biosphere degradation has been a consequence of human development, directly and indirectly, since the advent of civilization and place-based agriculture.

Climate change

As global temperatures rise, plants and animals are forced to shift their ranges northward in latitude or upward in elevation.[13] Some mobile species may adapt, but others will be forced into extinction.[14] The effects on species are often indirect; changes in temperature and rainfall patterns can confound the signals that trigger seasonal events such as migration and reproduction.[15] Climate change can also affect the development of organisms. For example, sea turtles are subject to temperature-dependent sex determination.[16]

Habitat loss and decline

Three-quarters of the land-based environment and about two-thirds of the marine environment have been significantly altered by human activities.[17] Common causes are unsustainable agriculture, logging, transportation, residential or commercial development, energy production and mining.[18] Tropical forests, which support at least two thirds of the world's species, are particularly vulnerable.[19]

Industrial agriculture and monoculture

Seventy five per cent of the world's food comes from just 12 plant and five animal species despite the more than 300,000 known edible plants.[20] For example, the Cavendish banana accounts for 99.9% of all bananas eaten globally, but it can no longer reproduce naturally and therefore requires cloning.[21] This reduction in genetic variety leaves the food supply vulnerable to disease and pests, and reduces the resilience of food production systems to increasingly erratic weather.[22]

Invasive species and disease

Since 1980, records of invasive species have increased by 40%.[23] These newcomers can devastate ecosystems that have not developed natural defences against them and can push endemic species into extinction. Similarly, diseases transported by humans not previously present in the environment can devastate populations.

Overexploitation

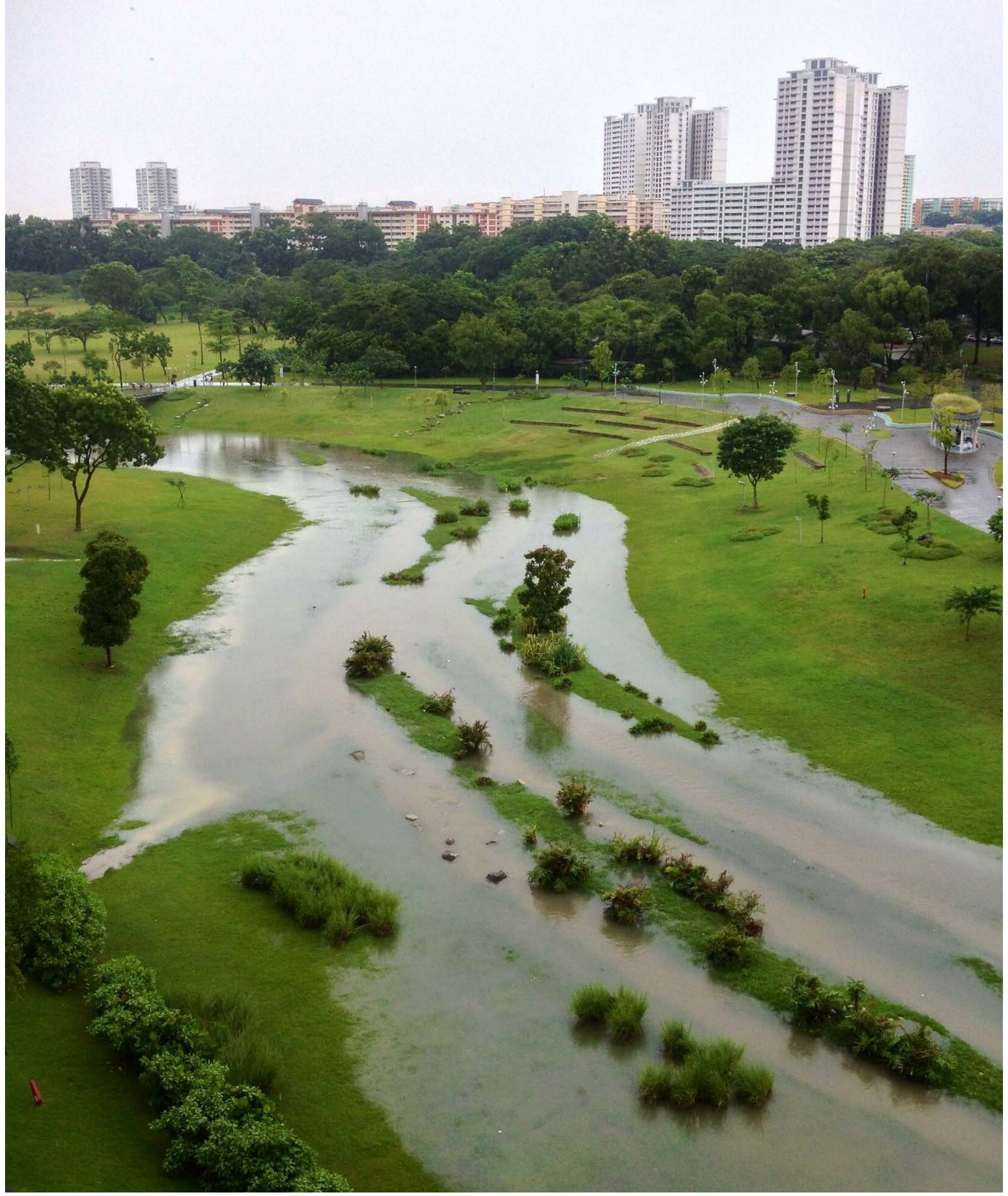
When species are harvested from the wild at rates faster than natural populations can reproduce, the total population declines. If unchecked, overexploitation of a species can lead to extinction. Around 60 billion tonnes of renewable and non-renewable resources are extracted annually, i.e. timber and oil; a doubling since 1980.[24]

Pollution

Pollution can have a direct effect on species' survival by interfering with physiological processes or making habitats unsuitable. Indirectly, it can impact biodiversity by altering food availability and reproductive performance, shifting population structures over time.

- Visible impact
Overexploitation of the
Pacific bluefin tuna

Unsustainable fishing practices drove the Pacific bluefin tuna population to just 2.6% of its unfished level in 2014.[25] Despite the imposition of catch limits, further population recovery has been hindered as juveniles that had never reproduced constituted more than 90% of the 2014 catch.[26]



+ Exemplar
Singapore's urban waterway regeneration

In Bishan-Ang Mo Kio Park, a concrete-sided canal was diverted through a public park and converted into a naturalised, meandering river. No wildlife was introduced to the park, yet biodiversity increased by 30%; a total of 66 species of wildflower, 59 species of birds and 22 species of dragonfly have been identified since the project began. The park is part of the Active, Beautiful, Clean Waters (ABC Waters) initiative that integrates 8,000 km of waterways and 17 reservoirs into the city's fabric, improving and connecting habitats to allow for diverse, resilient wildlife populations. The naturalised waterways also improve flood resilience, capture carbon, and filter pollutants, improving habitability for all.[27]

Biosphere integrity

How is the built environment contributing to degradation?

Urban sprawl fragments habitats
Fragmentation occurs when urban areas and infrastructure cross through continuous habitat, creating physical barriers to species movement. Entire ecosystems can become isolated, leaving species marooned on what are essentially 'islands' where they are prone to reduced genetic diversity and the harmful effects of inbreeding. Isolated species often become endangered or locally extinct.

Urban development destroys biodiversity hotspots
Urban expansion has tended to occur in low-elevation coastal zones and floodplains, which are particularly biodiverse.[28] At least 423 large cities (those in which over 300,000 people reside) are in biodiversity hotspots with animal and plant species found virtually nowhere else in the world.[29] Loss of these biodiverse ecological buffers is responsible for disastrous flooding from seasonal monsoon rains in many cities of South Asia.[30]

Urban areas are favourable for invasive species
Invasive species tend to do particularly well in urban areas as they are more adaptable to high levels of disturbance than their native counterparts.[31] Humans import non-native plants and animals to cities for their ornamental and emotional values, drastically altering the composition of the remaining urban biological communities. Biodiversity intactness declines with the age of the city.[32]

Polluted waterways and soil cannot support life
Impermeable urban surfaces, such as concrete and asphalt, cannot absorb rainwater, contributing to stormwater flooding that carries pollutants and nutrients into waterways and the marine environment. Paired with insufficiently treated wastewater, illegal dumping, waste leaching and more, urban waterways are often too toxic to support aquatic life. Soil pollution from heavy metals and chemicals found in medicine and personal care products can alter soil biodiversity and cause disease and mortality.[33]

- Visible impact
Insect decline in Germany

Insects create the biological foundation for all terrestrial ecosystems. Between 1989 and 2016, the biomass of insects across Germany decreased by an average of 76%, despite an increase in protected areas.[34] The critical ecosystem services that they provide – nutrient cycling, pollination, seed dispersal, food for other species, maintenance of soil structure and more – cannot be replaced. On the global scale, between US$235 billion and US$577 billion in annual global crop output is threatened by pollinator loss.[35]

Biosphere integrity

What can enable regeneration?

Ecological interventions and coordinated land use strategies can restore biosphere integrity and support regeneration of this Earth system.

Value natural capital and ecosystem services

Incorporating the multiple values of ecosystem functions into economic incentives has been shown to bring about better ecological, economic and social outcomes. Improved understanding of ecosystem dynamics, modelling, and monitoring will allow for more accurate valuation of natural capital by both private and public entities.[36]

Improve connectivity of habitats

Policies and partnerships that facilitate sustainable collective action, such as protecting watersheds beyond city jurisdiction and ensuring the connectivity of ecosystems and habitat, are important. The Mesoamerican Biological Corridor, stretching from Mexico to Panama, links more than 650 small protected areas with a network of forest fragments along river banks and across pastures and fields.[37]

Restore degraded ecosystems

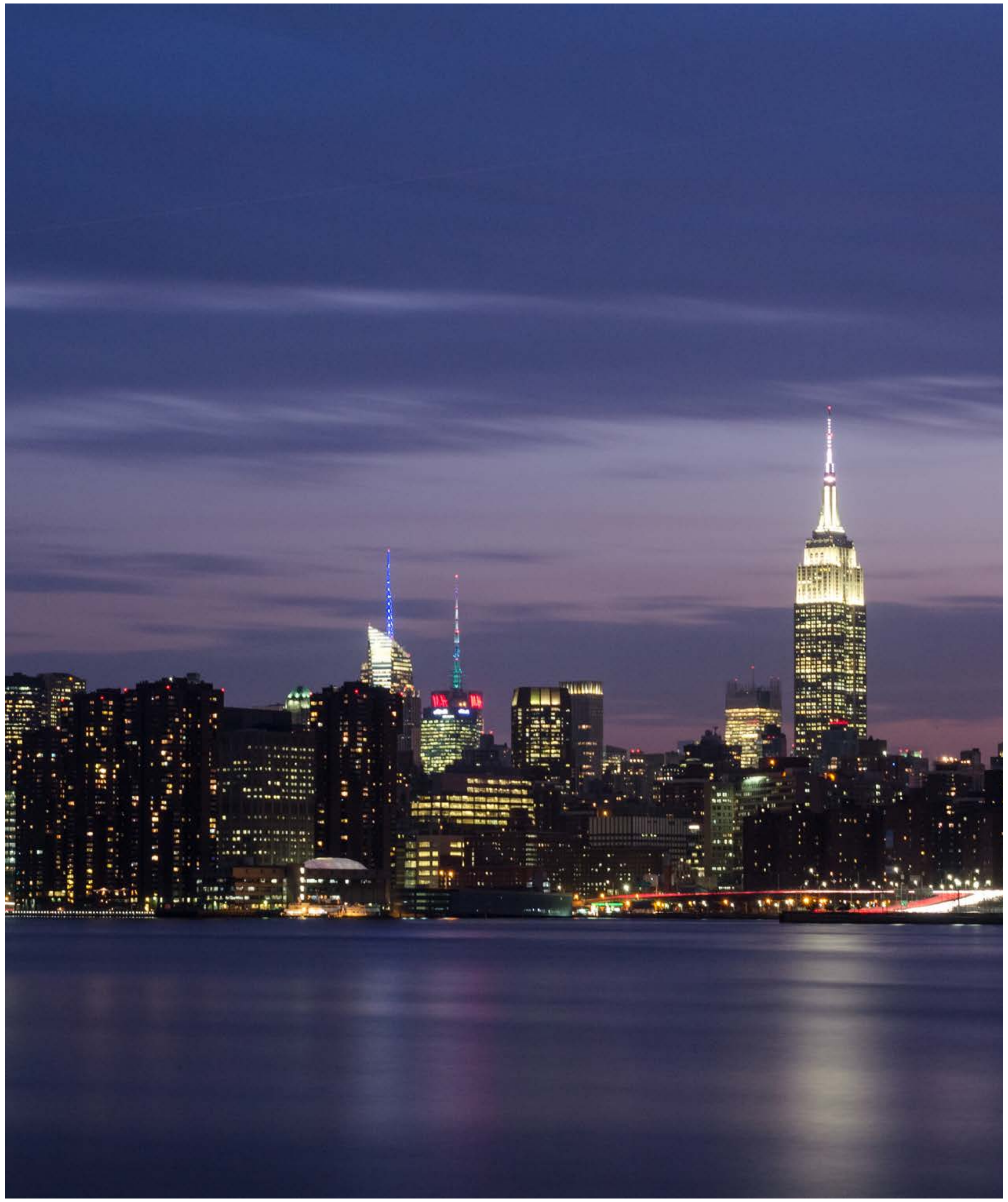
Given time, heavily impacted habitats can be restored through natural regeneration when human pressures are alleviated.[38] When ecosystems fall below a certain degradation threshold, more active restoration measures can be effective, such as invasive species removal, native species reintroduction, soil and watershed restoration, and controlled fires.[39]

Enable sustainable fisheries

For aquatic populations, actions must begin with conserving, restoring and sustainably using marine ecosystems. Rebuilding overfished stocks through targeted limits on catches based on measured sustainable yields could allow populations to regenerate.

Improve efficiency in existing converted land

Increasing the productivity of existing working land can help to reduce the need for further land conversion, protecting biodiversity, particularly in species rich biodiversity 'hotspots'. Ecologically grounded agricultural practices, including permaculture, integrated pest management, organic farming and agroforestry, are shown to increase the long-term productivity of land while protecting biodiversity.[40]



+ Exemplar
Billion oyster project

Oysters are ecosystem engineers, providing structured habitat for marine life and consuming algae and nitrogen to improve water quality. They also act as a storm surge buffer, attenuating wave energy to reduce damage inland. Following the extensive damage from hurricane Sandy, students and scientists came together to restore the native oyster population of New York Harbour that had been decimated by dredging, water pollution and overharvesting. To date, 47 million have been restored, 19 trillion gallons of water have been filtered, 72,500 pounds of nitrogen have been removed, and 1.3 million pounds of oyster shells have been reclaimed and recycled. The initiative aims to see 1 billion oysters in the harbour by 2035.[41]

Regenerative actions

The built environment can improve biosphere integrity and mitigate further degradation by maximising the quantity and quality of urban habitats; reducing the embodied ecological impacts in materials, food, and other products; and planning linear infrastructure to protect, restore, and connect habitats.

The prioritisation of native vegetation in green spaces can improve species intactness through appropriate habitat provision, yet habitats must be connected with interventions like wildlife corridors or highway crossings to support complex and diverse ecological communities. To prevent further degradation of peri-urban biodiversity, cities can manage sprawl by better utilising existing urban land. The delivering of these terrestrial solutions has direct co-benefits for cities, including water cycle regulation for greater resilience with regards to flood risk and water scarcity.

Aquatic biodiversity can be protected by improving water quality through the attenuation of contaminated runoff; the prevention of untreated sewage discharge; the reduction in water use; and the restoration of freshwater and coastal habitats. Healthy coastal ecosystems can serve as barriers against storm surge and other events. Natural infrastructure has a key role to play in the long-term viability and strength of resilient systems.

Using sustainably sourced and manufactured building materials can reduce the indirect impact of the built environment on biodiversity, thus mitigating embodied ecological consequences.

Further reading

Biodiversity Trend Cards

Climate Change

Climate change refers to long-term shifts in global weather patterns. Carbon Dioxide (CO_2) and other greenhouse gases (GHGs) alter the climate by trapping energy so that more heat enters the atmosphere than exits. This 'greenhouse effect' has caused a temperature increase of more than 1°C relative to preindustrial temperatures, which has largely been attributed to fossil fuels.[1] While Earth's climate has never been static, the current extent and rate of change is unprecedented in human history.

Along with biosphere integrity, climate change has been identified as a core boundary meaning it's transgression has colossal yet uncertain implications for every aspect of Earth system function.[2] The climate change boundary was crossed in 1990 when the concentration of CO_2 in the atmosphere exceeded 350 ppm.[3] Concentrations peaked for 2021 at 417 ppm.[4]

Climate change

Why is this boundary important?

Climate change has major consequences for all socio-ecological systems that evolved under the stable conditions of the Holocene climate, and has cascading effects on all other boundaries.

Higher temperatures increase weather intensity and variability

Warming has increased ocean temperatures, evaporation, and the water content of the air, fuelling the intensity of superstorms.[5] Meanwhile, rising sea levels exacerbate the damage caused by storm surges. Warming has also pushed the latitude of the peak intensity of typhoons poleward,[6] creating new risks further from the equator while decreasing water security in areas that rely on typhoons for their water supplies.

Extreme weather decreases food security

Where, when, and how crops are cultivated has been informed by relatively stable climatic patterns. Today, yields are threatened by extreme temperatures, declining average precipitation, and an increase in extreme rainfall events.[7]

Melting ice and warming oceans raise sea levels

Sea level rise is driven by melting glaciers, sea ice and thermal expansion of warming waters. If emissions continue at their current pace, global total seal level rise may exceed 2m by 2100, leading to the loss of 1.8 million km^2 of land, displacing up to 187 million people.[8] If waters rise and storm severity increases, opportunity for resettlement will be outpaced by need.

Higher temperatures expand disease ranges

The range of vector-borne diseases (viruses and bacteria carried by mosquitos, ticks and fleas) is expanding with warmer, wetter weather, rendering temperate populations vulnerable to tropical diseases.[9] Similarly, forests are increasingly prone to deadly infestations as climate change has allowed tree-killing pests to thrive and expand.[10]

Extreme weather and warming damage infrastructure

Damages from rising seas and storm surges are exacerbated by continued development of coastal areas which degrade natural defences.[11] Water bodies swollen by heavy, prolonged precipitation and melting of snowpack are overwhelming flood protection infrastructure designed for historical conditions. Record breaking temperatures and extreme weather are burdening electrical supplies and damaging transportation infrastructure.

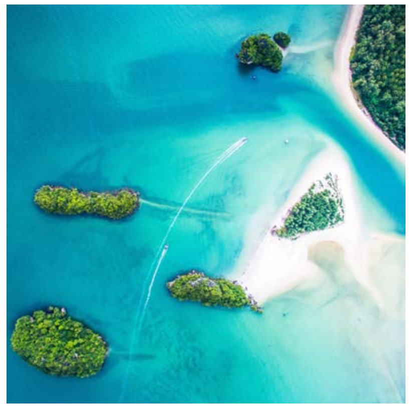
- Visible impact
Expanding range of bark beetle infestations

Bark beetles, which target trees weakened by prolonged drought and air pollution, have been devastating coniferous forests across North America and Europe that are experiencing lower rates of precipitation.[12] In 2018, 18 million cubic metres of spruce were infested by bark beetles in the Czech Republic, more than 10 times the rate seen in a typical year.[13]

+ Exemplar
Shenzhen Coastal Restoration

Fifty-one acres of coastal mangrove and tidal mudflats were restored in Shenzhen Bay, reestablishing local habitats and stabilising the city's shoreline against storm surge and erosion. Mangroves absorb eight times more CO_2 than any other ecosystem, with these stands capturing 848 tonnes per year. The restored vegetation also regulates temperatures for park users; temperatures rose on average 3.2°C from morning to afternoon while adjacent sites rose by 5.1°C on average during the same period.[14]

What is driving degradation?



- Visible impact
Rising seas and resettlement in Kiribati

The residents of Kiribati, a low-lying nation of islands and atolls in the central Pacific, are experiencing the effects of climate change. Incremental sea level rise and intensifying storm surges are causing extreme flooding and saltwater intrusion in the water supply. In 2016, 94% of Kiribati residents reported having been impacted by climate change, while 23% of migrants listed climate change as the reason for resettlement.[15] In preparation for impending forced migration, Kiribati purchased 13km^2 of land on a nearby, less exposed, Fijian island in 2014.[16]

The causes of climate change are well-established and are driven by elevated levels of CO_2 and other GHGs which trap the sun's energy in the atmosphere.

Greenhouse Gasses (GHGs)

Elevated levels of CO_2 and other GHGs drive climate change through the greenhouse effect, trapping the Sun's energy in the atmosphere. Sources include the combustion of fossil fuels and biomass, the release of stored carbon in biomass and soils through deforestation and land degradation, the release of nitrous oxides from fertiliser application, and the release of methane and CO_2 from the microbial activity of decay.

Change in albedo (reflectivity) of the Earth's surface and atmosphere

The reflectivity of the Earth's surface and atmosphere alters how much of the Sun's energy is absorbed or reflected; generally, lighter surfaces reflect and darker absorb. Common changes in albedo include loss of reflective ice, land-system change and atmospheric aerosol loading.

How is the built environment contributing to degradation?

Cities have an outsized contribution to GHG emissions

Covering less than 3% of the world's surface, cities house over half of the world's population, consume two thirds of the world's energy and account for more than 70% of CO_2 emissions.[17] Transportation, energy production, and buildings are the primary sources of these emissions.

Manmade materials create an 'urban heat island'

A warming phenomenon termed the 'urban heat island' effect occurs in cities due to the increased use of manmade materials, such as asphalt, cement and glass, that tend to absorb more solar radiation than vegetated land. Although dependent on a variety of interacting factors, a city of 1 million can experience annual mean air temperatures as much as 1–3°C warmer than the surrounding hinterland.[18] In the evening, the difference can be as high as 12°C.[19] Higher temperatures increase summertime peak energy demand due to air conditioning, further exacerbating cities' contribution to climate change.

Positive feedbacks in the climate system

We are approaching several system thresholds that, if surpassed, will trigger irreversible changes to Earth systems driven by intrinsic biogeophysical feedbacks.[20]

Loss of summer sea ice

Sea ice reflects the sun's rays, reducing heat absorbed by the Earth. When sea ice melts, less energy is reflected into the atmosphere, causing surface warming which drives more ice melting.

Permafrost thawing

The Arctic is warming twice as fast as the rest of the planet, causing carbon rich soil that has been frozen for tens or hundreds of thousands of years to thaw and release CO_2 and methane into the atmosphere, accelerating warming that drives further thawing.[21]

Weakening and reversal of carbon sinks

The weakening and reversal of carbon sinks, both terrestrial and aquatic, will accelerate the rise of atmospheric CO_2.

Forests
Forest loss causes the release of CO_2 stored in tree biomass; prevents future capture and storage; and increases local dryness. Rising temperatures are driving forest loss and CO_2 emissions by lengthening and intensifying the forest fire season and intensifying droughts. These in turn reduce tree survival and decrease their resilience to pests and disease that are expanding in range.[22]

Oceans
Oceans have absorbed 90% of excess heat trapped in the atmosphere by GHGs and 30% of CO_2 emitted since 1955.[23] Ocean phytoplankton (microalgae) absorb CO_2 and produce 70% of the world's oxygen, but they are vulnerable to waters that are warmer and more acidic.[24] A loss in phytoplankton productivity, paired with warmer waters that are less able to hold CO_2, are amplifying the effects of emissions. Outgassing of CO_2 has already been observed in the high-latitude Southern Ocean.[25]

- Visible impact
California wildfires

Rising temperatures are lengthening the forest fire seasons and expanding fire ranges globally. In arid areas, droughts and wildfires are intensifying, and dryland is expanding.[26] California has experienced 15 of the 20 largest fires in state history since 2000, with the 2017-18 seasons scorching a combined 14,725km^2. In 2019, the first climate change associated bankruptcy was filed by PG&E, California's largest electric utility, with the company facing an estimated US$30 billion in liability from the 2017 and 2018 wildfire seasons.[27]

Climate change

What can enable regeneration?

Reducing GHG emissions is key to brining atmospheric concentrations back into the safe operating space, yet GHGs must also be removed from the atmosphere through ecological restoration and engineered interventions.

Reduce the emission of GHGs

Fundamental to addressing climate change is radically reducing the emission of GHGs to mitigate further degradation of the climate system. This includes reducing the consumption of energy through conservation and efficiency, switching to clean sources of energy, reducing embodied carbon throughout supply chains, and designing out waste.

Protect and restore ecological systems

Protecting and restoring ecosystems to allow nature to do what it does best – sequester and store carbon, regulate weather, and enhance resilience – enables the regeneration of the climate system. Natural climate solutions, such as peatland restoration and regenerative agriculture, can provide up to 37% of global targeted decarbonisation.[28]

Remove carbon from the atmosphere with engineered interventions

The large-scale engineered removal of GHGs from the atmosphere, and their subsequent utilisation or storage, will be needed to address residual carbon. Solutions include direct air capture and utilisation of CO_2; enhanced terrestrial weathering to accelerate the natural formation of stable carbonate from atmospheric CO_2; and CO_2 mineralisation for storage and aggregate formation. Remove solutions will be necessary in reaching net-zero, yet their role should be mitigated as none have been fully evaluated across their lifecycle when applied at scale.

+ Exemplar
Modcell Prefab Straw Panels

The ModCell® system utilises the excellent thermal insulation qualities of straw and timber to create structural prefabricated panels. Their high performance reduces energy consumption associated with heating and cooling, while the materials capture and store carbon. Straw stores 60 times more carbon than is used to grow, bale, and transport to building sites in the same region, and provides a use for agricultural waste.[32,33]

20
of the warmest years on record have occurred since 1998, 19 of which were after 2001.[29]

20-25%
of agricultural incomes may be lost from drought in India's unirrigated farmland.[30]

37%
of global targeted emissions reductions can be provided by natural climate solutions.[31]

+ Exemplar
Zero Carbon Building (ZCB), Arup

Onsite renewable energy generation (solar PV and biodiesel tri-generation from waste cooking oil) covers all operational requirements for this sustainable technology demonstrator building. Surplus energy is exported to the grid to offset the embodied energy of construction and building materials (recycled materials and sustainable timber were prioritised). Passive design strategies, including a cross-ventilated layout, high-performance façade and daylighting, reduce energy consumption by 20%. Advanced HVAC systems achieve another 25% in energy savings. The property includes Hong Kong's first native urban woodland, which reduces the urban heat island effect, sequesters carbon, and increases biodiversity with 220 native trees of over 40 species and a diversity of shrubs.[34]

Regenerative actions

Cities, and the larger built environment, can reduce their outsized contribution to CO_2 emissions by radically reducing operational and embodied carbon across every aspect of the built environment, from mobility choices to material use. Integrating green spaces can provide benefits from capturing and storing CO_2 to reducing urban heat island effect and thus the energy demands associated with cooling.

Dense communities often have lower per capita emissions than sprawling areas due to more efficient energy, transportation, water, and waste systems.[35] Consequently, reducing sprawl and retrofitting urban environments for active transport can reduce reliance on fossil fuel-based systems, with further gains to be made through clean electrification and smart technologies that optimise supply and demand.

With regards to buildings, operational energy in both new build and retrofit can be improved with passive and clean heating, cooling, and ventilation systems; efficient and natural lighting strategies; optimised building envelopes; and efficient appliances.

Embodied carbon can be minimised by reducing virgin material use and opting for low carbon materials or circular economy processes. Through design considerations and innovation can improve performance and reduce material demand through increased efficiency. Essential materials must be optimised for carbon reductions in terms of their origin, extraction, processing, and end of life considerations. This includes material innovations such as low carbon concrete and strategies such as designing for reuse.[36]

Further reading

The Future of Urban Consumption in a 1.5°C World

Clean and renewable energy
Energy efficiency and conservation

Forest protection
Urban growth boundaries
Sustainable food sourcing
Sustainable materials
Circular material use
Computational design

Urban trees

Green roofs
Cool roofs
Wastewater treatment and recycling

Public and active mobility

Sustainable materials

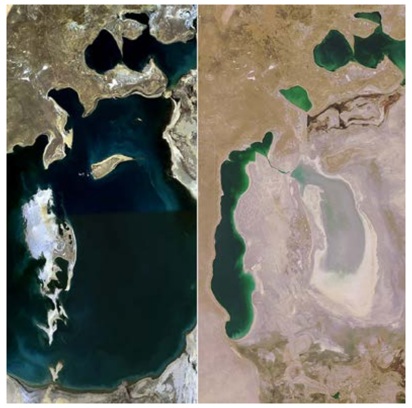
Wetlands and coastal habitats
Wildlife corridors
Rain gardens and bioswales

Freshwater use

Freshwater constitutes around 2.5% of the total volume of water on Earth, mostly stored in glaciers, ice caps or deep underground. Only one hundredth of 1% of all the water on Earth flows through the global water cycle every year.[1] This cycle delivers water to the Earth's surface through rain, sleet or snow and returns water to the atmosphere through transpiration (plants) or evaporation. Human activities also play a role; damming, irrigation, and diversion of water sources for human settlements in arid areas all increase the complexity of the water cycle.

Accessible freshwater is classified as 'blue' or 'green'. Blue water flows through rivers, lakes, and underground aquifers. Green water is stored in soil and plants.[2] Water flows between green and blue water stores, so impacts to one adversely affect the other.[3] The boundary for freshwater use is set to ensure ecosystem health while maintaining water security. Use has far surpassed safe ecological limits in some catchments but remains well within a safe boundary in others; global boundary status is uncertain.

Why is this boundary important?



- Visible impact
The disappearing Aral Sea

In the early 1900's, the Aral Sea, straddling Kazakhstan and Uzbekistan, was the fourth largest inland lake in the world, providing vital resources to local communities. In 1918, the two major rivers feeding the lake were diverted to grow cotton; with no inflow to balance rapid evaporation caused by the arid climate, the lake began to shrink and increase in salinity. By 2007, it had lost 90% of its surface area, exposing a lake bed laden with chemicals and pesticides from intensive agriculture and salt.[4] The fishing industry collapsed, and toxic dust storms increased air pollution, damaging crops up to 1,000km away.[5] Similar agricultural diversions have caused Lake Chad to lose 90% of its surface area in 50 years.[6]

Where, when, and how water falls, flows, and pools on Earth's surface influences the climate system, species mobility, and social, institutional, and economic security. Globally, major water bodies are vanishing;[7] rivers no longer reach their terminus,[8] and underground aquifers are so depleted that the land above them is sinking.

Water is the foundation of civilization
Since ancient times, most civilizations have originated at a major freshwater source.[9] Mesopotamia's Tigris-Euphrates, Egypt's Nile, and China's Yellow and Yangtze rivers provided water for drinking and sanitation, fertile floodplains for agriculture, and abundant wildlife to allow society to develop. Today, clean, reliable water supplies are vital for agriculture, industry, and energy production, sanitation, hygiene, and daily survival.[10]

Freshwater systems harbour biodiversity
Freshwater systems, including wetlands, floodplains, and deltas, are among the most productive and biodiverse ecosystems on the Earth.[11] Rivers transport sediment to floodplains and deltas providing essential nutrients for life. Dams and hydropower plants hinder species movement and turn deltas arid, destroying habitat and ecosystem services.[12]

Food security is reliant on engineered water supplies
Nearly half of our food comes from the warm, arid parts of the planet that cannot sustain crops with rainwater.[13] Consequently, irrigation requires extensive pumping of groundwater and the damming and diversion of rivers.

Climate resilient groundwater is being depleted
An estimated 38% of irrigated land depends on groundwater globally.[14] As a result, 13 of the largest 37 aquifers in the world are classified as significantly stressed.[15] These underground stores have been a reliable source, impervious to the weather variability and evaporation experienced by surface water. China, India, Pakistan and the United States, the world's top irrigators, are pumping groundwater faster than it is being replenished, precipitously lowering the water level in crucial crop-producing areas.[16]

Water sources are disappearing
By 2050, global water demand is conservatively projected to increase by 55%, yet shifts in weather patterns brought about by climate change and land-system change are expected to exacerbate shortages.[17] Flow changes from land degradation and disappearing glaciers, pollution and unsustainable use is greatly increasingly the vulnerability of already strained resources.[18] The availability and quality of freshwater is closely tied to the world's forests. Approximately 75% of the accessible freshwater comes from forests, and 90% of the world's cities rely on forested watersheds for their water supply.[19]

Water quality is declining
In addition to the decline in available freshwater, the global quality of that which remains is deteriorating. An estimated 80% of all industrial and municipal wastewater is released to the environment without treatment, rendering much of our surface water and groundwater unusable with detrimental impacts on ecosystems.[20]

- Visible impact
Urban water shortages in Cape Town

In the summer of 2018, Cape Town, South Africa was on a countdown to 'day zero'; the day taps would run dry. An unprecedented third consecutive year of drought, brought about by a southward shift in precipitation patterns and unsustainable use, threatened to cut off water to the city's four million citizens.[21] The city was able to narrowly forestall 'day zero' by enacting a 90-day personal water quota of 50 litres per day.[22]

56%
of endemic fish species in the Mediterranean water basin are endangered, largely because of unsustainable water management.[23]

Looking forward
Projections suggest that population growth paired with climate change will cause 1 billion people to face year-round water shortages and over 3 billion to face seasonal shortages by 2050.[24] Without sustainable solutions, many water-stressed regions may experience collapses in food markets, famines and mass migrations.[25]

What is driving degradation?

- Visible impact
Tehran sinking from groundwater depletion

Home to about 15 million people, the Iranian capital, Tehran, is sinking. Satellite imagery has shown that parts of the city are falling by as much as 25 centimetres a year due to excessive groundwater depletion.[26] Large fissures, some measuring several kilometres in length and up to four metres wide and deep, have opened up in areas just beyond the city threatening transmission lines and railways.

Freshwater use is pervasive across all human activities, particularly agriculture, industry, and domestic use, which are driving the degradation of systems.

Agriculture, industry, and domestic use
Around 70% of global freshwater is used in agriculture, mostly for irrigation; 15% goes into energy production for industry; 10% is used domestically; and 5% is used in manufacturing processes.[27]

Disruption of water flows
Built infrastructure such as dams, reservoirs, canals, and aqueducts are used for energy production, irrigation, and water security and can have disruptive impacts on water systems. While securing water resources for one region, these projects divert or disrupt flows from other areas.[28]

How is the built environment contributing to degradation?

Concentrated urban water use causes local ecological strain
Although cities only account for about 10% of total freshwater use, their concentrated water use can severely strain local and regional water sources with ecological consequences.[29] This strain is exacerbated in heavily populated and arid cities. Indirectly, cities are responsible for far more freshwater use through demand for food, energy, and industrial products.

Non-porous surfaces prevent ground water recharge and contribute to contamination
The lack of porosity of urban surfaces, such as buildings and roads, prevents rainwater from recharging ground resources and eliminates green water stores. Rainwater instead causes flooding and enters waterways in the form of runoff and sewage that has collected pollutants, degrading the health of aquatic habitats.

Illegal wells deplete the water table beyond regulated amounts
Although most water authorities monitor groundwater extraction, municipal entities in expanding cities including Mexico City, São Paulo, Bangalore and Jakarta have not been able to manage the unregulated digging of wells that have caused land sinking.[30] Mexico City, built on a former lake bed, has experienced rates of subsidence of up to 40 cm per year due to water extraction, with consequences for infrastructure.[31]

+ Exemplar
Chongqing Water Basin Masterplan, Arup

Four decades of rapid development around the Liangtan River Basin of the Chongqing District have increased flood risk and greatly deteriorated local water quality and ecology. With plans to expand a city of 200,000 to 4 million people in the next 15 years, Arup was brought on to reintegrate a healthy water cycle with a masterplan that maximises the environment's capacity to balance ecological health and economic development. Bespoke digital tools were used to map land use and identify sustainable interventions that linked human activities and natural elements in an integrated and resilient approach.[32]

+ Exemplar
Aquifer recharge with stormwater

In 2006, Adelaide's water supply was highly stressed and increasingly saline due to over extraction. To address this, the city turned to urban stormwater harvesting in the form of Aquifer Storage Transfer and Recovery (ASTR). ASTR involves injecting stormwater that has been treated by being passed through a reed bed or wetland into an aquifer. The water is stored in darkened conditions for a prolonged period and becomes potable by natural processes. By, 2009 the city had established 20 wetlands for treatment of stormwater and twenty-two aquifer storage boreholes. Five million m^3 of stormwater was collected in the wet months, stored and then distributed in the dry months. Typical stormwater hazards are significantly reduced: suspended solids (77%), E. coli (65%), total nitrogen (65%), total phosphorous (76%), total lead (86%), and total zinc (81%).[33]

What can enable regeneration?

Closing consumption loops and employing smart, locally contextualised practices will support natural water cycling and enable sustainable integration with our anthropogenic systems.

Employ water-smart agricultural practices

Eighty-five per cent of irrigation is still done by flooding fields and furrows.[34] Sprinkler and drip irrigation can greatly reduce loss to evaporation, runoff, and use by non-crop plants. Subsurface irrigation can reach up to 95% water-use efficiency.[35] Drought-friendly crops and agricultural practices such as tree intercropping and agroforestry can reduce water demand.[36]

Maximise water conservation and efficiency in industry

Routine maintenance ensures losses from leaks are avoided while equipment upgrades and smart enabled systems can greatly reduce net use. For some industrial applications, it is possible to conserve water by reusing it for two or more cycles without pre-treatment.

Invest in water funds

Water funds are a proven investment mechanism in which downstream water users collaboratively compensate upstream land managers for forest restoration and improved management of agricultural land.[37] Fortifying the watershed regulates flows and reduces erosion and nutrient runoff, decreasing costs for water service providers.[38] More than 100 corporations have invested over US$38 million in water funds to date, but this is just scratching the surface of potential investments and solutions.

+ Exemplar
Center for Sustainable Landscapes (CSL) at Phipps Conservatory and Botanical Gardens

The CSL in Pittsburgh, USA, treats and reuses all water that is captured on site and facilitates water retention and capture through a green roof, lagoon, rain gardens, permeable surfaces and wetlands. Restorative and sustainable landscaping features native plants that provide habitat for wildlife and are irrigated using water collected on site. The building also generates all of its own energy and is passively heated and cooled. The CSL was designed as one of the world's greenest buildings and is the first building to achieve the Living Building Challenge SM, LEED® Platinum, and Sustainable Sites Initiative™ (SITES™) certification.[39]

Freshwater use

Regenerative actions

Global freshwater systems can be supported by embedding considerations about the local water cycle in the urban planning and design processes;[40] improving water efficiency and conservation; and selecting building materials and products with low water inputs.

Proactively managing or mimicking natural water processes with nature-based solutions, from catchments to buildings, can improve the resilience of water sources while minimising ecological impacts and reducing flood risk.[41] Central to this is supporting safe and natural drainage systems, supported by more engineered solutions when applicable.

From the building to the municipal and catchment scales, water efficiency and conservation must comprise the elimination of waste in transmission and use, and the recycling of grey- and blackwater at various scales of intervention, depending on water quality and system needs. Materials should be selected based on their low embodied water use, such as mycelium bricks, hempcrete, recycled concrete aggregate or recycled plastic tiles as this is essential to reducing net water use in the built environment.

Further reading

Design with Water

Urban growth boundaries

Green roofs

Sustainable materials

Computational design

Circular material use

Sustainable food sourcing

Forest protection

Urban trees

Water efficiency and conservation

Wastewater treatment and recycling

Wetlands and coastal habitats

Native landscaping

Rain gardens and bioswales

Wildlife corridors

Permeable pavements

Sustainable materials

Land-System Change

Land-system change is the conversion or destruction of natural vegetation for human use.[1] While land systems encompass all terrestrial biomes, the PBF primarily focuses on forests due to their outsized role in the regulation of the Earth's climate by cycling water, stabilising local temperatures, acting as a major carbon sink, and moderating regional and global weather patterns.[2] Land change occurs on a local scale, yet the aggregated impacts affect the climate and weather on a global scale.[3] For example, tropical deforestation is disrupting the movement of water in the atmosphere, triggering major shifts in precipitation patterns that may cause drought in India, China and the United States.[4] Our current position within the land system change boundary is within the zone of uncertainty.

Land-system change

Why is this boundary important?

- Visible impact
Decreased rainfall in deforested Borneo

Since the 1930's, the southeast Asian island of Borneo has lost around half of its forests to the production of palm oil and rubber, the export of hardwood, and agriculture.[5] Across the island, there is a strong relationship between forest loss and reductions in daily rainfall, with the most pronounced effects in the southeast region that has seen the most severe forest loss. Generally, watersheds on the island with more than 15% forest loss had more than a 15% reduction in rainfall.[6]

Healthy forest biomes regulate the water cycle and temperature, support most of the world's terrestrial biodiversity, and capture and store carbon.

Forests regulate the water cycle

Forests and soil quality play a critical role in the water cycle as they transfer water from the soil to the atmosphere from their leaves in the form of water vapour, forming clouds. These clouds carry moisture for hundreds to thousands of miles.[7] For example, reducing Amazonian forests to 40% of their potential tree cover would reduce rainfall in areas that are over 3,200 km away, while complete deforestation would reduce rainfall in the US Midwest.[8] During dry seasons, mature forests with deep roots maintain water cycling by accessing water deep in the soil column.[9] Deforestation leads to soil compaction, preventing groundwater recharge and accelerating runoff and flooding.[10]

Forests regulate temperature

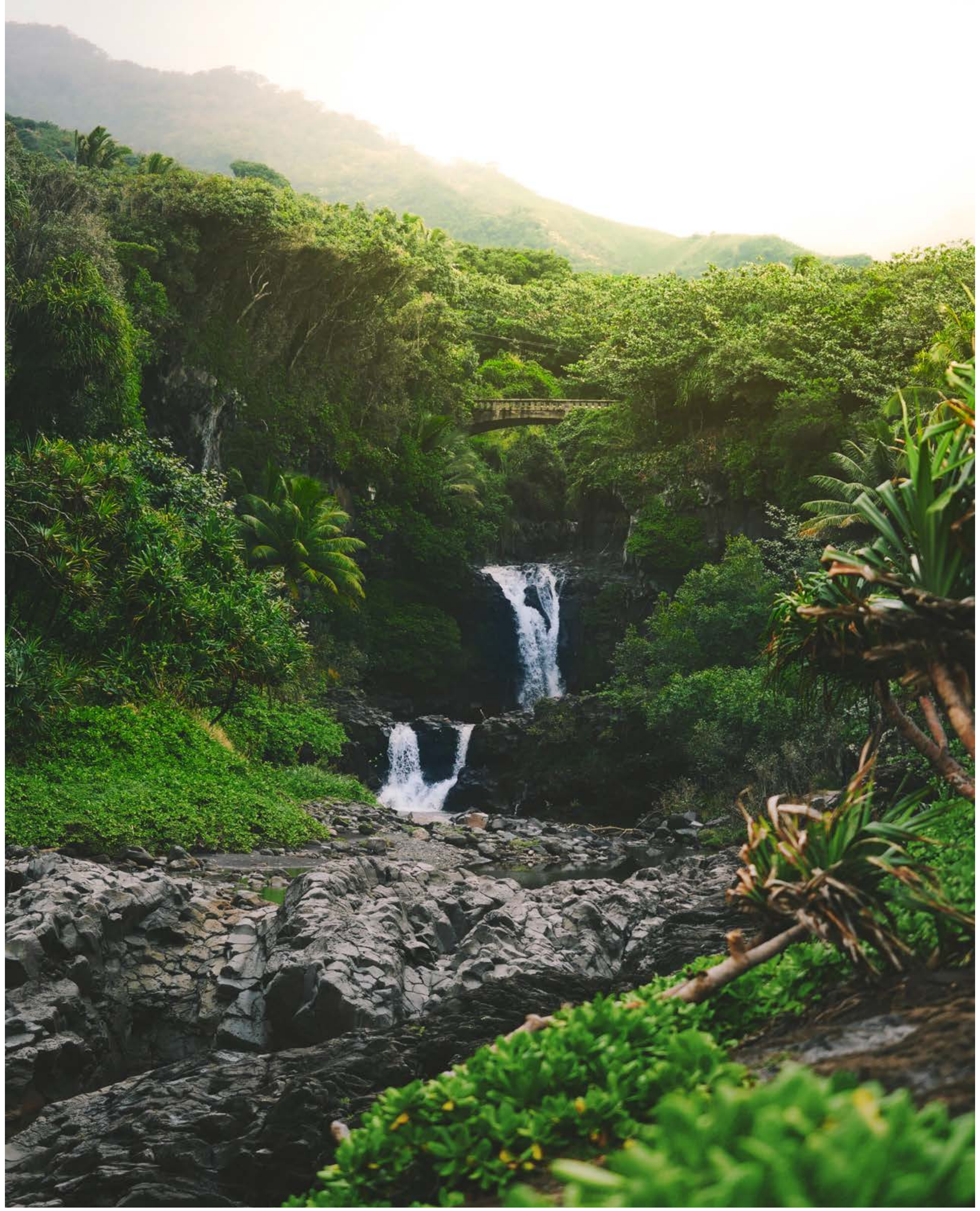
In tropical and temperate regions, forests cool the Earth's surface through the humidification of the air.[11] Loss of tree cover amplifies the variation between day and night temperatures and increases overall temperature, with the strongest effect in arid regions.[12]

Forests capture and store carbon

Forests absorb approximately a quarter of anthropogenic CO_2 emissions through photosynthesis and store large carbon pools.[13] When they are cleared and burned, CO_2 sequestration is halted and stored carbon is released back into the atmosphere, contributing to climate change.[14]

Forests support biodiversity

Forests house an outsized share of the Earth's species, with tropical, temperate, and boreal forests holding more than 80% of the world's terrestrial biodiversity, despite covering just 30% of the Earth's land area.



+ Exemplar
Costa Rica Payment for Ecosystem Services

Deforestation upstream of urban areas and hydropower plants threatened potable water and energy supplies. To improve security, Costa Rica developed a national Fund for Forest Financing in 1996. Between 1997 and 2017, more than 17,000 contracts were signed with landowners to carry out forest protection, restoration and agroforestry, with a focus on improving ecological connectivity through wildlife corridors. Between 1997 and 2016, nearly 1.2 million hectares of forest were protected or restored, increasing forest cover to 50% of the country's land area, from a low of just over 20% in the 1980s.[17]

What is driving degradation?

- Visible impact
Weakening South Asian monsoon

Forests produce much of their own rainfall through the release of water vapor, so their clearing can greatly reduce regional water security. The Indian summer monsoon rainfall, which accounts for 80% of annual rainfall in India, has weakened significantly since 1950 due to forest loss.[18] Scientists have attributed this trend, in part, to the reduction in water cycling performed by trees.

Forests are destroyed to meet human consumption and development demands, and are indirectly degraded through climate change.

Human land use and resource extraction

Between 2010 and 2015, 32 million hectares of old growth and recovering tropical forest were lost;[19] commercial large-scale agriculture and smallholder farming accounted for 40% and 33% of the loss respectively, while infrastructure, urbanisation, logging and mining were responsible for the rest.[20] Palm oil, beef and soy account for an outsized share of food-based forest clearing.[21]

Climate change

Climate change is altering the frequency and intensity of forest disturbances, including wildfires, storms, insect outbreaks, and the occurrence of invasive species.[22] Changes in temperature, rainfall and the amount of CO_2 in the air could affect forest productivity and regional survival.[23] Drought can reduce tree survival and decrease resilience to pests and diseases that are expanding in range with rising global temperatures.[24]

70%
of rainforests' precipitation can be generated by the rainforest itself.[25]

75%
of the Earth's accessible freshwater comes from forested watersheds.[26]

70kwh
of cooling equivalent is provided for every 100 litres of water cycled by a tree, equal to two household air conditioners[27]

How is the built environment contributing to degradation?

Urban sprawl fragments and degrades forests and other land uses

Although the conversion of forested land to agriculture far outpaces the spread of urban areas, rising populations and a surge toward cities has and will continue to expand urban land area, which is responsible for 10% of deforestation.[28] Historically, cities were compact with high population densities and slow growth of their physical extent. In the last 30 years, this trend has flipped and urban areas around the world are expanding on average twice as fast as their populations.[29]

Unsustainable timber products degrade forests

Illegal and unsustainable logging for timber building products contributes to global deforestation. Clearcutting of old growth natural forests is particularly harmful. On the other hand, plantation forests comprised of monocultures reduce forest resilience and soil carbon and are detrimental to biodiversity.[30]

Cities are sinks for resources that degrade forests in extraction

Steel for structures, metals and minerals for electronic products and energy resources can drive deforestation through mining.[31] Oil, gas, coal and mineral extraction threaten forests, accounting for an estimated 7% of global deforestation in the tropics and subtropics.[32] In the global north, oil transport infrastructure is degrading forests, with consequences being seen in the Canadian boreal and the Russian taiga.

- Visible impact
Fragmentation and reduced resilience in the Upper Xingu watershed

In 2011, the Amazon's Upper Xingu watershed, a forested region fragmented by agriculture with 92,000km of forest edge, lost over 10% tree cover to fire.[33] Forest clearing increased local surface temperatures, but it also degraded bordering forests that remained. Excessive heat and dryness kills trees along forest edges and facilitates grass invasion which can fuel large, intense fires. Paired with increased exposure to weather, these processes systematically erode forests inward from agricultural edges, multiplying loss from human deforestation.[34]

+ Exemplar
Community-based forest landscape restoration (CBFLR) in Nepal

In the late 1970s, the forested watershed in Nepal's Phewa Lake region was severely degraded due to deforestation and overgrazing. To address persistent erosion, landslides and lake sedimentation, the Nepalese government instigated a conservation and restoration programme that gradually shifted to a community-based effort. Between 1975 and 2015, dense forest cover increased by 82%, the lake turned from brown to blue, and landslides were greatly reduced. The success of this restoration has been largely attributed to strong community engagement and effective compensation for restoration.[35]

What can enable regeneration?

Recognising and protecting the intrinsic, intangible value of forests through policy and integrating the quantifiable values into economics and finance will enable large scale, coordinated regenerative land use strategies.

Protect natural, old growth forests

While reforestation is an important measure, it takes decades to centuries to replace the lost climate regulating and carbon storage functions, and even longer for biodiversity to reach pre-disturbance levels.[36] Consequently, it is critical that old growth forests and their irreplaceable services are protected.

Value forest services

Valuing forests' role in regulating temperature and water flows, and protecting biodiversity, in addition to capturing and storing carbon, could improve decision making in future land use and restoration initiatives.[37] Alternative financing to promote the value of forests and avoid their conversion for cash crops has been successfully implemented around the world.[38,39]
Water funds are a popular valuation mechanism, wherein stakeholders such as water authorities and hydropower operators invest in the protection and restoration of forested land upstream of the water supply.[40]

Improve the productivity of existing agricultural land

When forests are cleared for agricultural purposes, soil productivity declines driving further deforestation in search of better land.[41] Activities like agroforestry (trees grown among crops) can keep previously forested agricultural land healthy by maintaining some of the soil formation and preservation services provided by trees.[42]

Undertake greenbelt and 'green wall' initiatives

In some regions, vast stretches of trees are being planted to reverse desertification of agricultural dryland brought on by bad land practices and climate change. Initiatives range in scale, with the most ambitious spanning 8,000km and more than 20 countries.[43] Grassroots initiatives inspired by indigenous knowledge and respecting local conditions have been the most successful.[44]

+ Exemplar
Keyn Glas Green Ribs, Arup

As part of the enhancement scheme to restore the Cornish countryside led by Highways England, Arup designed green infrastructure corridors following valleys, emanating like ribs from the spine of the A30. The Green Ribs include nearly thirty bespoke and locally distinctive landscape interventions, including woodlands, grasslands, field boundaries, ponds, and orchards. These interventions work together to enhance biodiversity; improve water quality and mitigate runoff; and benefit local farms and communities. Phase 1 has delivered interventions across nine farms and connected 32 previously fragmented habitat areas, providing 97% to 242% net gains in biodiversity and absorbing around 10 tonnes of CO_2 annually.[45]

Land-system change

Regenerative actions

Forest protection and regeneration can be enabled through built environment actions like sustainable material sourcing, the prevention of urban sprawl, and the protection and restoration of local catchments.

Timber can serve as low carbon alternative to steel and concrete if sourced from sustainably managed, biodiverse plantation forests to avoid the degradation of old growth areas to maximise carbon sequestration. Similarly, mined products such as iron, limestone and rare earth minerals should be selected to avoid land degradation; principally, by utilising recycled materials. When appropriate, a number of fast-growing bio-based materials can be used as an alternative to timber, such as bamboo and hemp, which have lower ecological consequences and greater carbon sequestration potential.

The built environment can mitigate its direct contribution to land system change through urban growth boundaries by better utilising land already converted to prevent sprawl and avoid further degradation of land and forests. Similarly, transport and utilities infrastructure can be planned to avoid further degradation of high quality and forested land, especially old growth.

City governments and utilities can develop policies and directly invest in the protection and restoration of their local forested catchments to improve the provision of ecosystem services including improved water quality and seasonal flow resilience; reduced downstream flood risk; temperature regulation; improve biodiversity and deliver more cultural value.

Further reading

Rethinking Timber Buildings

Forest protection

Urban growth boundaries

Computational design

Sustainable food sourcing

Brownfield remediation

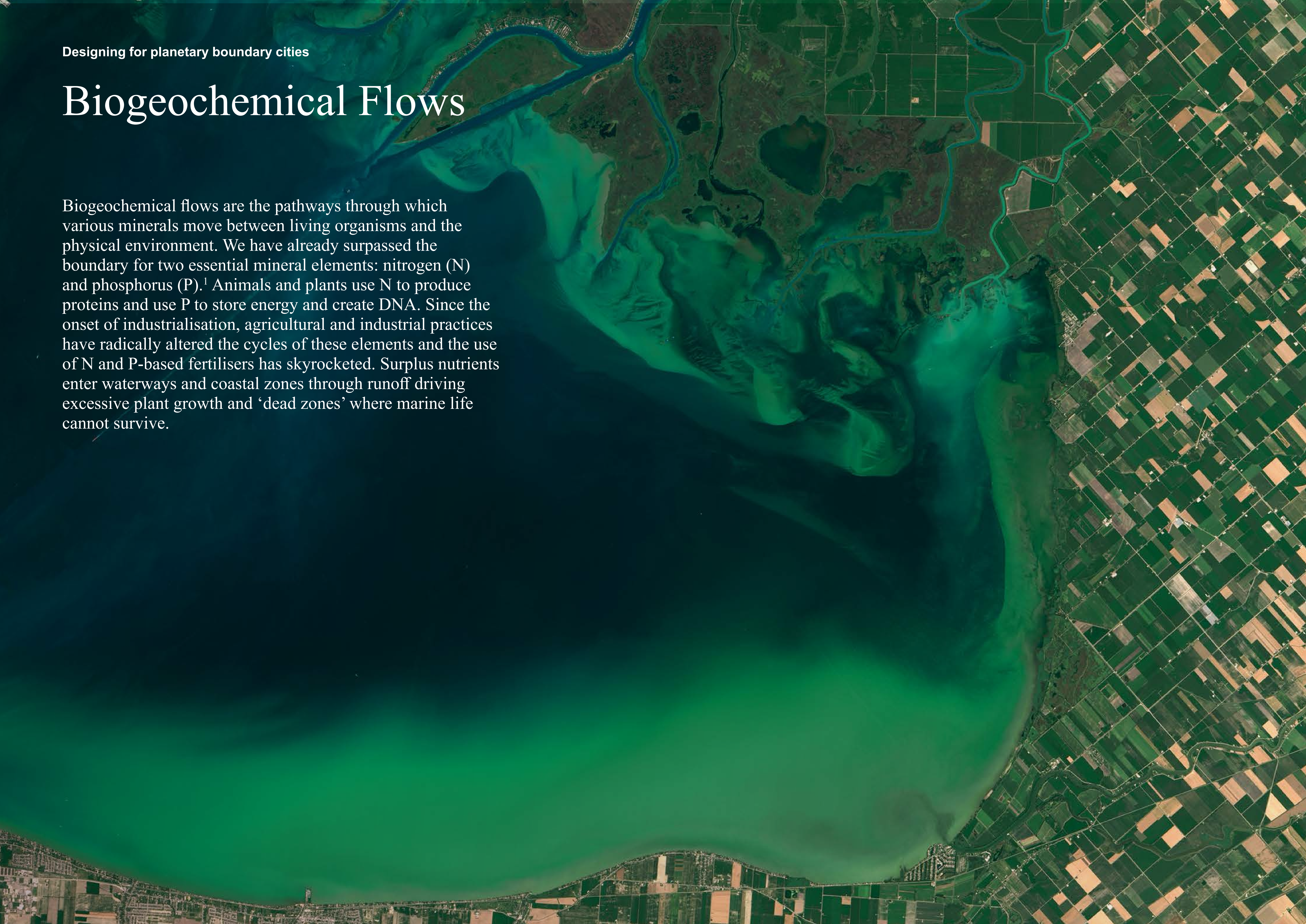
Wetlands and coastal habitats

Sustainable materials

Circular material use

Biogeochemical Flows

Biogeochemical flows are the pathways through which various minerals move between living organisms and the physical environment. We have already surpassed the boundary for two essential mineral elements: nitrogen (N) and phosphorus (P).[1] Animals and plants use N to produce proteins and use P to store energy and create DNA. Since the onset of industrialisation, agricultural and industrial practices have radically altered the cycles of these elements and the use of N and P-based fertilisers has skyrocketed. Surplus nutrients enter waterways and coastal zones through runoff driving excessive plant growth and 'dead zones' where marine life cannot survive.



Why is this boundary important?

- Visible impact
Gulf of Oman dead zone

The world's largest dead zone exists in the Gulf of Oman and encompasses nearly the entire 165,000km^2 body of water.[2] Since studies began in the 1990's, the dead zone has undergone a dramatic increase in both size and severity. High rates of nutrient runoff and warming waters have led to the extreme oxygen declines in the gulf.

N and P are essential nutrients for all life on Earth. Agricultural systems are dependent upon them, yet their overuse in the form of fertilisers degrades natural systems.

N and P are essential nutrients for all life

N and P are essential building blocks in the creation of the DNA of every cell on Earth, from plants and animals to microbes and algae. N is also a key element of protein, and P is needed for cell membranes, and skeletal formation. Due to their importance to life, nitrogen and phosphorous are typically in short supply in natural environments and are considered 'limiting nutrients' to growth.

Agriculture is dependent on non-renewable N and P inputs

To meet food demand and keep up with soil productivity, we extract P and N from the environment, and convert these nutrients into fertiliser for agriculture. Today, half the world's crops are grown with the aid of engineered fertilisers synthesised by capturing N from the air and mining P from rock stores.[3]

Excess N and P in aquatic ecosystems causes eutrophication

Nutrients enter aquatic ecosystems via the air, surface water or groundwater. Over-enrichment of nutrients in aquatic ecosystems causes eutrophication – the excessive growth of algae and phytoplankton. When these organisms die, CO_2 is released through their decay and consumption, and oxygen is used up.[4] Aquatic ecosystems are considered 'dead zones' when oxygen levels are too low to support respiring aquatic life. There are more than 400 major dead zones in the world's oceans, covering an area four times greater than in 1950.[5,6]

P supplies are limited

The current model of intensive nutrient extraction without recycling is unsustainable as global P rock stores, 90% of which are mined in just five countries, are becoming scarce.[7] At current consumption levels, it is estimated that there won't be enough phosphorous available to meet agricultural demand in 30 to 40 years.[8]

What is driving degradation?

Fertilisers and bio-waste, in the form of sewage, manure, and food, are the major drivers of eutrophic conditions. Nitrous oxides from fossil fuel combustion also play a role.

Agriculture (fertilisers and manure)

When applied in excess, agricultural fertilisers are transported by heavy rains and irrigation to surface and groundwater where they wreak havoc on ecosystems. Manure, particularly from concentrated livestock operations, is also a major source of nutrient pollution.

Industrial aquaculture

Fish and shrimp farms generate concentrated amounts of N and P from excrement, uneaten food, and other organic waste.

How is the built environment contributing to degradation?

Sewage discharge is a major pollution source

Sewage is laden with N and P from human waste and detergents, yet most wastewater treatment plants do not remove the nutrients before discharging the effluent into local waterways. Some regions of the world do not treat their sewage at all; globally, over 80% of all wastewater is discharged without treatment.[9]

Landscaping runoff contributes to eutrophication

Parks, lawns, gardens and other landscaped elements in urban areas are often heavily fertilised.[10] These nutrients enter the sewage system or enter waterways directly following rainfall or irrigation.

Fossil fuel combustion increases N pollution

N oxides are released into the atmosphere when fossil fuels are burned and enter waterways through rainfall and gravitational settling. Impervious surfaces in urban areas accumulate settled N which enters surface waters following precipitation. A quarter of N inputs in the Baltic Sea are attributed to nitrogen oxides.[11]

Cities are sinks for agricultural products

Cities drive demand for food, biofuels, cotton and other agricultural products, propelling the industrial application of nutrients in large-scale agricultural practices.

- Visible impact
Toxic algal blooms

Eutrophication is particularly harmful when there is a bloom of toxic algae; these 'red tide' events can kill aquatic organisms and cause illness in humans through shellfish poisoning and the contamination of drinking water.[12] In the spring of 1998, the most destructive harmful algal bloom to date wiped out more than 80% of the entire stock of Hong Kong's fish farms and resulted in an estimated economic loss of US$40 million.[13]

What can enable regeneration?

Closing cycles through reuse and biological attenuation of nutrients, as well as maximising efficiency in fertiliser application, ensures the health of ecologically sensitive areas.

Harvest and reuse nutrients in agriculture

Food waste, sludge from the paper industry, surplus grass and other N and P-laden waste products can be recycled to create nutrient rich soil. High recovery rates can be achieved through the use of wastewater and livestock manure as fertiliser. Wastewater is sometimes applied directly to crops in water and nutrient constrained regions, but this practice comes with health concerns.[14] Recovered N and P from urine can be turned into crystallised ammonium sulphate and used as a chemical fertiliser. Some techniques are able to recover up to 98%.[15]

Reduce nutrient runoff with nature-based solutions

Poor soil quality and bare land is highly susceptible to erosion and nutrient runoff. Perennials and cover crops planted between harvests keep soil and nutrients in place while aerating the soil sturture. Similarly, ecological infrastructure like riverbank vegetation and wetlands can reduce nutrient flows to surface waters.[16] Agricultural practices that protect and cultivate bacterial and fungal communities, including the avoidance of pesticides, herbicides and artifical fertilisers, are fundamental to maintaining soil quality.

Increase nutrient application efficiency

While efficiency has been on the rise with most of the world's resources, efficiency in the application of nitrogen has been declining.[17] Applying fertilisers in the right amount, at the right time of year, with the right method, can improve nutrient efficiency.

+ Exemplar
Living Machine onsite water reuse

At the headquarters of the Public Utilities Commission, nutrient rich blackwater is treated onsite with a Living Machine® system housed in a discrete planter box. Based on the principles of wetland ecology, bio-cells are alternately flooded and drained to create 'tidal cycles' that remove solid particles from the wastewater while microorganisms and plants in the tanks feed on the nutrients. treated water is reused in the building's toilets. The system recycles approximately 19m3of water per day, reducing the building's total water use by 65% and eliminating its contribution to municipal sewage.[21]

80 million
people that depend on fisheries for their livelihoods are vulnerable to the effects of eutrophication.[18]

> 400
major dead zones now exist in the world's oceans, covering an area four timesgreater than in 1950.[19]

>80%
of the entire stock of Hong Kong's fish farms was lost to a harmful algal bloom in 1998, a loss of US$40 million.[20]

+ Exemplar
Riyadh Bioremediation Facility

Riyadh treats 92.5 million gallons of wastewater per day using natural processes. One hundred and thirty-four bioremediation cells support primary producers (algae and plants) and consumer organisms (fish, birds, insects, etc.) that break down waste compounds. Stone barriers at the inlet and outlet of each cell alter flows to oxygenate the water, reducing coliform bacteria; 33% of phosphorous, 13.5% of nitrogen and 89% of fecal coliforms are removed during this passive process. Previously, untreated wastewater constituted a public health hazard and jeopardised the downstream Wadi Hanifa wetland. Now, the treated water is recycled to accommodate other urban functions, including a new city-wide river park system, and flows into the restored wetland.[22]

Biogeochemical flows

Regenerative actions

Urban infrastructure is a critical component in redirecting nutrient flows to balance areas of excess to areas of need to complete cycles. Sewage sludge, food, and yard waste can become a value add rather than a cost if appropriately managed.[23]

These nutrient inputs can be converted into biogas through anaerobic digestion, which produces a by-product called digestate. Digestate from food and yard waste can be applied as a fertilizer and/or soil amendment to improve soil health, reducing the need for chemical fertiliser. Nutrients can be safely extracted from sludge digestate for fertiliser use. The built environment has an opportunity to create local facilities to enable these circular nutrient flows.

In cities, strategically placed green infrastructure, such as raingardens, bioswales and wetlands, can reduce eutrophication by safely soaking up nutrients in runoff. Cities can reduce indirect nutrient pollution from agricultural imports through sustainable food sourcing and by scaling up local food production. Hydroponics and other production systems, when contained in controlled environments, tend to have high nutrient efficiency and little to no runoff.

Further reading

The Urban Bio-Loop

Atmospheric Aerosol Loading

Atmospheric aerosols are a complex mix of solid and liquid particles suspended in the air (diameters of 10^{-9} to 10^{-4}m),[1] often taking on the appearance of dust, smog, haze and fog. They interact with water vapor to interfere with atmospheric circulation, altering the intensity and duration of weather events,[2] and reflect and absorb solar radiation. Primary aerosols are emitted as particulate matter while secondary aerosols are formed in the atmosphere through chemical reactions of gases. Some aerosols are emitted naturally from volcanic eruptions, forest fires, ocean spray, desert dust storms and other processes, while others, such as smoke, soot, and various industrial chemicals, are emitted by humans and have led to unnaturally high aerosol concentrations in the atmosphere. While the global boundary has not been quantified, evidence from South Asia suggests we are within the zone of uncertainty.

Why is this boundary important?

- Visible impact
Impacts of air pollution on child health in India

India is home to 14 out of the 15 most polluted cities in the world. It was found that across the subcontinent, exposure to air pollution during the first trimester of pregnancy decreases both height-for-age (6.7%) and weight-for-age (7.8%) for children aged below five years.[3]

The quality and quantity of aerosols impacts atmospheric hydrology and air quality, impacting visibility, temperature and the overall health of flora and fauna.

Aerosols alter the formation of rain in clouds

During cloud formation, excess water vapour condenses on aerosol particles, essentially forming the building blocks for clouds. Increased concentrations of atmospheric aerosols can therefore disrupt the dynamics of cloud formation, and subsequent precipitation, as the amount of aerosol particles affects the number of water droplets within a cloud.[4] If there are more aerosols in a given area, the cloud droplets that are produced will be smaller as available water vapour is divided among more droplets. In this case, the clouds are less likely to produce precipitation.

Aerosols alter the Earth's temperature

Aerosols are the second largest contributor to climate change after greenhouse gases.[5] Through a process called radiative forcing, they directly alter how much solar radiation is reflected or absorbed in the atmosphere. While some aerosols reflect the sun's rays, others act as insulators, creating a net contribution to the warming of the Earth.[6]

Aerosols reduce air quality

At street level, aerosol pollution can have devastating effects on human health. The World Health Organization reports that ambient air pollution worldwide accounts for 29% of all lung cancer disease and death, 24% of all deaths from stroke, and 43% of all deaths from lung disease.[7]

14/15
of the most polluted cities in the world are in India, contributing to poor child health.[8]

43%
of all deaths from lung disease can be attributed to ambient air pollution.[9]

91%
of the world's population lived in places that did not meet WHO air quality guidelines in 2016.[10]

What is driving degradation?

Unnaturally high aerosol loading is driven by fuel combustion, wild and managed fires, and dust emissions from land exposed by vegetation loss.

Fossil fuel combustion and land-system change

Human activity has doubled the global concentration of most aerosols since pre-industrial times.[11] Direct anthropogenic sources come from biomass burning, the incomplete combustion of fossil fuels, and dust from transport, agriculture, and mining activity.[12] Humans have also increased the amount of aerosols emitted naturally; deforestation, overgrazing, drought, and excessive irrigation destabilise the soil and increase the rate at which dust and fire-associated aerosols enter the atmosphere.[13]

How is the built environment contributing to degradation?

Cities are major energy consumers due to heating, cooling, transport, and industry

Cities have significant energy demands for heating and cooling, transportation, and industrial production. When this energy comes from fossil fuels, it produces aerosol pollution.[14] Inefficient combustion of biomass and coal, resulting from rudimentary industrial activities and cookstoves, also contributes to particularly high rates of aerosol pollution in the least developed cities.[15]

Construction and demolition produce particulate matter

Construction dust emissions originate from onsite activities such as excavation, cutting and drilling, material transport and open-air storage, the movement of equipment and more.[16] The demolition process at a building's end of life is also a significant source of dust emissions.

- Visible impact
South Asian monsoon disruption

Aerosol loading over India may have increased the frequency of extreme rain events[17] and contributed to asymmetric rainfall patterns with drought in some places.[18] Black carbon over the Indian Ocean has been shown to warm the surrounding atmosphere and cause cloud droplets to evaporate, turning clouds into a smoky haze that suppresses rainfall.[19]

What can enable regeneration?

At landscape scale, aerosol emissions can be mitigated through vegetation management and agricultural practices that stabilise soils and prevent wildfires.

Improve land management to reduce ‘natural’ emissions

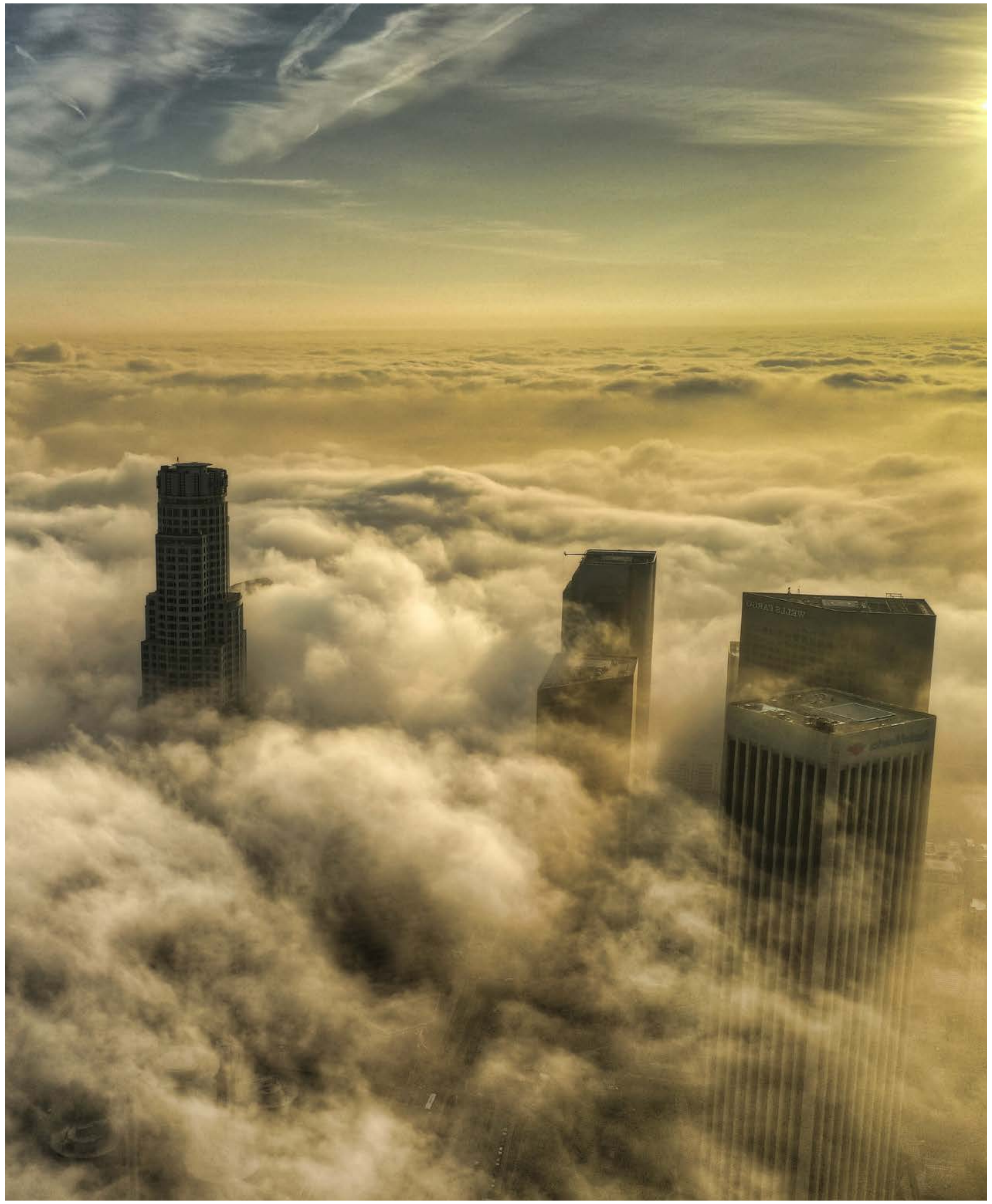
Reducing the risk of forest fires also lessens the effect of ‘natural’ atmospheric aerosols. Actions such as selective harvesting, thinning treatments, brush removal and pruning can reduce the risk of wildfires.[20] The Forest Resilience Bond, an innovative financing tool that raises private capital to fund such interventions, is one such approach. Capital for project implementation is provided by investors, and stakeholders that benefit financially from reduced fires reimburse the investors over time.[21]

Manage aerosols from agriculture

Practices that reduce dust and particulate matter from soil tillage and crop residue burning can help mitigate the aerosol emissions from the agriculture industry.[22] Likewise, managed fertiliser use can reduce agricultural emissions that react with other pollutants to make atmospheric aerosols.[23]

Exemplar
Automated Emissions Reduction (AER)

WattTime’s technology enables smart devices (thermostats, appliances, electric vehicles and more) to automatically reduce emissions associated with their electricity use. By controlling these flexible energy loads, AER optimises their operation to use energy when the grid is cleaner and avoid use when it is dirtier.[24]



+ Exemplar
Sustainable demolition process

To reduce the environmental concerns associated with tall building demolition (over 100m), Taisei corporation developed the Ecological Reproduction System that disassembles structures one floor-at-a-time, from the top down and inside out. A protective scaffolding ‘hat’ on the top three floors reduces dust and debris from entering the atmosphere, moving down as soon as two of the three covered floors are demolished. The careful disassembly process increases site safety and allows for material reuse, preventing aerosol pollution associated with extracting and producing new materials. The system also generates energy from the weight of the disassembled parts as they descend.[25]

Atmospheric aerosol loading

Regenerative actions

The built environment can reduce aerosol pollution by mitigating the major sources of particulate emissions including use of fossil fuel combustion for energy, transport, and industry, and minimising construction and demolition dust.

Clean or electrified heating and cooling, transport, cooking, and industry can reduce local emissions. Electricity generation must also be emissions free to avoid simply shifting the geography of aerosol loading. Clean and renewable energy generation (in addition to demand reduction) is fundamental to reducing net loading, yet intermediate actions can be taken during the infrastuture transformation to immediately reduce aerosol emissions such as retrofitting existing power plants with wet scrubbers that remove particulates at the source. In sectors that are challenging to electrify, hydrogen fuel can be used; the only aerosol emitted through its combustion is water, yet the hydrogen must be produced cleanly as well.

Dust emissions can be reduced during construction and demolition through controlled deconstruction (which supports component reuse), the use of protective screening, and the application of water for damping down. Vegetating temporarily vacant lots can reduce dust emissions and mitigate the urban heat island effect while supporting local biodiversity.

Further reading

Ideas for Clean Air: Copenhagen

Clean and renewable energy

Cool roofs

Green roofs

Urban trees

Forest protection

Energy efficiency and conservation

Sustainable materials

Computational design

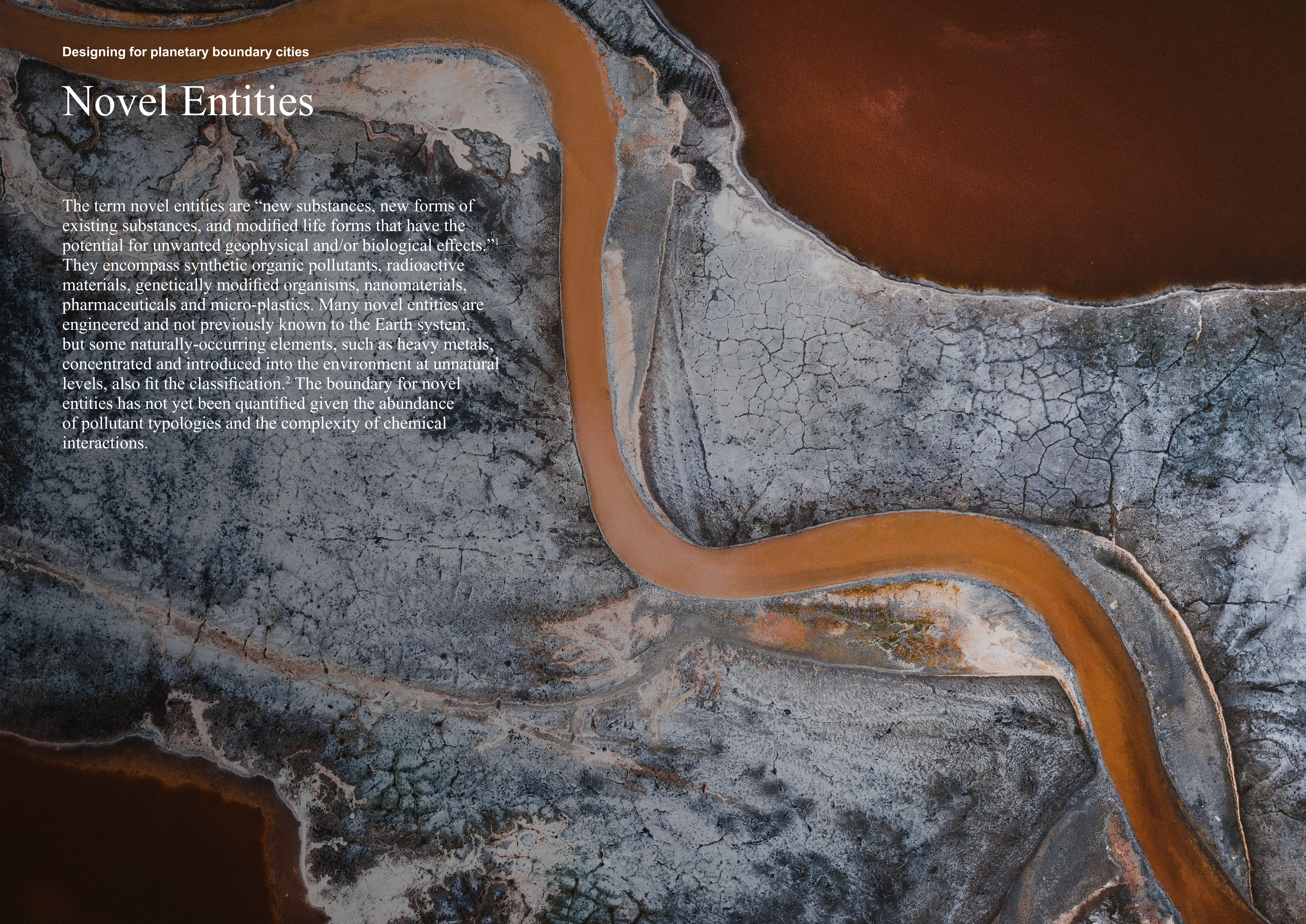
Circular material use

Brownfield remediation

Public and active mobility

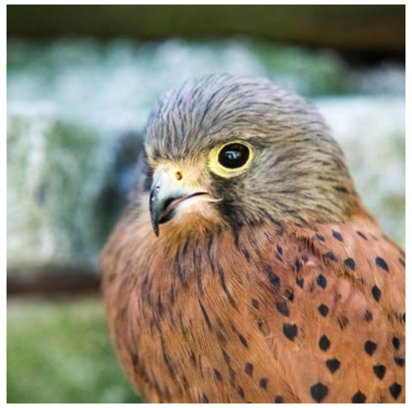
Novel Entities

The term novel entities are “new substances, new forms of existing substances, and modified life forms that have the potential for unwanted geophysical and/or biological effects.”[1] They encompass synthetic organic pollutants, radioactive materials, genetically modified organisms, nanomaterials, pharmaceuticals and micro-plastics. Many novel entities are engineered and not previously known to the Earth system, but some naturally-occurring elements, such as heavy metals, concentrated and introduced into the environment at unnatural levels, also fit the classification.[2] The boundary for novel entities has not yet been quantified given the abundance of pollutant typologies and the complexity of chemical interactions.



Novel entities

Why is this boundary important?



- Visible impact
DDT and bird shell thinning

Rachael Carson's 1962 book *Silent Spring* detailed the consequences of pesticide use for bird populations in the US. It was found that the pesticide DDT was decimating bird populations by altering their calcium metabolism, causing eggshells to thin and crack under the weight of nesting mothers. The North American brown pelican population was nearly eradicated, and bald eagles, peregrine falcons and ospreys saw significant declines. While DDT use was banned in the US in 1972, it is still used in much of the world on mosquitos for malaria control, making its regulation particularly controversial.[3]

Novel entities are pervasive across our industrial processes and products and, as such, are deeply intertwined in our economy, yet they have severe and uncertain consequences for the functional integrity of the natural world.

Engineered chemicals provide valuable services

Engineered chemicals are indispensable to modern medicine, agriculture, consumer goods, clean energy technologies, and more, yet their social benefits come at the cost of pollution associated with their irresponsible manufacture, use and disposal.

Pollutants affect all life on Earth at multiple scales

Chemical pollutants affect all life on Earth and the physical environment. The effects can be global or local; temporary or permanent; and short-lived (acute) or long-term (chronic). At the species level, chemical pollution can result in mutation and reduced fertility, as well as changes in growth, development, and behaviour.[4] At the ecosystem levels, these changes alter diversity, community structure, and system processes such as nutrient and water cycling.

Pollutants inhibit ecosystem service provision

The decline of wildlife populations exposed to chemicals can have dramatic impacts for global biodiversity. For example, neonicotinoid pesticide pollution is a major factor in the ongoing collapse of global bee populations.[5] Bees are indispensable as pollinators, and their decline presents major ecological, food security and economic concerns, with the value of their pollination estimated at US$295 billion.[6]

Chemicals proliferate through air, water, plastics, and the food chain

Although their impacts are most visible at the scale of the individual, novel entities have global implications. Travelling on atmospheric and ocean currents, these compounds can be found in all ecosystems on Earth; from Antarctica to the deepest trenches of the ocean.[7] Ocean transport is facilitated by plastic particles that absorb and concentrate the chemicals.[8] When aquatic organisms ingest pollutants, they accumulate up the food chain through a process called biomagnification.[9]

Interactions are uncertain and dangerous

The ways in which various pollutants and chemicals interact can be difficult to predict. Although a single substance may be benign in isolation, it can become toxic when combined with others.[10] The impacts of novel entities might only become recognisable once they manifest on a global scale and can no longer be reversed.[11] It has been suggested that chemical pollution may already be pushing us beyond the safe operating space delineated by the planetary boundary for novel entities.[12]

Engineered chemical are present in humans

Chemical pollutants are detectable in most humans. Ninety per cent of the US population has detectable levels of Bisphenol A (BPA), an industrial chemical used to make plastics and resins, linked to fertility problems and heart disease.[13] The World Health Organization estimates that the loss of 1.6 million lives and around 45 million disability-adjusted life years (DALYs) in 2016 could have been prevented through sound management and reduction of chemicals in the environment.[14]

- Visible impact
Leather tanning

In the Hazaribagh tannery zone in Dhaka, Bangladesh, about 85,000 tonnes of rawhides are processed annually for leather production. Chromium, a chemical used to increase the durability of leather goods, is a common pollutant at under-regulated tannery sites and is highly toxic. Processing one tonne of rawhide generates 50,000kg of wastewater containing 5kg chromium. Over 8,000 workers in Hazaribagh suffer from gastrointestinal, dermatological, and other diseases.[18]

10x
increase in marine plastic pollution since 1980, affecting at least 267 species.[15]

90%
of the US population has detectable levels BPA, an industrial chemical used to make plastics and resins.[16]

1.6 million
deaths could have been prevented through sound management and reduction of chemicals in 2016.[17]

What is driving degradation?

The introduction of novel entities is driven by nearly all industrial and human activities related to production and consumption.

Industrial activity

Every sector of the industrial economy employs manmade chemicals, with more than 100 million varieties, but some industries have a disproportionately outsized role in polluting the environment. Used lead acid battery recycling, pesticides, mining and ore processing, leather tanneries, dumpsites, industrial parks, smelting, artisanal small-scale gold mining, product manufacturing, chemical manufacturing and the dye industry collectively account for putting over 32 million people at risk of ill health.[19] These industries also collectively account for 7-17 million Disability-Adjusted Life Years (DALYs) in low and middle-income countries.[20]

How is the built environment contributing to degradation?

Building materials cause pollution throughout the supply chain

Mined products, such as steel and precious metals, use copious pollutants in the extraction and refining process. Other building materials are inherently toxic, including lead roofing and paint, asbestos tile and insulation, vinyl flooring, flame retardants, adhesives and sealants, some engineered woods, and spray foam insulation.[21] These materials off-gas volatile organic compounds (VOCs) into the air that we breathe, leach into the water supply, and contaminate soils.

Industrial sites are often contaminated

Contaminated sites such as industrial land, shipyards, power plants, military testing areas and hazardous waste dumping sites yet to be remediated are inherently problematic locally, but the issues are mobilised when natural disasters strike. Flooding and heavy winds can facilitate leaching, runoff and atmospheric proliferation of stored contaminants.

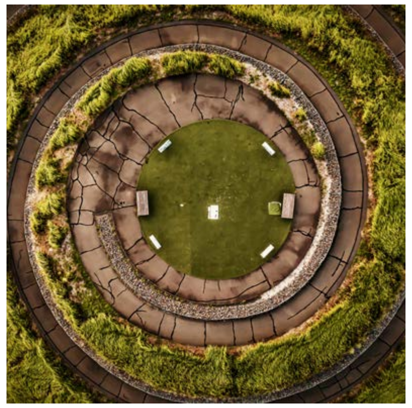
- Visible impact
Illegal rare Earth mining

China has sourced a significant share of the rare Earth elements used in the world's high-tech products. The southern Jiangxi province, once home to illegal and small-scale rare-Earth mining, is dotted with concrete leaching ponds and plastic lined wastewater pools filled with a mix of extraction chemicals and water. These abandoned sites are just one landslide or barrier failure away from spilling their contents to further contaminate waterways and soil. It is estimated that clean-up could take 50-100 years and cost around US$5.5 billion.[22]

+ Exemplar
Water reuse in the textile sector

The river and groundwater in Tiruppur suffers from poor water quality due to the heavy presence of the textile industry in the area, compounded by scarcity due to overdraft and limited reservoir capacity. Following the Indian High Court's zero liquid discharge mandate, nine of the area's existing effluent treatment plans were updated to include a combined reverse osmosis and thermal evaporation system which has allowed 96% of the effluent to be treated and released as freshwater. The process also recaptures dye salts which can be locally reused, avoiding their release into freshwater systems.[23,24]

What can enable regeneration?



+ Exemplar
Sydney Olympic Millennium Parklands Remediation, Arup

Once one of Sydney's most contaminated sites, this 1,000-acre former industrial area was remediated to become a thriving parkland providing habitat to more than 180 native species of birds and the once-endangered Green and Golden Bell Frog. Contaminated soil was collected and capped to create a series of landforms, preventing further damage. Groundwater, contaminated with benzene and other chemicals, was treated by microorganisms in bioremediation ponds.[25]

The introduction of novel entities is the one system process that is completely driven by human-development meaning there is great opportunity for action. Coordinated policy interventions for more responsible production and consumption paradigms can enable sustainable solutions across the economy.

Coordinate precautionary actions through supply chains

The globalised economy has allowed wealthy countries to stop using some chemicals by outsourcing polluting activities to developing countries, resulting in 'pollution havens'.[26] The supply chain of most products today is long and complex; from extraction and refinement of raw materials, to transportation, production, consumption, and eventually disposal, there is a pressing need to transform the use of chemicals at every step. To do so will require increased transparency.

Uphold international agreements

Targeted international agreements have proven successful in the past, namely in the phase out of ozone depleting CFCs. Following the 1987 Montreal Protocol, the ozone layer began to repair itself.[27] Since then, the Stockholm Convention on Persistent Organic Pollutants (2001) and the Minamata Convention on Mercury (2013) have been signed, providing internationally agreed upon standards on how these entities should be used and managed at the end of their lives.

Improve indicators for chemical pollution

Current research attempts to develop indicators for chemical pollution that will allow scientists to better identify harmful chemicals, measure their impact, and control pollution levels.[28] The existing challenge posed by unquantifiable effects and missing data must be overcome. Technological and social innovations implemented multilaterally by international bodies, national and local governments, civil society and scientists can prevent the dissemination of harmful pollutants.[29]

Shift to a circular economy

Shifting to a circular economy by closing the loop of production and consumption would radically reduce pollution from both extraction and end of use disposal. Chemical Leasing, an innovative service-oriented business model that reduces inefficiency and overconsumption of chemicals, applies value-oriented pricing to decouple payment from consumption.[30]

Employ nature-based agricultural solutions

Agroecological practices and integrated pest management can radically reduce the need for harmful pesticides in agriculture.[31] Increased efficiency in the application of fertilisers and the planting of riparian buffer zones can decrease runoff of novel entities that are applied.

Replace novel entities with nature-derived solutions

Mycelium is a naturally occurring component of fungus that can be used to create a variety of products that typically rely on novel entities, such as polystyrene, composite materials and insulation.[32]

+ Exemplar
Harvard Sustainability Plan

Harvard Green Building Standards aim to reduce toxic chemical use and exposure on campus through the identification and tracking of high-risk chemicals in building materials, as well as the development of plans to eliminate chemical exposure. In 2015, Harvard signed a national pledge that stated a preference for the purchase of furniture that is free from chemical flame retardants. In 2016, the University launched the Healthier Building Materials Academy which aims to standardise the process and expectations for procuring healthier materials. In partnership with Google's Portico, they are developing a robust scoring system grounded in science and based on several health criteria.[33,34]

Novel entities

Regenerative actions

The built environment can reduce the exposure and proliferation of existing novel entities through remediation and control measures on the ground. It can also reduce the introduction of new contaminates through the selection of sustainable building materials and products.

The clean-up of contaminated sites and waterways is essential to improving the ecological and human health of a city, and can often be achieved by leveraging the natural processes of bioremediation.[35] With regards to pollution control, distributed green infrastructure can prevent the transport of diffuse contaminants by absorbing and remediating runoff with plants and microorganisms that degrade pollutants. To manage point source pollution, municipal wastewater treatment should be employed, including strategies to prevent combined sewage overflow during heavy precipitation events.

The built environment can reduce the emission of novel entities into the environment by selecting non-toxic building materials and products to support the health of inhabitants and the local ecosystem. Material selection must also consider the embodied pollutants associated with mining and processing, favouring alternative sustainable methods.

Further reading

Prescription for Healthier Building Materials

Ocean Acidification

Ocean acidification is a chemical change in sea water caused by the absorption CO_2; it is inextricably linked to climate change. When oceans acidify, the concentration of calcium carbonate falls and corals and shellfish struggle to build their skeletons and shells; sometimes causing the corrosion of existing shells.[1] Oceans have absorbed ~30% of anthropogenic carbon dioxide (CO_2) from the atmosphere.[2] Without this absorption, the concentration of atmospheric CO_2 and its associated impacts would be far greater. The current rate of ocean acidification is unprecedented within the last 65 million years, possibly even the last 300.[3] The boundary for ocean acidification has not yet been transgressed but, if carbon emissions continue, acidification is expected to worsen. Acidity is already more dire in polar regions because colder water can absorb more CO_2 than warm water.

Ocean acidification

Why is this boundary important?

Acidification alters ocean chemistry, hindering physiological processes for a multitude of marine species with cascading effects through ecosystems and food chains. Its integral link to climate change means it similarly has effects on many of the other boundaries.

Acidification hinders shell and skeleton formation

Absorbed CO_2 increases the acidity of surface seawater by reacting with water to form carbonic acid, which dissociates to create bicarbonate and hydrogen ions. These free hydrogen ions join with calcium carbonate to produce even more bicarbonate, reducing the concentration of calcium carbonate, a marine ‘building block’ essential for shell and skeleton formation.[4]

Acidification impairs physiological functions

Ocean acidification has direct and indirect effects on physiological processes such as metabolic performance, gas exchange, reproduction, growth, and neural function.[5]

Acidification is an economic risk for fisheries and aquaculture

Acidification threatens the productivity of fisheries and aquaculture, and the security of regional livelihoods. People who depend on the ocean as a vital source of food and income would be hurt by losses of shellfish and other marine organisms.[6] The U.S. Environmental Protection Agency (EPA) estimates that acidification-related shellfish losses alone could cost the country’s consumers US$480 million per year by 2100.[7]

Acidification alters ecosystem functioning and the food chain

While some species, like seagrasses, may thrive in carbon rich waters, others, like phytoplankton, corals and molluscs, struggle to adapt. Phytoplankton serve as the base of marine food webs, while coral reefs are biodiversity hotspots and ecosystem engineers that create and modify habitat that supports complex communities.[8] The loss of these organisms could have cascading impacts on ecosystems and the entire biosphere.[9]

Phytoplankton capture CO_2 and are vulnerable to acidic oceans

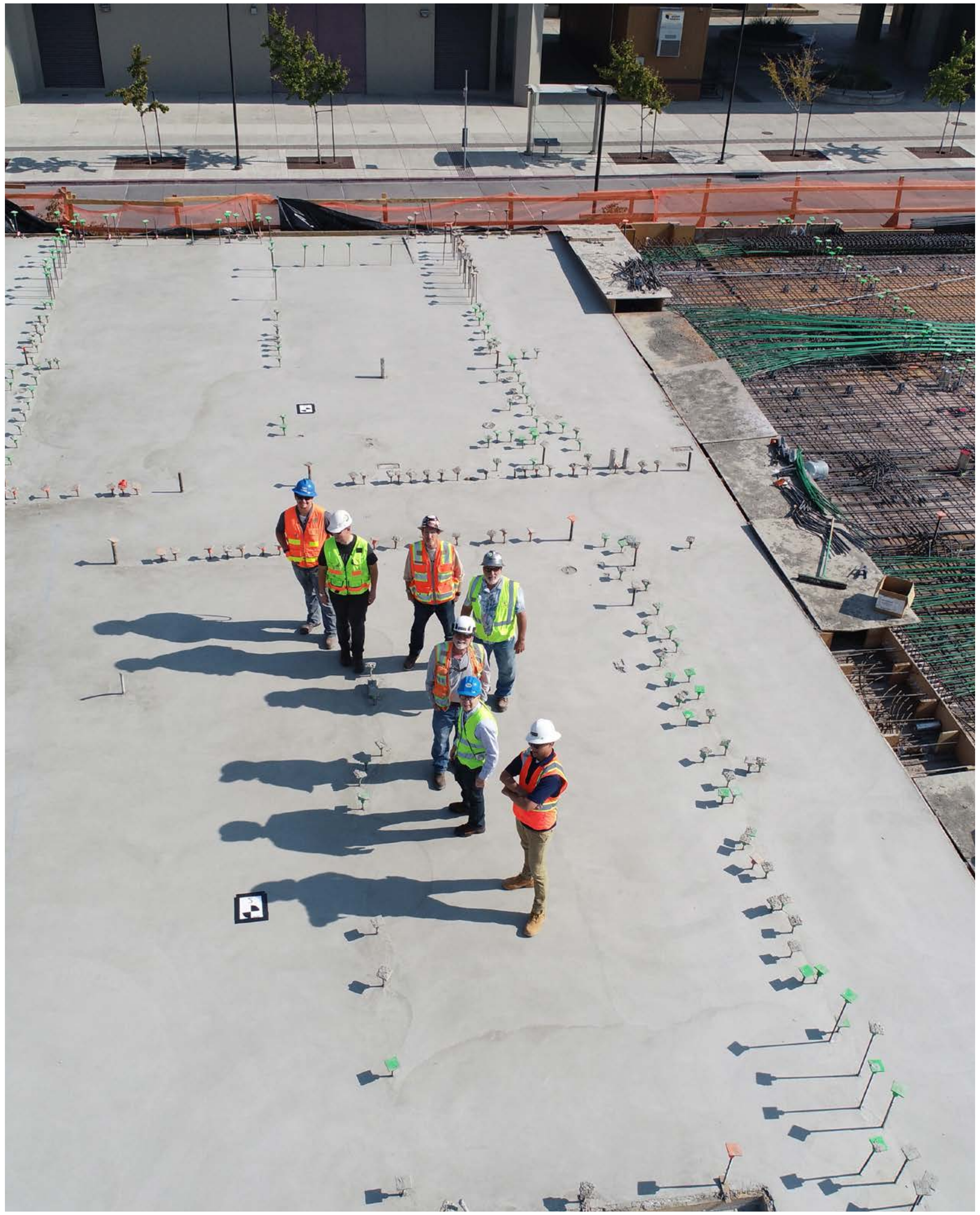
Phytoplankton, which are responsible for absorbing CO_2 through photosynthesis and producing 70% of the world’s oxygen, are vulnerable to increasing ocean acidity.[10] Loss in their productivity could accelerate ocean acidification in a positive feedback.

- Visible impact
Great Barrier Reef Decline

Calcification rates (growth) of the Great Barrier Reef have declined by 14% between 1990 and 2005, just barely outpacing rates of erosion from the acidic water. Data suggests that such a severe and sudden decline in calcification is unprecedented in at least the past 400 years.[11]

+ Exemplar
Kelp farming for shellfish

Researchers in Washington State are exploring the use of kelp farming to reduce local acidity and improve conditions for threatened shellfish cultivation. Kelp can be farmed for food, biofuel and fertiliser, and as one of the fastest growing organisms on Earth (as much as 15 feet in a season), it absorbs an incredible amount of dissolved carbon from the ocean. Requiring no fertilisers, pesticides, freshwater or arable land, it helps the environment rather than degrading it as most farming does. Furthermore, kelp and shellfish play important roles in establishing a healthy ecosystem for other species and dissipate wave energy to protect shorelines from erosion.[12,13]



+ Exemplar
Blue Planet concrete

To address the carbon-intensive practice of concrete production, Blue Planet developed a technology that mimics the process of coral formation to capture CO_2 and create a carbonate rock product. CO_2 is combined with a water-based capture solution to produce carbonate minerals; this 'synthetic limestone' is added layer by layer to a central substrate, producing a coating that is 44% CO_2 by mass. These resulting rock particles are used as a replacement for limestone in traditional concrete production. Blue Planet's technology shifts concrete production from carbon intensive to carbon positive.[14]

Ocean acidification

What is driving degradation?

Oceans acidify when atmospheric CO_2 concentrations increase, driving aquatic absorption, and when organic matter decomposes underwater.

CO_2 emissions
Ocean acidification is primarily driven by the release of CO_2 into the atmosphere. The main anthropogenic driver of CO_2 emissions is fossil fuel combustion, while forest clearing land use changes, and the degradation of soils also play a major role.[15]

Nutrient inputs
Nutrient runoff in the ocean can cause coastal acidification. Ocean chemistry changes due to decomposing algae releasing CO_2 when it erupts in response to high nutrient inputs.[16]

Feedbacks in the climate system:
The weakening and reversal of carbon sinks
(see the climate change chapter on degradation).

How is the built environment contributing to degradation?

CO_2 emissions
Covering less than 3% of the world's surface, cities house over half of the world's population, consume two thirds of the world's energy and account for more than 70% of CO_2 emissions.[17] Transportation, energy production, and buildings are the primary sources of these emissions.

Sewage and urban runoff contribute to coastal acidity
Cities contribute to coastal acidification through nutrient inputs from sewage, fertiliser and nitrous oxides associated with fossil fuel combustion.

- Visible impact
Oregon oyster farm losses

An oyster farm in Oregon noticed 70-80% mortality in their oyster larvae. When they enlisted researchers to help them diagnose the problem, the scientists found high levels of dissolved CO_2 in the water. Ocean circulation patterns had made the Pacific Northwest of North America a hotspot for acidification.[20] As global CO_2 levels continue to increase, farmers in other parts of the world will begin to experience similar losses.

150%
increase in ocean acidity is expected by 2100 under business as usual CO_2 emissions scenario.[18]

Looking forward

Colder water is able to hold more CO_2, so the polar oceans tend to be more acidic than those at lower latitudes. As ocean temperatures and CO_2 concentrations rise, oceans are increasingly resistant to absorbing carbon, driving an acceleration in atmospheric concentrations.[19]

Ocean acidification

What can enable regeneration?

Reducing atmospheric CO2 concentrations and increasing aquatic primary productivity will reduce ocean acidification.

Cut CO_2 emissions and increase sequestration

Ocean acidification is strongly correlated with atmospheric CO_2 concentrations. Lowering atmospheric CO_2, by reducing emissions and increasing sequestration, is the only global solution.

Reduce local acidity with algae and plants

Seagrass meadows and kelp forests could play a limited, localised role in alleviating ocean acidification in coastal ecosystems.[21] By metabolising dissolved CO_2 through growth, these organisms can provide a short-term solution to fisheries impacted by acidification.

Regenerate oceans with marine permaculture

Marine permaculture is a scalable blue carbon sink that restores overturning circulation, enabling kelp forests and other seaweed to thrive offshore. These forests regenerate fish habitat essential for forage fisheries, game fish and apex predators. Approximately 100M square kilometres of open ocean accessible area is available in the [sub]tropical Pacific Ocean alone.[22]

+ Exemplar
Alliander headquarter renovations

In the renovation of Alliander's headquarters, 83% of the existing structure was maintained and new construction was designed for disassembly. The implementation of a 'raw materials passport' will also make future use of the components far easier. Energy efficiency measures, solar power and underground thermal water storage allow the building to generate more energy than it uses and send the excess back to the grid. The building design optimises energy use through natural ventilation and an atrium that acts as a 'second skin' for the existing facades to improve thermal performance.[23]

Regenerative actions

The built environment can play a central role in mitigating ocean acidification due to its outsized role in global CO_2 emissions.

Healthy and resilient marine ecosystems are better able to adapt to acidic conditions, in large part, by directly reducing local acidification through the photosynthetic absorption of dissolved CO_2 to improve habitability for vulnerable species.

Coastal cities can enhance ecosystem resilience through the reduction of anthropogenic stressors on the marine environment, such as unsustainable fishing practices, surface water runoff (which can exacerbate local acidification) and coastal overdevelopment. They can enable these solutions by setting policies to protect the oceans, creating programs that educate and raise awareness, encouraging communities to plant more seagrass meadows or kelp forests, and by coordinating clean waterway groups.

Further reading

Five Minute Guide Zero Net Energy and Carbon

Further ideas and solutions for minimising operational and embodied carbon and supporting healthy plants and soils that sequester carbon is detailed in the climate change section on page 24.

Clean and renewable energy

Energy efficiency and conservation

Urban growth boundaries

Wastewater treatment and recycling

Sustainable food sourcing

Urban trees

Forest protection

Green roofs

Sustainable materials

Circular material use

Computational design

Public and active mobility

Rain gardens and bioswales

Wetlands and coastal habitats

Wildlife corridors

Stratospheric Ozone Depletion

The stratospheric ozone layer is a belt of naturally occurring gas that sits 15-30km above the Earth.[1] It serves as a shield from short-wave ultraviolet radiation (UV-B) emitted by the sun, which is harmful to living things.[2] This protective layer is threatened by chemical compounds containing chlorine or bromine, including chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl compounds and halons.[3] Together, these types of chemicals are referred to as ozone depleting substances (ODS's). ODS's are broken down into atoms of elements like chlorine by ultraviolet rays when the rays reach the upper atmosphere. ODS's have historically been used in refrigerators, air conditioners, fire extinguishers, aerosol sprays, and other household and industrial products. We are currently within this boundary and, following the success of the Montreal Protocol, ozone levels are expected to recover this century.

Why is this boundary important?

- Visible impact
Phytoplankton photosynthesis reduction

Increased exposure to UV-B radiation in the Antarctic due to ozone thinning caused a 6-12% reduction in photosynthesis by phytoplankton in surface waters.[4] In other parts of the world, results are more diverse. Present rates of phytoplankton photosynthesis range from a 40% reduction to a 10% increase.[5]

The ozone layer protects fauna and flora, including humans, from harmful UV-B rays.

UV-B radiation can cause skin cancer and cataracts
The ozone layer protects the Earth's surface from UV-B radiation. When the ozone layer is depleted, heightened levels of UV rays get through. UV-B rays can cause skin cancer, cataracts, and other medical problems in humans.[6]

UV-B radiation impacts plant processes
Increased levels of UV-B radiation can reduce leaf size in plants, limiting their ability to perform photosynthesis needed for growth. Secondary impacts of UV-B radiation can include decreased reproductive rates and changes in how nutrients are distributed through the plant.[7]

UV-B exposure can disrupt marine ecosystems
UV-B radiation inhibits the reproductive cycle of phytoplankton, single-celled organisms like algae which make up the lower level of the food chain. A reduction in phytoplankton populations could result in lower populations of other animals higher up the food chain. UV-B radiation also reduces the reproductive capacity of fish, shrimp, crabs and some amphibians.[8]

What is driving degradation?

The ozone is degraded by the emission of ozone depleting substances.

Ozone depleting substances
Ozone depletion is primarily driven by ODS's– chemicals used in the manufacture of aerosol sprays, blowing agents (for foams and packing materials), solvents and refrigerants.[9]

How is the built environment contributing to degradation?

Heat transfer fluids were ozone depleting
ODS's are commonly used as a heat transfer agent in air conditioning, refrigeration, and other applications. Although most ODS's have largely been removed from modern products, many pre-regulation products continue to slowly vent these harmful compounds and are susceptible to catastrophic leaks.

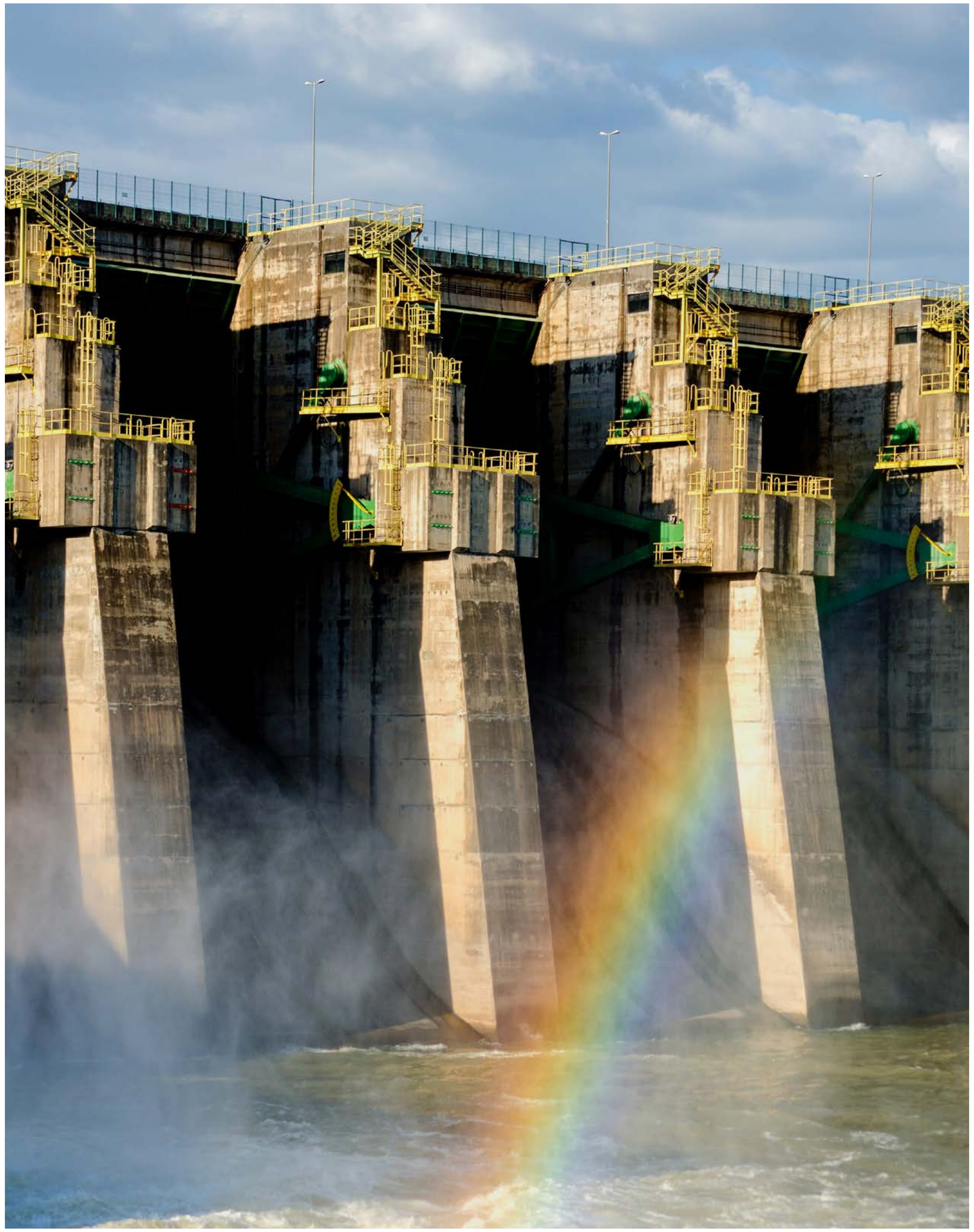
ODS's continue to be used illegally
Progress has been made in regulating ODS's in the built environment with the Montreal Protocol. However, some banned substances, such as CFC-11, are still being used illegally in the manufacturing of foam panels and spray foam insulation.[10]

- Visible impact
Antarctic ozone hole

The Antarctic has been particularly impacted by ozone depletion because of its extremely cold temperatures which produce polar stratospheric clouds containing nitric acid or water ice. The compounds in these clouds react with ODS's to 'activate' them.[14] During the austral spring (after the formation of these clouds in the winter), about half of the total ozone column disappears. This ozone 'hole' commonly spans more than 20 million km2 at its widest in October.[15]

6-12%
reduction in photosynthesis by phytoplankton in the Antarctic due to ozone thinning.[11]

Looking forward
Since the late 1990's, ozone loss has been slowing and some non-polar ozone has increased.[12] However, new research suggests that in the lower stratosphere, ozone levels have actually been decreasing, compromising the health of the whole ozone column and inhibiting recovery efforts.[13]



+ Exemplar
Dew Point air conditioner uses water instead of refrigerants

Dew Point is a prototype sustainable air conditioner that substitutes water for refrigerants, eliminating the need for ODS's. The Dew Point conditioning unit consumes 40% less electricity than a standard air conditioner and can cool a space to as low as 18° Celsius. The technology absorbs water from ambient air, passing the drier air through a counter-flow dew point evaporative cooler which removes heat from the air through evaporative cooling, the same process used by the human body to reduce body temperature through perspiration.[16]

What can enable regeneration?

The actions taken to tackle ozone depletion show how concerted global action and binding international agreements can help humanity draw back from the brink of a planetary boundary.

Observe global treaties

The 1989 Montreal Protocol is an international treaty where nearly 200 countries pledged to protect the ozone layer by phasing out the use of CFCs.[17] However, ODS's are still in use (often illegally) in products around the world. The Montreal Protocol has been successful in curtailing the production of ODS's and promoting the recovery of the ozone layer. Since 2000, global ozone levels have largely stopped declining, and, in some locations, have started to creep back up. In 2012, atmospheric chlorine and bromine levels had decreased 10-15% from peak levels at the turn of the millennium.[18]

Eliminate black market ODS's

Despite new mandates to continue phasing out ODS's under the Montreal Protocol and concerted efforts in developing and developed countries alike, the black market for HCFCs and other ODS's remains strong.[19] To curtail the black market for CFCs, countries need comprehensive regulatory enforcement tools that can tackle transnational trade. This will require sustained funding, transnational cooperation, and consistently strong laws to empower enforcers.[20]

+ Exemplar
Market based decommissioning of CFCs

City Waste Recycling in Accra, Ghana, received 30,000 pounds of CFCs in 2018. As there are no disposal facilities in all of West Africa, they worked with Tradewater, a US firm selling carbon offset credits on carbon markets, to have the materials destroyed in the US. CFC gas is destroyed through incineration in special kilns which break down the molecules into a benign mixture. Although the credit was carbon focused, preventing the release of more than 123,000 tonnes of CO_2, it also worked as an effective way to address ozone depletion.[21]

Regenerative actions

Although ODS's are largely being phased out thanks to the Montreal Protocol, they are still used in some parts of the world. Cities have a key role to play in enforcing existing regulation and creating the necessary enabling environments to facilitate the decommissioning of ODS reliant products and processes.

Development of low cost and environmentally friendly materials and heat transfer alternatives could reduce the black market for ODS's to support an effective global transition. Furthermore, the elimination and proper disposal of operational and stockpiled ODS's is essential to eliminate the potential for venting and leaks.

Sustainable materials

Regenerative Actions

Designers, planners and engineers are in a unique position to address the risks associated with crossing Planetary Boundary thresholds. The design and construction choices that are made today can actively push the planet towards - or pull it away from - more unpredictable Earth systems outcomes. Built projects and their long-term impacts affect the lives, behaviours and activities of all life on Earth. Design decisions and physical interventions influence how people travel, inhabit space, consume goods and use energy. If projects are re-thought, re-considered, retrofitted and created to minimise impact on the natural environment, the benefits will be felt for decades and centuries to come.

● Strong positive effect

○ Weaker effect

	Biosphere integrity	Climate change	Novel entities	Stratospheric ozone depletion	Atmospheric aerosol loading	Ocean acidification	Biogeochemical flows	Freshwater use	Land-system change
Boundary condition	◐	●	●	●	●	●	◐	●	●
Cross scale									
Computational design	●	●	●		●	●		●	●
Sustainable materials	●	●	●	●	●	●		●	●
Circular material flows	●	●	●		●	●		●	●
Buildings									
Cool roofs		●			○	●			
Green roofs	●	●			○	●		○	
Neighbourhoods									
Water efficiency and conservation	○							●	
Energy efficiency and conservation		●			●	●			
Permeable pavements	○		○				○	●	
Rain gardens and bioswales	●	●	●			●	●	●	
Wetlands and coastal habitats	●	●	●			●	●	●	●
Wastewater treatment and recycling	●	●	●				●	●	
Brownfield remediation	●		●		○				○
Native landscaping	●							●	
Cities									
Urban trees	●	●			●	●		○	
Clean and renewable energy		●			●	●			
Public and active mobility		●			●	●			
Wildlife corridors	●	○				○		●	
Catchments									
Urban growth boundaries	●	○					○	○	●
Forest protection	●	●			●	●	●	●	●
Sustainable food sourcing	●	○	○			○	○	●	●

Figure 3
Actions for cities

The matrix represents the response of the PBs to a range of built environment interventions.

Regenerative actions

Actions for the built environment

Outlined here are 20 regenerative actions and design choices that can be incorporated into projects. Considering regenerative solutions from the outset will deliver more positive planetary outcomes to restore and regenerate Earth's natural systems.

20 actions
for cities to regenerate natural environments

These interventions operate at varying scales. Some, such as preventing urban sprawl, require regional approaches or policy changes while others, such as rain gardens and native landscaping, occur at the local or buildings scale. While these actions can be applied on individual projects, their benefits are amplified when applied on a variety of projects at scale to enable the reintegration of natural system functioning.

Built environment interventions can address multiple boundaries; those listed here are a selection of solutions to highlight how the built environment can be regenerative. Regeneration - the replenishing of Earth systems - requires a holistic approach and combination of strategies to thrive, and cannot occur by acting on each planetary boundary in a silo.It is important to note that just as these interventions may have synergies across multiple boundaries, there may also be trade-offs dependent on the location and method in which they are implemented. These actions showcase global best practice and do not reflect specific local or regional conditions.

The PBF reveals the scale of the challenge facing the planet and all living organisms. It also provides a catalyst for action. By enabling the visualisation of systems change, practitioners can better understand how the decisions made interact with and impact on other systems. This provides engineers, designers, planners, and policymakers with greater confidence around the course of action to take.

Cross scale

+ Exemplar
Kuwait International Airport, Kuwait - Arup

Each shell making up this 1.3km concrete roof is unique; shaped to exact the response of their structural requirements. Arup developed a mass customisable thin concrete panel system, wherein computer controlled hydraulic jacks curved each piece of formwork to the required shape. Each of the 48 thousand panels were cast using the same adaptable mould system but to a unique geometry. This system required half the concrete of an ordinary 300mm reinforced concrete shell and no formwork.

Computational design and digital fabrication

Design considerations and material innovations that improve structural performance can reduce material demand through increased efficiency. Computational design can optimise the allocation of material for maximal performance (topological optimisation). Digital fabrication practices, such as 3D printing, can realise the resulting complex geometries while eliminating waste.

Climate change
Design and material innovations can reduce demand for carbon intensive materials such as steel and concrete.

Biosphere integrity
Habitats can be spared from destructive resource extraction through more efficient material use.

Land-system change
Land conversion associated with resource extraction can be reduced with increased efficiency in material use.

Freshwater use
Efficiency in material use reduces the water use and consumption associated with extraction and production.

Atmospheric aerosol loading
Efficiency in material use reduces particulate emissions associated with extraction and production.

Novel entities
Efficient material use reduces pollutants associated with extraction and production.

Ocean acidification
Design and material innovations can reduce demand for carbon intensive materials such as steel and concrete.

Further reading
Designing with Digital Fabrication

+ Exemplar
HAUT timber tower, Netherlands - Arup

The cross-laminated timber frame of this 73m residential tower will make it the tallest timber hybrid tower in the Netherlands. The timber used will store 2,500 tons of carbon, equivalent to the emissions from the energy use of the tower's 52 apartments over 10 years, contributing to the design's BREEAM Outstanding rating.[1]

Sustainable materials

Low carbon and sustainable building materials are sustainably grown, extracted, transported, and processed, and do not contain compounds that are harmful to the environment, resulting in a reduced ecological footprint throughout the supply chain. Examples include bamboo, timber from sustainably managed forests, mycelium, and low-carbon concrete.

Climate change
Low carbon or carbon negative building materials can reduce embodied CO_2.

Biosphere integrity
Sustainably sourced materials can reduce built environment contributions to habitat pollution and destruction.

Land-system change
Land conversion associated with resource extraction can be reduced through sustainable sourcing and eliminated with material reuse and the utilisation of waste by-products.

Freshwater use
Materials with low water use and consumption associated with production diminish embodied water demand.

Atmospheric aerosol loading
Materials that are sustainably extracted and processed have low associated particulate emissions.

Novel entities
Natural and sustainably sourced materials, along with environmentally friendly manufacturing practices that make use of 'green chemistry,' can reduce the built environment's introduction of novel entities.

Ocean acidification
Low carbon or carbon negative building materials can reduce embodied CO_2.

Stratospheric ozone depletion
Development of low cost and environmentally friendly heat transfer alternatives and materials could eliminate the black market for ozone depleting substances.

Further reading
Rethinking Timber Buildings
Prescription for Healthier Building Materials
Forestry Embodied Carbon Methodology

Regenerative actions

Buildings

+ Exemplar
Werflink construction marketplace, Belgium

This online platform reduces waste in the construction sector by allowing users to share, rent, borrow and exchange materials, equipment, resources, freight space and facilities. Users can post their supply or demand on the site to make better use of existing resources for a more circular construction sector.[2]

Circular material flows

A circular materials market can mitigate environmental degradation associated with material use by minimising the need for virgin material extraction, refining, transport, manufacture, and disposal, and can give new life to wastes such as agricultural by-products, plastics and more. Circular materials flows can be categorised hierarchically in order of environmental damage mitigation: 1. Life extension (use materials longer to reduce total throughput); 2. Direct reuse (give materials new life in their current state); 3. Remanufacturing (upgrading obsolete elements while directly reusing still-current elements); 4. Recycling (reducing a product to its basic materials for reuse, as a last resort).

Climate change
Circular materials avoid greenhouse gas emissions associated with extraction, refining, transport, manufacture, and disposal.

Biosphere integrity
Circular materials spare the habitat from destruction associated with virgin material extraction including mining and logging.

Land-system change
Land conversion associated with virgin material extraction is avoided through the use of circular materials.

Freshwater use
Using circular materials avoids most of the water use and consumption associated with production, particularly with life extension and direct reuse.

Atmospheric aerosol loading
Recycled materials avoid particle emissions associated with extraction and, if directly reused, production.

Novel entities
Chemicals used in extraction and refining of resources, and leached in waste systems, can be avoided through circular materials use.

Ocean acidification
Circular materials avoid CO2 emissions associated with extraction, refining, transport, manufacture and disposal.

Further reading
Evaluating Re-use Potential: Material profiles
First Steps Towards a Circular Built Environment
Realising the Value of the Circular Economy in Real Estate

+ Exemplar
Ahmedabad's Heat Action Plan, India

Ahmedabad's cool roofs program is whitening the roofs of 15,000 informal settlements and city-owned buildings. Following a deadly heatwave in 2010, the city implemented a Heat Action Plan focused on preparedness for low-income households most vulnerable to extreme heat. A 3,000-home pilot in 2018 helped lower indoor temperatures by 2-5°C.

Cool roofs

Cools roofs utilise reflective materials such as white paint or reflective tiles to scatter UV radiation, drastically reducing heat absorbed compared to a standard roof. Asphalt and concrete streets can also receive a UV reflecting treatment.[3]

Climate change
Low carbon or carbon negative building materials can reduce embodied CO_2.

Biosphere integrity
Sustainably sourced materials can reduce built environment contributions to habitat pollution and destruction.

Land-system change
Land conversion associated with resource extraction can be reduced through sustainable sourcing and eliminated with material reuse and the utilisation of waste by-products.

Freshwater use
Materials with low water use and consumption associated with production diminish embodied water demand.

Atmospheric aerosol loading
Materials that are sustainably extracted and processed have low associated particulate emissions.

Novel entities
Natural and sustainably sourced materials, along with environmentally friendly manufacturing practices that make use of 'green chemistry,' can reduce the built environment's introduction of novel entities.

Ocean acidification
Low carbon or carbon negative building materials can reduce embodied CO_2.

Stratospheric ozone depletion
Development of low cost and environmentally friendly heat transfer alternatives and materials could eliminate the black market for ozone depleting substances.

Further reading
Reducing Urban Heat Risk

+ Exemplar
California Academy of Sciences, USA - Arup

The undulating green landscape that covers 87% of the museum's 2.5-acre rooftop absorbs 100% of stormwater runoff and maintains an average temperature 22°C cooler than a standard roof. Home to 1.7 million native plants, the roof provides habitat and food for birds, bees, butterflies, and other beneficial animals.[4]

Green roofs

Green roofs range from simple groundcover to advanced gardens or agricultural production areas. They provide habit and insulation, capture and store carbon, and manage stormwater by intercepting and storing rainwater. The benefits of green roof types lie in their design objectives and implementation. Green facades offer similar benefits.

Climate change
Green roofs provide insulation, reducing CO_2 emissions from heating and cooling. The vegetation sequesters CO_2 and provides ambient cooling, lessening the heat island effect.

Biosphere integrity
Green roofs can provide habitat for some animals and landing areas for migratory birds.

Freshwater use
Green roofs prevent water quality degradation by reducing stormwater runoff and combined sewage overflow.

Atmospheric aerosol loading
Green roofs with larger vegetation filter PM.

Ocean acidification
Green roofs provide insulation that reduces CO_2 emissions associated with heating and cooling, while the vegetation sequesters CO_2.

Further reading
Cities Alive: Green building envelope

Neighbourhoods

+ Exemplar
Drinking water from wastewater, Namibia

Mimicking natural processes, the water treatment plant in Windhoek, Namibia transforms wastewater from the capital's 350,000 residents into drinking water, meeting 35% of demand. Water conservation is essential as only 1% of Namibia's 250mm of average annual rainfall infiltrates the ground while 83% is lost to evaporation.[5]

Water efficiency and conservation

Water efficiency reduces the amount of water required to provide services by minimising waste. Water conservation is the effort made to reduce water consumption. At the building scale, water efficient interventions such as low flush toilets and smart taps can reduce consumption without compromising the provision of services. At the municipal scale, efficiency can be increased by eliminating loss from leaks in distribution systems. Water can be conserved through greywater utilisation, such as harvesting from household sinks, showers and washing machines for use in landscaping, reducing municipal demand.

Biosphere integrity
Reducing the consumption of water allows for it to remain in natural ecosystems for healthy, intact habitats

Freshwater use
Increasing the efficiency of water use reduces demand.

Further reading
Cities Alive: Rethinking cities in arid environments

+ Exemplar
Cornell Tech Bloomberg Centre, USA – Arup

To meet its net-zero energy goals, this all-electric building employs multiple strategies including an energy efficient facade that balances light and heat gain to maximises building insulation and decrease energy demand; smart building feature that monitor lighting and plug load use; a green roof that provides cooling; geothermal ground source heat pumps, and solar power.

Energy efficiency and conservation

Energy efficiency reduces the amount of energy required to provide services by minimising waste. Energy conservation is the effort made to reduce consumption. Operational energy efficiency in both new build and retrofit can be improved with LEDs and natural lighting strategies, tighter building envelopes and insulation, and efficient heating, cooling, and appliances. Smart devices can facilitate energy conservation by automating operation needs and, particularly when used in conjunction with energy storage, can autonomously shift consumption to times with lower grid emissions while improving grid flexibility for the integration of intermittent renewables. At scale (cities, campuses, and neighbourhoods), measures such as increased efficiency in transmission infrastructure and district heating and cooling can decrease net consumption.

Climate change
Energy efficiency decreases demand for generation. This can reduce CO_2 emissions when generation is fossil fuel- or biomass-based.

Atmospheric aerosol loading
Energy efficiency decreases demand for generation. This can reduce emissions of aerosols from power plants when generation is fossil fuel- or biomass-based.

Ocean acidification
Energy efficiency decreases demand for generation. This can reduce CO_2 emissions when generation is fossil fuel- or biomass-based.

Further reading
Zero Carbon Buildings – 3 Steps to Take Now
Reimagining Facility Management for the Digital Age

+ Exemplar
Topmix Permeable, UK

Tarmac’s permeable paving system directs stormwater off streets, parking surfaces, driveways, and walkways. The top layer has a permeability rate of 1,000 litres/minute/m2, one thousand times what is needed to cope with a 100-year storm event. Below sits an absorbent storage layer composed of aggregate and 30-40% voids.[7]

Permeable pavements

Permeable materials are designed to enable the infiltration of stormwater, and come in varying forms such as pervious concrete, porous asphalt, paving stones, and interlocking pavers. In cities, large areas of land are covered with non-permeable surfaces, increasing runoff into the municipal stormwater systems. This runoff carries any toxins, nutrients, and other contaminants from streets into waterways and coastal zones where they can degrade ecosystems.[6]

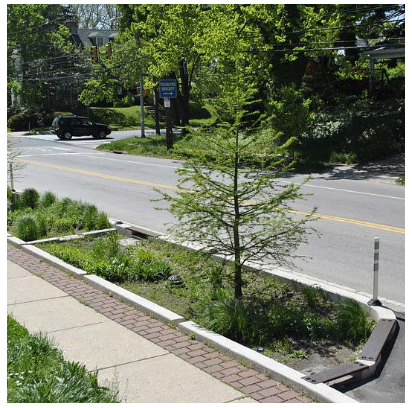
Biosphere integrity
Some permeable paving systems provide small pockets of habitat for insects in what would otherwise be a completely inhospitable paved area.

Freshwater use
Permeable pavements allow freshwater to infiltrate urban surfaces, replenishing groundwater stores.

Biogeochemical flows
Permeable pavements reduce nutrient runoff into surface waters and coastal zones, but do not filter nutrients infiltrating the groundwater.

Novel entities
Permeable pavements reduce contaminated runoff into surface waters and coastal zones, but do not prevent contaminants infiltrating the groundwater.

Further reading
Design with Water



+ Exemplar
Philadelphia Green City, Clean Waters, USA

The city of Philadelphia is converting 4047 hectares of land into raingardens, bioswales and other nature-based solutions to manage and filter stormwater, aiming to reduce combined sewage overflow by 85%. This approach boasts further benefits for urban liveability and biodiversity and offers 75% cost savings as compared to underground grey stormwater infrastructure.[8]

Rain gardens and bioswales

Rain gardens are areas that are depressed into the ground, designed to collect rainwater from a roof, driveway, street, or other impermeable nearby area. Bioswales function similarly but are typically larger in scale to accommodate greater quantities of runoff. By allowing precipitation to slowly infiltrate the ground instead of running off impervious surfaces, rain gardens and bioswales reduce flooding and lessen the strain on municipal grey stormwater management systems.

Climate change
Energy efficiency decreases demand for generation. This can reduce CO_2 emissions when generation is fossil fuel- or biomass-based.

Biosphere integrity
Rain gardens and bioswales provide pockets of habitat in urban areas and are often comprised of native vegetation that supports local species.

Freshwater use
Rain gardens and bioswales promote groundwater recharge and purification through infiltration.

Biogeochemical flows
Rain gardens and bioswales filter N and P from runoff, using it to nourish their vegetation.

Novel entities
Rain gardens and bioswales can filter heavy metals and other chemicals, preventing their spread.

Ocean acidification
The vegetation and soil that make up rain gardens and bioswales captures and stores carbon.

Further reading
Cities Alive: Water for people
Cities Alive: Rethinking green infrastructure

+ Exemplar
Brooklyn Bridge Park: Pier 1 & Pier 3-4 Uplands, USA

Stretching 2 km along New York's East River, this 85-acre former shipping facility sequesters 1,982 kg of carbon per year and is home to 119 species of birds. The integrated wetland system reduces runoff by 80%, captures and stores 62 cubic metres of stormwater, and removes 438 kg of pollutants annually, reducing erosion and keeping the river clean.[9]

Wetlands and coastal ecosystems

Wetlands and coastal areas, such as mangroves, tidal marshes, and seagrass beds, are some of the most biologically active ecosystems on Earth, providing a multitude of services to cities, from filtering pollution to flood protection. Coral and oyster reefs, kelp forests, marshes and mangroves serve as natural coastal barriers. They dissipate wave energy and prevent coastal erosion, providing essential services as rising sea levels and more frequent extreme weather events brought about by climate change increase coastal vulnerability. Both natural and artificially constructed wetlands improve flood resilience, remediate contaminants, and provide habitat.[10]

Climate change
Wetlands and coastal ecosystems and have some of the highest rates of carbon sequestration and storage per square metre of any ecosystem on Earth.

Biosphere integrity
Wetlands and coastal ecosystems are some of the most biodiverse areas on Earth and provide breeding grounds for many aquatic animals and birds.

Land-system change
Mangroves are small but important components of global forest cover

Freshwater use
Wetlands promote groundwater recharge, storing water during wet-seasons and slowly releasing it during dry seasons.[11]

Biogeochemical flows
Wetlands filter and use nutrient rich runoff, keeping it from entering coastal zones and waterways.[12]

Novel entities
Wetlands use or break down some pharmaceuticals, heavy metals pesticides, and other contaminants.

Ocean acidification
Wetlands and coastal ecosystems reduce coastal acidity by absorbing dissolved CO_2.

Further reading
Trialling 'mushi': using mycelium to create sustainable wetlands for healthier waterways

Wastewater treatment and recycling

Wastewater treatment involves removing biological and chemical contaminants so that treated water can be safely released into the environment. Wastewater recycling is the recovery and reuse of water and sewage sludge, the semi-solid by-product of wastewater treatment. Nutrient rich diluted and minimally treated wastewater can be used directly for some agricultural irrigation and landscaping, while sewage sludge can be converted into fuel and fertilisers, and mined for precious metals. Natural wastewater treatment processes, such as bioremediation, use plants, oxygenation, and microbial digestion to process contaminants in an engineered ecosystem.

+ Exemplar

T·PARK sludge treatment, Hong Kong - Arup

This sludge treatment facility in Hong Kong integrates a power station with a spa resort. Its fluidised bed incineration technology converts 2,000 tonnes of sludge into electricity daily, which powers the entire operation (up to 2MW extra sent to the grid), reduces sludge volume by 90%, and provides heat for the spa that would otherwise go unused.[13]

Climate change

Methane produced through microbial digestion of sewage sludge is a renewable, low carbon energy source. Bioremediation facilities capture carbon through plant growth.

Biosphere integrity

Removing contaminants from wastewater prevents aquatic habitat degradation. Bioremediation facilities can provide habitat for wildlife.

Freshwater use

Wastewater reuse reduces demand for new water sources.

Biogeochemical flows

Nitrogen (N) and phosphorous (P) from wastewater can be captured and reused as fertiliser or for energy production.

Novel entities

Treating wastewater prevents the spread of toxins into natural systems.

Ocean acidification

Methane produced through microbial digestion of sewage sludge is a renewable, low carbon energy source.

Further reading

The Urban Bio-loop

Guideline for Building Services Design Inspired by the Cradle to Cradle Concept

Brownfield remediation

Brownfield remediation is the clean-up of soil contaminated with hazardous waste so that a site may be used again. Remediation may require the removal, washing, or incineration of contaminated soil. A similar outcome can be achieved through leveraging natural methods with bioremediation[15] where certain plants and microorganisms are introduced to degrade the target pollutant.

+ Exemplar

Shougang Industrial Services Park, China - Arup

Once one of the most important manufacturing bases in Beijing, pollution control measures forced the Shougang steel mill to relocate. Over 80% of the 8.63km^2 this vacated, prime city centre land was heavily polluted, necessitating major soil remediation. The site is now home to China's first C40 Climate Positive Development Project.[14]

Biosphere integrity

When brownfields are turned into green space, they can provide habitat.

Land-system change

Remediating brownfield for use reduces demand for the conversion of forested land.

Atmospheric aerosol loading

The vegetation of brownfields protects exposed soil from wind, reducing dust emissions.

Novel entities

Remediating contaminated brownfield land prevents the spread of toxins by removing them.

+ Exemplar
Xuhui Runway Park,
China - in progress

The diverse wildlife habitats integrated into this 14.6-hectare Shanghai park are made up entirely of plant species native to the Yangtze River Delta. These terrestrial and marine habitats – including a bird watching garden, fruit tree groves, a bioengineered riparian edge, and a floating wetland module – provide a valuable ecological patch in the urban environment.[17]

Native landscaping

Native landscaping relies on using plants that are indigenous to the geographic area. As these plants are already adapted to the climate, geography, and hydrology of the area, they require less maintenance.[18]

Biosphere integrity
These plants provide habitat for native species and can help prevent against invasive species.

Freshwater use
Native and drought resistant plants require little to no irrigation, reducing water consumption.

Cities

+ Exemplar
Tiny Forests (Miyawaki Forests)

Miyawaki forests, inspired by protected areas around Japanese temples and shrines, prioritise the natural development of forests using a native species and can grow into mature ecosystems in just 20 years. The complex ecosystems support up to 20 times as many species as non-native, managed forests, and are perfectly suited to local conditions, thus maximizing habitat provision and carbon sequestration.[19]

Urban trees

Urban trees include stand-alone street trees and trees in urban parks. Although they do not offer the scale of climate and biodiversity services provided by forests, they do provide social and environmental benefits including improvements to psychological and physical health and noise reduction.[20]

Climate change
Trees sequester carbon. By casting shade and releasing water vapour, trees also provide cooling services, lessening the urban heat island effect.[21]

Biosphere integrity
Trees provide habitat for a variety of animals.

Freshwater use
Trees improve the infiltration of rainwater.

Atmospheric aerosol loading
Urban trees filter aerosols.

Ocean acidification
Trees sequester carbon.

Further reading
The Benefits of Large Species Trees in Urban Landscapes

Clean and renewable energy

Clean energy refers to energy sources that are zero-carbon. Renewable energy refers to energy sources that can be naturally replenished. Renewable energy sources are often also clean energy sources. Clean and renewable energy sources include solar, wind, hydro and geothermal. Clean heating and cooling systems, such as air and ground source heat pumps and solar thermal systems, can reduce traditional heating and cooling systems emissions. Electrification of buildings, vehicles and industry can reduce local emissions, but a truly global impact requires electricity that is generated cleanly.

+ Exemplar
Wind and wave powered hydrogen production, Scotland

The Scottish Orkney Islands rely entirely on wind, tidal and wave energy for their electricity supply, generating 130% of what they need even after exporting some excess to the UK national grid. Surplus electricity is now employed to produce hydrogen through water electrolysis which is fuelling cars and will eventually fuel ferries.[22]

Climate change
Clean and renewable energy reduces atmospheric CO_2 associated with generation.

Atmospheric aerosol loading
Transitioning to clean and renewable energy sources would eliminate aerosols emitted from fossil fuel and biomass combustion.

Ocean acidification
Clean and renewable energy reduces atmospheric CO_2.

Further reading
Establishing a Hydrogen Economy: The future of energy 2035
Towards Sustainable Solar Energy

Public and active mobility

Public transit modes, such as the bus, tram and metro can move up to 45 times as many people,[24] and are more energy efficient per passenger mile travelled than private motor vehicles. Active transportation options, such as walking or cycling, are human-powered and do not need additional energy sources. Cities can encourage the use of public and active transport through well-designed public transit systems and cycling and walking infrastructure.

+ Exemplar
Amsterdam smart mobility, The Netherlands

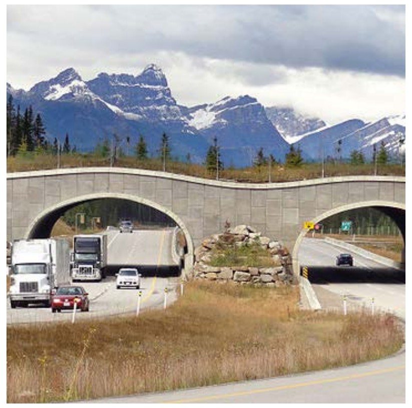
In Amsterdam, there are more than 500 km of bike lanes and 84% of people live within 1 km of a public transport service area making car-free, multimodal journeys common. The new Smart City Program enables collaboration between the city government, the private sector and residents to develop innovative solutions to mobility problems.[23]

Climate change
Clean, efficient and active mobility options can reduce CO_2 emissions.

Atmospheric aerosol loading
Clean, efficient and active mobility options can reduce aerosols emitted from combustion engines.

Ocean acidification
Clean, efficient and active mobility options can reduce CO_2 emissions.

Further reading
Cities Alive: Towards a walking world
Rethinking Urban Mobility



+ Exemplar
Wildlife highway crossings, Canada

In Banff National Park, wildlife can safely cross a four-lane highway via six overpasses and 38 underpasses. This infrastructure has reduced wildlife-vehicle crashes by 80% and supported 140,000 documented wildlife crossings since 1996.[25]

Wildlife corridors

Wildlife corridors provide physical connections between areas of habitat separated by human activities, reducing species isolation and inbreeding. Corridors range in scale and impact, and include bridges and tunnels, vegetated road medians, green roofs, de-culverted rivers and streams, and more. When wildlife can safely cross transport corridors, populations are more mobile and sustainable, and traffic accidents are reduced.

Climate change
Vegetated corridors capture and store carbon and reduce the heat island effect.

Biosphere integrity
Wildlife corridors can connect previously separated habitats, allowing for species movement throughout a larger natural area.

Ocean Acidification
Vegetated corridors capture and store carbon

Freshwater use
Freshwater wildlife corridors protect water sources for healthy ecosystems

Further reading
Biodiversity Trend Cards

Catchments

+ Exemplar
Tirana Orbital forest, Albania - Arup

As a rapidly growing city, Tirana is seeking to ensure sustainable growth by protecting and restoring the catchment with a mix of forests, shrubland, agricultural land and recreational areas around the urban perimeter. The four key design principles – protect, restore, provide and connect – address multiple environmental and socio-economic challenges, including urban sprawl, flood and heat risk, air quality, and green space access.

Urban growth boundary

Urban growth boundaries prevent sprawl by promoting densification to protect natural and agricultural land. Dense cities tend to have lower per capita resource use and cost of service provision due to greater efficiencies in energy, water, and transportation systems.[26] Protecting peri-urban land can improve the health and quality of life for people, flora, and fauna.

Climate change
Compact cities have greater energy and transport efficiency leading to lower associated CO_2 emissions.

Biosphere integrity
Limiting urban growth prevents habitat degradation, protecting biodiversity.

Land-system change
Limiting urban growth can protect forest cover from development.

Freshwater use
Compact cities have greater efficiencies in water transmission infrastructure and can better monitor groundwater extraction.

Biogeochemical flows
Urban growth boundaries prevent conversion of land to impervious surfaces that facilitate nutrient runoff

Ocean acidification
Compact cities have greater energy and transport efficiency leading to lower associated aerosol emissions.

Forest protection

Forest protection is the preservation and restoration of forested land. Forested areas near cities are invaluable to their residents as they play a critical role in the quality and provision of water. 75% of the world's accessible water comes from forests, and 90% of the world's cities rely on forested watersheds for their water supply.[29] Healthy forested catchments can reduce the costs of water treatment (biological and chemical impurities, erosion and sedimentation), improve dry season flows, and reduce flooding.[30] Forests also play a role in storing carbon, purifying air, and providing habitat for species.

+ Exemplar
Hong Kong forest protection, Hong Kong

In the 1970s, Hong Kong established a reforestation program to restore its degraded watershed; 41% of total land was designated as parks and restricted areas, of which two thirds is now forested. Tree nurseries like Kadoorie Farm, which grows 25,000 seedlings of 400 native species annually, sustain the restoration.[28]

Climate change
Forests sequester and store CO_2 in their biomass and soils

Biosphere integrity
Forests are home to 80% of the world's terrestrial species.[31]

Freshwater use
Forested catchment areas increase infiltration, improving the reliability of water flows year-round.

Biogeochemical flows
Forests mitigate erosion and maintain soil quality, preventing high rates of nutrient runoff into waterways.

Atmospheric aerosol loading
Forests filter atmospheric aerosols.

Ocean acidification
Forests capture and store CO_2.

Sustainable food sourcing

As the primary sink of agricultural products, cities can minimise the impacts of food production by eliminating waste through supply chains; sourcing food produced with low carbon, water and artificial fertiliser inputs; focusing on local and seasonal production; and favouring production that closes resource flows and ensures long term soil health. Sustainable procurement must consider all embodied environmental impacts, from transport to climatic appropriateness (e.g. water and energy demands). Food grown in controlled environments (e.g. hydroponics and aquaponics) can play a key role in the local production of highly perishable, high value foods with minimal resource inputs.

+ Exemplar
Aero Farms, USA

This indoor aeroponic agriculture technology is 390 times more productive per square foot than a commercial field farm. LEDs provide the precise spectrum, intensity, and frequency for maximised photosynthesis, cutting growth time in half. Roots are misted with nutrients, water, and oxygen, consuming 95% and 40% less water than field farming and hydroponics respectively.[32]

Climate change
Sustainable food sourcing can minimise net CO_2 emissions. Regenerative agriculture that boosts soil carbon can play a key role in climate action.

Biosphere integrity
Sourcing food from farms that apply agroecological principles can improve rather than degrade biodiversity. Hydroponics and agroecological practices do not require pesticides that are damaging to the biosphere.

Land-system change
Improved agricultural efficiency and a reduction in food waste can mitigate demand for further land conversion.

Freshwater use
Sourcing food from farms that employ water smart strategies for greater efficiency such as hydroponics, efficient irrigation, and healthy soils, can have a big impact in the sector that consumes most freshwater.

Biogeochemical flows
Hydroponics reduce nutrient use and waste when nutrients are applied to the plant's roots in a controlled environment with high efficiency[33] while natural farming practices focused on soil health do not require artificial inputs.

Novel entities
Sourcing food from farms that apply agroecological principles can reduce net use of novel entities (pesticides and artificial fertilisers) in agriculture. Foods grown in a controlled environment do not require harmful pesticides.

Ocean acidification
Local acidification can be mitigated by halting eutrifying nutrient runoff and employing plant-based aquaculture that sequesters CO_2. Sustainable food sourcing based on embodied emissions accounting can minimise net CO_2 emissions.

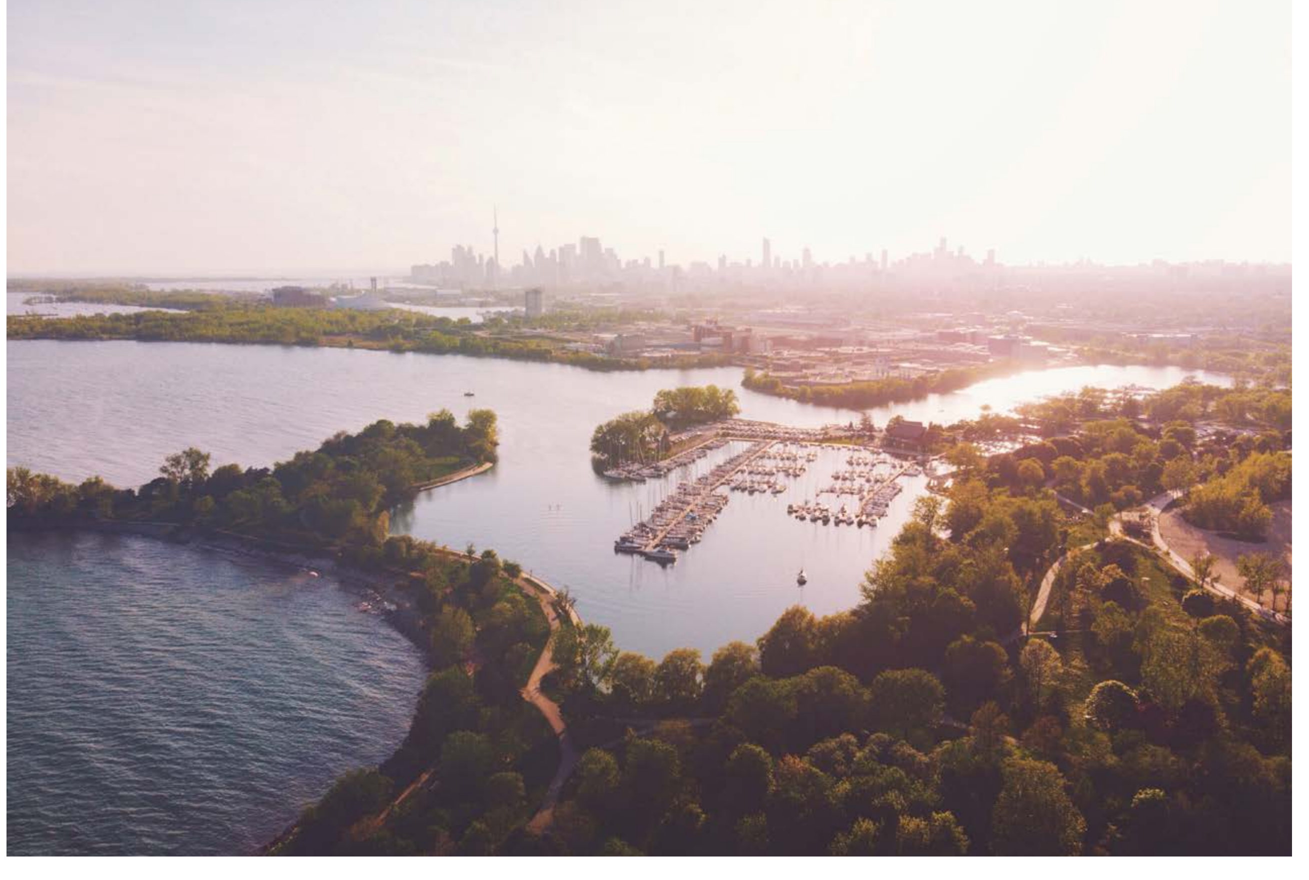
Further reading
Circular Bites: Reworking our urban food ecosystems for city-wide resilience.
Exploring sustainable food systems

Call to action

If we continue on our current trajectory humanity is guaranteed to experience: sea level rise, which will alter the physical landscape of the majority of global cities; resource depletion, which will impact the materials we design and build with; food scarcity, which will impact diets and cultural behaviours; temperature rise, which is already creating climate refugees and altering global populations; bad air quality, which will impact human health and wellbeing; and many other frightening outcomes. All of these are exacerbated by the continued urbanisation globally.

While it might sound dire, the positive outlook is that we can still change direction. If we combine opportunities from large scale policies at the government level, medium impacts achieved by corporations, and small changes in daily life, we can chart a new course towards a more hopeful future - one where the land can regenerate its natural resources, where waterways are free from pollution, where the air is clear, and where human life is in harmony with nature.

Regeneration of the full Earth system will require a fundamental shift in the way we think about our relationship with the planet.



The analysis of the PBF, and how it relates to the built environment, leads us to three conclusions:

It's time to act
Now is the time for action. The trajectory we are on is dire and must change. There is still time to act; to course correct and recalibrate our future. Today's actions will have a significant impact on the health of the planet for future generations.

Behaviour change is needed
The PBF helps us to understand the Earth's limited capacity to support the consumption patterns of modern humanity. Staying within the boundaries will require a substantial shift in daily 'norms' including: the way we produce and consume goods; travel into, out of and within cities; what and how we eat; how we design and build; and how we interact with the natural environment.

Regeneration is possible
The actions highlighted in this document offer a starting point for a regenerative model for the built environment, yet further change is needed. Incorporating environmental and sustainability assessments in projects, bringing diverse stakeholders to the table for project planning and implementation, respecting indigenous knowledge, and taking a systems-based planetary-centric approach can all support regeneration.

Regeneration of the full Earth system will require a fundamental shift in the way we think about our relationship with the planet. By reading through this document, we hope to have inspired you to think differently about your relationship with the Earth, inspired you to think about what a balanced human-planet relationship might look like and provoked your passion to drive change for yourself and the next generation.

Each and every one of us has the ability to shape the future.

What impact will you make?

How will you help shape a better world?

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Contributors and Reviewers

Arup
Adam Ozinsky
Alvise Simondetti
Andrew Chalmers
Anne Kovachevich
Chris Barrett
Damien Canning
David Harding
Dima Zogheib
Eike Sindlinger
Erica Levine
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Stephanie Merenbach
Stephanie Schemel
Summer Davies
Tom Butler
Tom Gray

External
Brian von Herzen
Climate Foundation

Chris Luebkeman
ETH Zurich

Holger Hoff
Potsdam Institute for Climate Impact Research [PIK]

Johan Rockström
Potsdam Institute for Climate Impact Research [PIK]

Kate Brauman
University of Minnesota

Lisa Churchill
Climate Advisory

Neal Spackman
Regenerative Resources Co

Project team

Lead Author
Lola Bushnell

Project Leader
Jonelle Simunich

Project Directors
Jo da Silva
Josef Hargrave

Copy Editor
Len Williams

Lead Designer
Eleanor Tomlinson

Graphic Designers
Emily Clements
Billy Searle

Marketing
Annabel Rabbets

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Arup University is the firm’s global excellence programme of directed learning, expert skills development, collaborative research, foresight, and knowledge and information management. Arup’s Foresight team analyse the major trends shaping the future of the built environment.

Our planet is accelerating rapidly out of the Holocene, the geological epoch that supported the evolution of our species and the rise of the modern world. Propelled by our collective patterns of consumption, production, mobility and urbanisation, this historic shift can be measured across nine key Earth system processes, each with a ‘planetary boundary’ that signifies the Earth’s capacity to tolerate change. The limits of these planetary boundaries must not be surpassed if Earth is to remain a hospitable state for generations to come.

Designing for planetary boundary cities describes the current status of each boundary and the forces driving change. It highlights international best practice in tackling the impacts and causes of environmental degradation and regenerative actions that the built environment could take now.

As designers, engineers, consultants and advisors we have a collective responsibility to build a better future: a built environment that helps drive our planet towards regeneration to ensure our species – and all life on Earth – continues to operate within the limits of Earth systems. Identifying ways to design, build, nurture and operate restorative urban systems will be key to whether all living species survive or thrive.