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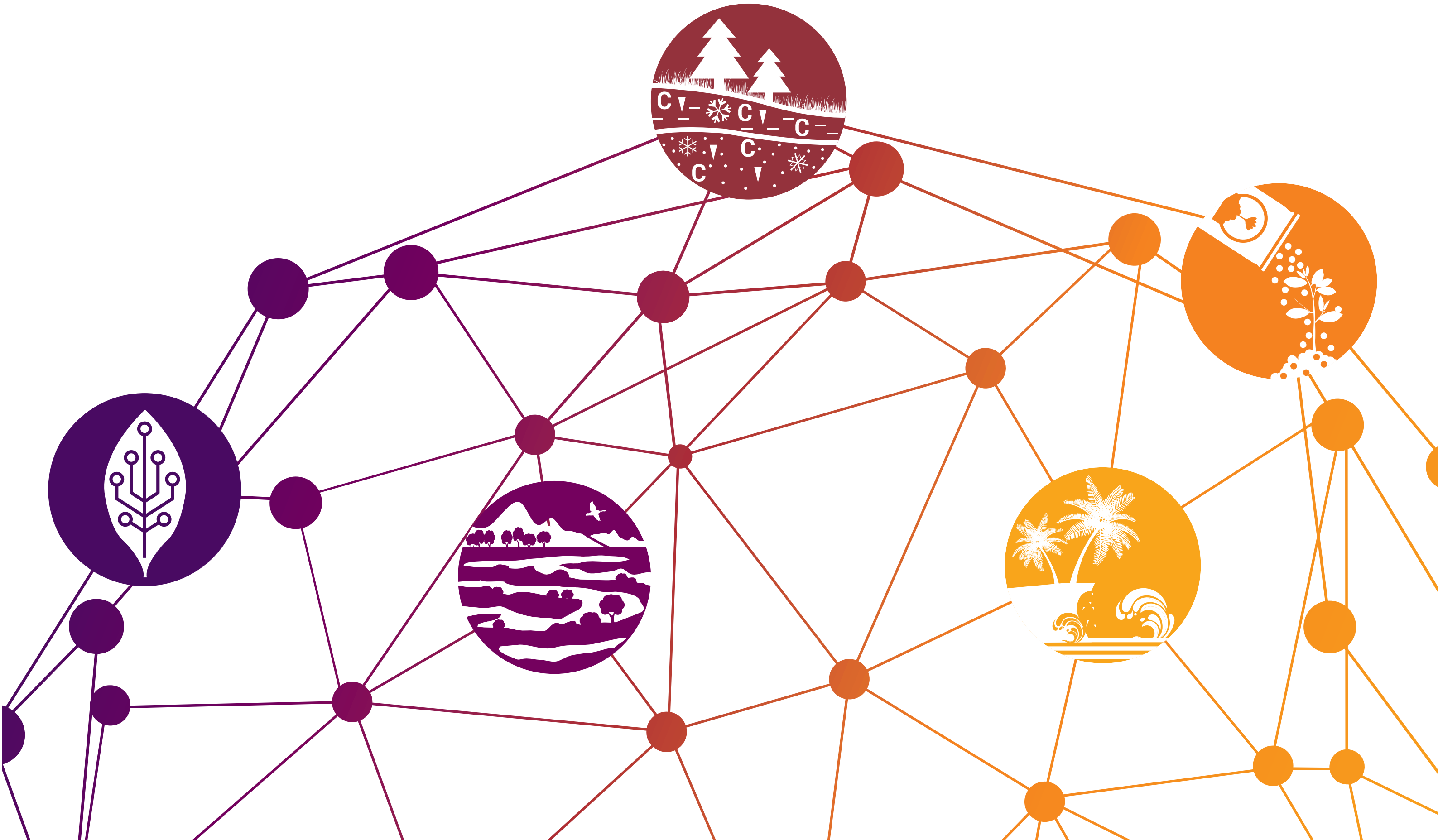
FRONTIERS 2018/19

Emerging Issues of Environmental Concern



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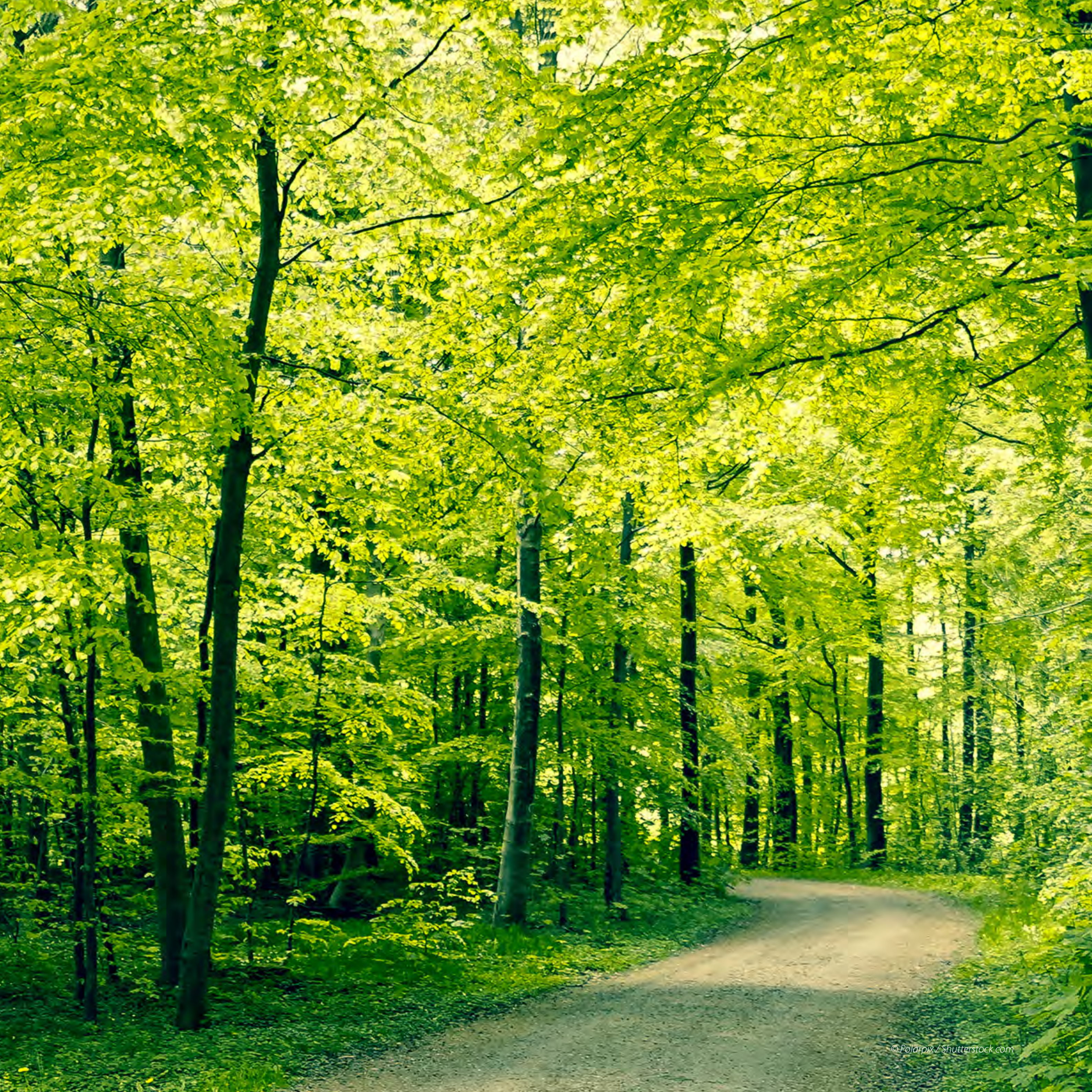


Foreword

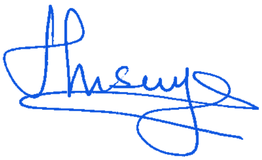
In the first decade of the 20th century, two German chemists – Fritz Haber and Carl Bosch – developed a way to produce synthetic nitrogen cheaply and on a large scale. Their invention spurred the mass production of nitrogen-based fertilizers, and thus transformed farming around the globe. It also marked the beginning of our long-term interference with the Earth's nitrogen balance. Every year, an estimated US$200 billion worth of reactive nitrogen is now lost into the environment, where it degrades our soils, pollutes our air and triggers the spread of "dead zones" and toxic algal blooms in our waterways.

It's no wonder that many scientists are arguing that "the Anthropocene" should become the official name of the current geological era. In just a few decades, humankind has caused global temperatures to rise 170 times faster than the natural rate. We have also deliberately modified more than 75 per cent of the planet's land surface, and permanently altered the flow of more than 93 per cent of the world's rivers. We are not only causing drastic changes to the biosphere, we are also now capable of rewriting – and even creating from scratch – the very building blocks of life.

Every year a network of scientists, experts and institutions across the world work with UN Environment to identify and analyze emerging issues that will have profound effects on our society, economy and environment. Some of these issues are linked to new technologies that have astonishing applications and uncertain risks, while others are perennial issues, such as the fragmentation of wild landscapes and the thawing of long-frozen soil. Another issue, nitrogen pollution, represents an unintended consequence of decades of human activity in the biosphere. While the final issue analyzed here, maladaptation to climate change, highlights our failure to adequately and appropriately adjust to the shifting world around us.

There is some good news to report. As you can read in the pages that follow, a holistic approach to the global challenge of nitrogen management is beginning to emerge. In China, India and the European Union, we are seeing promising new efforts to reduce losses and improve the efficiency of nitrogen fertilizers. Ultimately, the recovery and recycling of nitrogen, as well as other valuable nutrients and materials, can help us to farm cleanly and sustainably, a hallmark of a truly circular economy.

The issues examined in Frontiers should serve as a reminder that, whenever we interfere with nature – whether at the global scale or the molecular level – we risk creating long-lasting impacts on our planetary home. But by acting with foresight and by working together, we can stay ahead of these issues and craft solutions that will serve us all, for generations to come.



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Synthetic Biology: Re-engineering the environment

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Synthetic Biology:
Re-engineering the environment

Opportunities and challenges

The world is facing unprecedented challenges to a healthy and sustainable future. Habitat destruction, invasive species, and overexploitation are contributing to immense biodiversity loss.[1] Unsustainable, extractive industry practices further burden the environment, and by extension, human welfare. Vector-borne infectious diseases pose a major threat to global health.[2] Rapid climate change is likely to expand the geographical range of tropical diseases and further stress already taxed species and ecosystems.[3]

A number of approaches devised to meet these challenges – some proposed and others already implemented – share a common strategy. That is, they depend upon the genetic manipulation of living organisms to acquire new functions that otherwise do not exist in nature, in order to serve human needs. Scientists can modify microorganisms like *E. coli* by rewriting their genetic code to turn them into tiny living factories that produce biofuel.[4] Both baker's yeast and *E. coli* can be engineered to produce adipic acid – a petroleum-derived chemical key to the fabrication of nylon – thus offering an alternative to petroleum-dependent production.[5,6] Baker's yeast can also be reprogrammed to derive an antimalarial drug called artemisinin, which is normally sourced from the sweet wormwood plant.[7] These are all examples of products made possible by the advanced genetic-engineering technology known as synthetic biology.

The majority of commercially available synthetic biology products have been developed to provide alternatives to existing high-value commodities, especially those dependent

Succinic acid is a high-value chemical used in the food, pharmaceutical and chemical industries. *Basfia succiniciproducens* as shown above is a natural succinic acid producing bacterium found in bovine rumen. To achieve the industrial-scale production, it is genetically engineered for improved productivity. 4,000x magnification.

Photo credit: BASF

on the petroleum supply chain and non-renewable resources.[8] Moreover, synthetic alternatives and replacements for substances conventionally derived from nature are also gaining ground in research and market spaces.[9-12] Modern Meadow, a company behind the invention of a collagen-producing yeast, aims to deliver a sustainable leather alternative with properties and texture similar to animal-derived leather.[11] Synthetic biology has also opened up a new landscape for advanced materials with novel functionalities and performance, such as materials that can self-assemble or self-repair.[13]

The recent emergence of CRISPR (pronounced *crisper* and short for *clustered regularly interspaced short palindromic repeats*) as a gene-editing tool has enabled even more precise and inexpensive methods of engineering individual organisms, biological systems, and entire genomes.[14,15] Applications of synthetic biology are advancing beyond the manipulation of microbes in the laboratory to engineering the propagation of species outside controlled settings, for specific ends. Strategies to release genetically engineered organisms into the environment to permanently alter entire populations of target species have been proposed as a means to eradicate vectors of disease, eliminate invasive species, and lend resilience to threatened plants and animals.[16]

The Convention on Biological Diversity considers that the following operational definition is useful as a starting point for the purpose of facilitating scientific and technical deliberations under the Convention and its Protocols.

"**Synthetic biology** is a further development and new dimension of modern biotechnology that combines science, technology and engineering to facilitate and accelerate the understanding, design, redesign, manufacture and/or modification of genetic materials, living organisms and biological systems."[20]

The intentional or accidental release of genetically engineered organisms into the environment could have significant negative impacts on both human and environmental health. Misuse of these technologies and a failure to account for unintended consequences could cause irreversible environmental damage and pose significant geopolitical threats.[17] The potential far-reaching impacts of synthetic biology demand governance methods and research guidelines that promote its ethical and responsible use.[18,19]

The filamentous fungus, *Aspergillus niger*, can naturally produce enzymes that are commercially important in the food and animal feed industries. The microorganism is genetically modified to enable the large-scale enzyme production. 180x magnification.

Photo credit: BASF

Rewriting the code of life

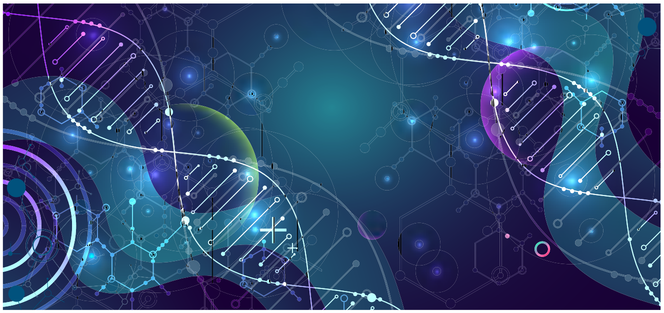
The development of recombinant DNA technology in the 1970s marked a major shift in how humans control genomes.[21] Genetic sequencing technologies allowed for tracts of DNA to be read and understood, providing the blueprint to engineer genomes for new gene expressions. DNA sequences can be completely rewritten by deleting, adding or replacing segments. Entire portions of DNA can now be chemically synthesized and assembled, which has led to the creation of synthetic life.[22]

The latest gene editing tool, CRISPR-Cas9, has garnered significant excitement in the scientific community and general public alike. First described in 2012, CRISPR is faster, cheaper, more accurate, and more efficient than any of its gene-editing predecessors.[23,24] It has speeded up the editing process from several months to just a few days.[25,26]

The CRISPR-Cas9 gene-editing technique was inspired by a naturally occurring defence system of certain bacteria against viral invasion.[27,28] In nature, a bacterium can deploy the Cas9 enzyme to cut invasive genetic material inserted by a virus, effectively disabling the attack. Researchers have adapted this mechanism to cut DNA at any specific location. In CRISPR-Cas9 gene editing, scientists use a guide RNA to direct the Cas9 enzyme to a precise portion of DNA.

The Cas9 enzyme then acts as a pair of molecular scissors, cutting or deleting the targeted segment. By exploiting the natural DNA repair process, researchers can also insert a customized DNA segment into the disrupted strand.[29]

Video: Synthetic biology explained



Video link: https://www.youtube.com/watch?v=rD5uNAMbDaQ *© techNyouvids*
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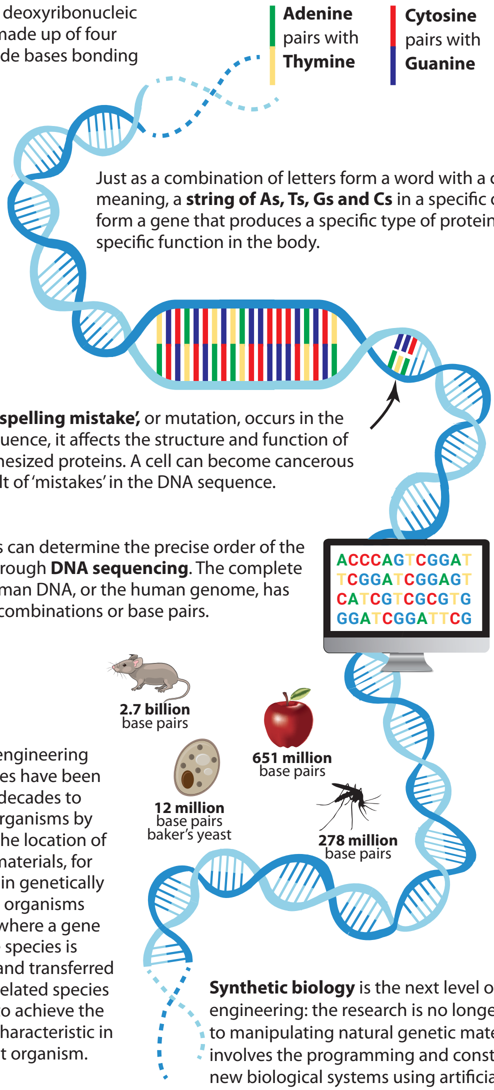
DNA is in every living organism's blueprint. It guides the production of proteins needed for an organism to function.

DNA, or deoxyribonucleic acid, is made up of four nucleotide bases bonding in pairs.



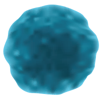
Just as a combination of letters form a word with a certain meaning, a **string of As, Ts, Gs and Cs** in a specific order form a gene that produces a specific type of protein for a specific function in the body.

When a **'spelling mistake'**, or mutation, occurs in the DNA sequence, it affects the structure and function of the synthesized proteins. A cell can become cancerous as a result of 'mistakes' in the DNA sequence.

Scientists can determine the precise order of the letters through **DNA sequencing**. The complete set of human DNA, or the human genome, has 3 billion combinations or base pairs.

Genetic engineering techniques have been used for decades to modify organisms by altering the location of genetic materials, for example in genetically modified organisms (GMOs), where a gene from one species is isolated and transferred to an unrelated species in order to achieve the desired characteristic in the target organism.

Synthetic biology is the next level of genetic engineering: the research is no longer confined to manipulating natural genetic materials, but involves the programming and construction of new biological systems using artificially synthetized DNA.



In 2010, scientists announced their success in creating the world's first synthetic bacterial cell after a decade of learning to design, synthesize and assemble a DNA sequence from scratch.

Using the natural baker's yeast genome as a blueprint, a consortium of scientists are now working to construct a yeast cell made out of entirely synthetic DNA.

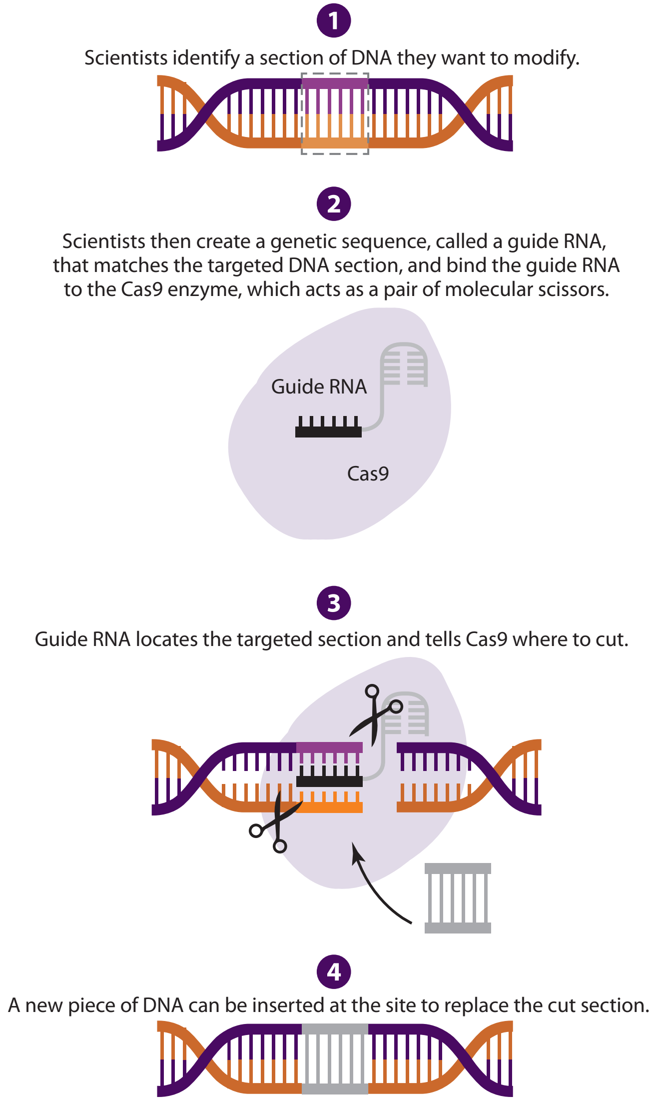
The spherical spores produced by fungus *Emericella nidulans* are coated in a layer of the protein hydrophobin which repels water. The gene responsible for hydrophobin production has been introduced into *E. coli* bacteria to manufacture the protein with commercial applications. 400x magnification
Photo credit: BASF

This editing process can be likened to locating and precisely cutting a specific word or a sentence out of a document, and if desired, replacing it with new wording. CRISPR is now being used to repair disease-causing mutations in humans, achieve new traits in crops, and synthesize novel microorganisms.[14] More recent developments include the use of CRISPR-Cas13 to edit RNA instead of DNA.[30]

CRISPR gene editing is being used in research aiming to engineer wild organisms outside human-controlled environments. *Gene drives* are a synthetic biology application that depends on CRISPR gene editing to ensure the expression of desired gene edits in future generations of a wild species.[31] The process involves an organism being engineered in a laboratory to encode a CRISPR-based gene drive and a desired gene edit. This organism is then released to mate with the normal population in the wild, forcing the inheritance of the desired gene edit along with the gene drive system in its offspring. The gene drive is a self-perpetuating process that repeats whenever the offspring mates with the wild population. And over time, the entire population of that species will all carry both the desired gene edit and the gene drive system. CRISPR-based gene drives can also ensure the inheritance of traits that disrupt reproduction, such as sterility, which could spread in a population and potentially lead to extinction. The application of CRISPR-based gene drives is most suited to sexually–reproducing species with short generation times, like most insects and some rodents.[32]

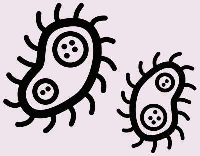
CRISPR-Cas9 genome editing technique

In nature, CRISPR-Cas9 is the bacteria's defense and immunity strategy against viral attacks, utilizing the system to precisely identify and cut the DNA of an invading virus, thus disabling the attack. Scientists have adapted the CRISPR-Cas9 mechanism for genome editing as it offers a more precise, relatively cheaper and faster way to modify a genome.



Synthetic Biology

Sustainability applications



Many industries have made use of synthetic biology. Microorganisms, from bacteria to yeasts, are genetically engineered to become tiny factories producing more sustainable ingredients for medicines, vaccines, biofuels, green chemicals and new materials.

Pharmaceutical products

E. coli is altered to manufacture a **vaccine** against chlamydia, which is becoming more resistant to conventional antibiotics

Green and bio-based chemicals

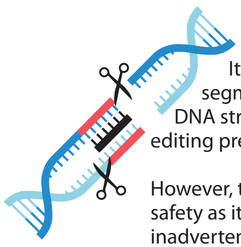
A variety of chemicals in everyday products are derived from petroleum. Synthetic biology enables the production of substances that can replace petroleum-based chemicals.

Alternatives to chemicals derived from unsustainable sources

The blood of horseshoe crabs is a major biomedical commodity used in pharmaceutical testing for bacterial contamination. A synbio substitute could reduce or replace the need for harvesting the nearly extinct species from the oceans.

Lactic acid, succinic acid and **propanediol** are among chemicals made by genetically engineered microbes that are commercially available in the global market

CRISPR-Cas9 genome editing technique



The discovery of CRISPR-Cas9 has changed the entire outlook of synthetic biology research. It enables scientists to cut out a particular DNA segment of a desired sequence or replace it with a new DNA strand. Many fields of medical research require such editing precision to revolutionize treatments.

However, the technique is also subject to scrutiny for its safety as it involves a potential off-target effect, whereby it inadvertently cuts out DNA that has a similar sequence to the targeted strand, potentially triggering cancer in edited cells.

Market and investment

US$13.9 billion

Projected global market value of synthetic biology applications by 2022

US$1.9 billion

2018 Global investment in synthetic biology **startups**

Do-It-Yourself Biology or DIY Bio

The movement of so-called 'citizen scientists' interested in performing synthetic biology experiments has gained significant traction globally. Biology enthusiasts – many without scientific background – meet in garage labs to conduct experiments using specialised DIY kits and simple protocols available online.

Some of the group have specialised equipment and hire professional staff to help citizen scientists, biohackers and biology enthusiasts in developing their projects.

Risks and policy considerations

There are concerns that synthetic biology could be used to re-engineer existing pathogenic viruses, making them more dangerous or produce biochemicals with only modest resources and organizational footprint.

Synthetic biology presents new challenges that need to be addressed through the consolidated action of governmental and international bodies. Development of effective methods to better manage emerging risks is essential in ensuring technological safety.

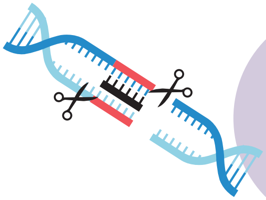
Applications for conservation and public health

CRISPR-based gene drives may be key to addressing some global challenges, such as vector-borne diseases or invasive species, but they require multifaceted societal debate because of their power to modify, suppress or replace the entire population of the target species, bypassing the fundamental principles of evolution

Gene drives with suppression intent can force the inheritance of detrimental genetic alterations, such as sterility, potentially reducing the target population to zero. The suppression drive is intended to control the populations of malaria-carrying mosquitoes in the environment.

The release of only a few gene-drive-bearing organisms into the environment can transform an entire species population and potentially the whole ecosystem

Gene drives have been made possible by the development of CRISPR-Cas9 technology

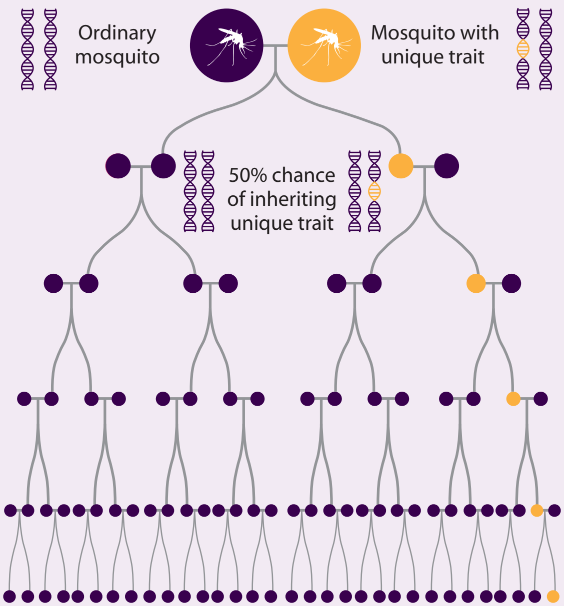


American chestnut trees are near extinction due to chestnut blight, a fungal disease native to Asia. Pending regulatory approval, the American chestnut can be engineered to be blight-resistant and spread in the wild.

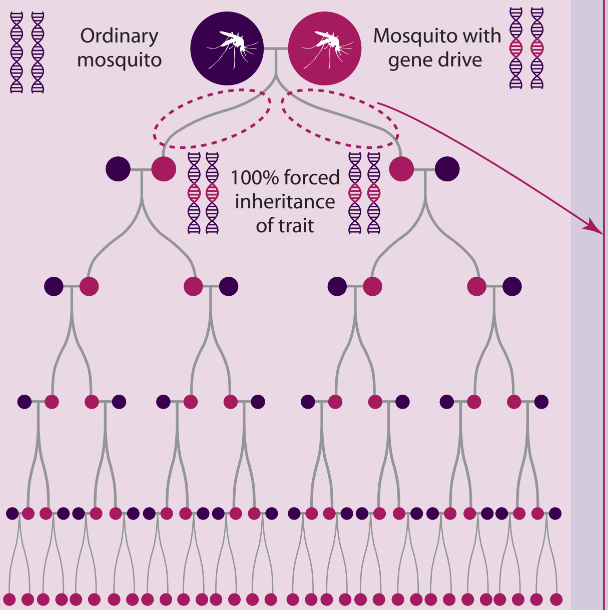
Genetic cross-contamination between species and unintended ecological damage are some of the legitimate concerns that have not yet been resolved

CRISPR-based gene drives: Manipulating the wild populations of plants and animals

Normal inheritance
In sexual reproduction, each parent passes half its DNA to its offspring. A parent's unique genetic trait has a 50-50 chance of being inherited by the next generation. Over many generations the unique genetic character still remains in the population but at low frequency. The normal inheritance also applies to the case of an offspring produced by a normal parent and a classic GMO parent.



Gene drive inheritance
A synthetic gene drive circumvents the rules of normal genetic inheritance. This self-perpetuating mechanism is designed to ensure preferential inheritance of a modified genetic trait in future generations. Over time the entire population inherits the preferred engineered trait.



During fertilization, the offspring inherits one set of DNA from the ordinary parent and one containing the CRISPR-equipped gene drive from the genetically engineered parent. CRISPR-Cas9 looks for the target site in the ordinary DNA and cuts it.

When the cut DNA attempts to repair the damage, it copies the engineered strand containing the gene drive.

The offspring ends up having two copies of the genetically engineered DNA with gene-drive capability to pass on to future generations.

Applications redefined: From laboratory to ecosystem

Synthetic biology could indirectly benefit conservation efforts by allowing the development of artificial alternatives to commercial products normally sourced from the wild. For example, the blood of the horseshoe crab is a major biomedical commodity used to test pharmaceuticals for bacterial contamination. Unsustainable harvesting is pushing the species towards global extinction.[33] A synthetic substitute has been developed that could reduce or replace the need to harvest the endangered crabs.[34,35] Likewise, engineered microbes and microalgae capable of producing alternatives to omega-3 oils could lessen pressure on declining wild fish stocks.[36]

Conservation measures that propose a more direct application of the technology on target species have recently emerged. Releasing genetically engineered organisms into the environment could restore the health or enhance the resilience of damaged populations. For example, using an approach that predates CRISPR, scientists have synthesized the oxylate oxidase gene normally expressed by wheat, and forced its expression in the American chestnut tree. This gene can neutralize the toxin secreted by the blight that has driven the tree functionally extinct.[37,38] Pending regulatory approval, blight-resistant chestnuts could be planted to re-establish this once-dominant species in eastern U.S. forests. Unlike genetically modified crops, where safety concerns largely centre around containment, the engineered American chestnut is deliberately designed to spread and flourish in the wider environment.

As climate change is predicted to increase rates of species extinction worldwide, CRISPR's availability is likely to hasten applications for ecosystem restoration.[39] Scientists have proposed using CRISPR for threatened species, such as corals that are under immense stress from increased ocean temperatures, acidification and pollution. Proof-of-concept CRISPR research is underway to rewrite coral genomes to express mutations that endow resilience.[40,41] However, frameworks for field implementation of this research have yet to be developed.

Video: Genetically modified mosquitoes

Video Link: https://www.youtube.com/watch?v=zlSTGkDyEfM *© biointeractive*
Photo credit: Ajintai / Shutterstock.com

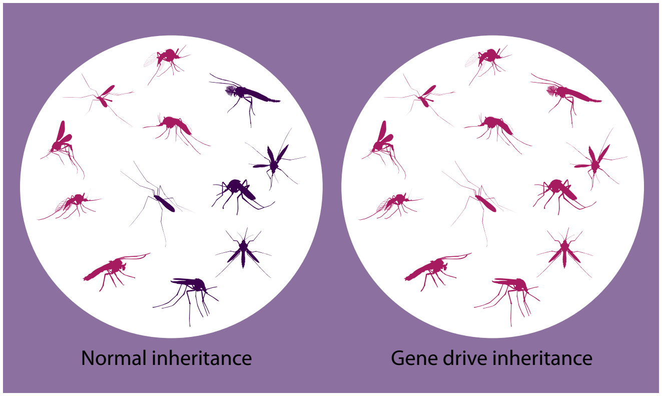
CRISPR-based strategies could also remove invasive species from threatened ecosystems. On many Pacific islands, for example, invasive rodents are decimating native bird populations.[42] Through international collaboration, the Genetic Biocontrol of Invasive Rodents programme is developing CRISPR-based gene drives that would spread sterility.[43,44] In New Zealand, CRISPR-based gene drives are being considered to help achieve the elimination of all invasive predators by 2050.[45] In Hawaii, gene drives have been proposed to reduce avian malaria spread by house mosquitoes that has caused serious declines in rare bird populations.[46,47] However, recent research indicates that gene drives may face resistance and limited efficacy in wild mosquito populations.[48,49]

It has even been suggested that extinct species could be resurrected for their ecological benefits, such as reviving a woolly-mammoth-like animal by gene editing the DNA of its closest living relative, the Asian elephant.[50,51] Proposals for de-extinction of species are not only highly debatable, but also re-emphasize the importance of addressing the root cause of extinctions. Such possible genetic interventions, even if unrealized, encourage a valid debate on how biotechnology can support, coexist with, or undermine the goals of conservation.[52]

De-extinction

Attempts to revive species that have recently become extinct or are close to extinction have been made to date using back-breeding and cloning techniques.[58-60] These approaches depend on the availability of tissues from extinct animals to clone, and extant species for crossbreeding or to serve as a surrogate.[61,62] None of the de-extinction efforts have succeeded so far. Bringing back species that have long disappeared from the planet and left very little trace of their DNA is only remotely plausible. It would require the reconstruction of the entire genome and the existence of a closely related species for viable surrogacy. Even if the technological difficulties can one day be overcome, significant challenges remain in relation to how the de-extinct species would function in today's environment. Fundamental ecological concerns include the uncertainty of species competition and interaction; the susceptibility of de-extinct species to diseases and parasites; the possibilities of serving as a disease vector or becoming invasive species themselves; and the probability of establishing and sustaining a healthy population from individuals with low genetic diversity.[61]

Video: What is a gene drive?



Video Link: https://www.youtube.com/watch?v=75iP50LEHrU *© STAT*

Video: Why horseshoe crab blood is so expensive

Video link: https://www.youtube.com/watch?v=LgQZWSILBnA *© Business Insider*
Photo credit: Lysogor Roman/ Shutterstock.com

To reduce the global disease burden, various synthetic biology strategies aim directly at suppressing populations of disease vectors. A company called Oxitec has genetically engineered mosquitoes to express a synthetic lethal gene and has released them in South America, South-East Asia, and several Caribbean nations to suppress the vector for Dengue fever, Zika virus, yellow fever, and chinkengunya.[53,54] These so-called 'self-limiting' mosquitoes pass a lethal gene to their offspring, preventing them from surviving to adulthood. This method of suppression is, however, reversible without continual releases to sustain the engineered mosquito population in the wild. To circumvent this issue, Target Malaria, an international consortium funded by the Bill and Melinda Gates Foundation, is developing CRISPR-based gene drives to permanently control the malaria vector in sub-Saharan Africa.[55] CRISPR-based gene drives are highly invasive as, in theory, a one-time release of a few gene-drive-bearing organisms could completely suppress an entire wild population. Another strategy is to use gene drives that do not suppress the population, but instead limit the ability of mosquitoes to transmit pathogens.[56] CRISPR-based gene drives have also been devised to permanently immunize white-footed mice against Lyme disease on islands in Massachusetts, USA.[57]

Innovating with wisdom

The release of genetically engineered organisms accidentally or intentionally into the environment has raised valid concerns about biosafety and unpredictable consequences. For organisms engineered in closed research or industrial facilities, containment procedures and enforced regulations on waste disposal help to avoid an escape, although this is never fail-proof.[63] In the case of intentional release, concerns over potential genetic cross-contamination between species, ecological interactions and impacts on ecosystems and their services remain largely unresolved.[64] Altering a disease carrier genetically could potentially cause a pathogen to evolve and become more virulent, or to be carried by a new vector.[65]

To date, CRISPR-based gene drives have been tested only on small populations in controlled settings, with one recent experiment successfully collapsing the entire malaria-carrying mosquito population in the laboratory.[66] As a first step towards wider trials, Target Malaria has recently gained permission to release 10,000 modified mosquitoes in Burkina Faso. These specimens will be genetically engineered to be sterile, but with no gene drives, to test how well they compete with wild males.[67] However, such field trials to evaluate the efficacy of the gene-drive system could pose inherent risks.[68,69]

Under the precautionary principle, stringent risk assessment and the inclusion of diverse stakeholder perspectives should be applied in the development and handling of innovative synthetic biology applications and products.[19,70,71] The precautionary principle states that when human activities may lead to unacceptable harm that is scientifically plausible but uncertain, action should be taken to avoid or diminish that harm.[72] A concept of substantial equivalence – that a genetically modified organism is as safe as its traditional counterpart – is often mentioned in conjunction with the precautionary principle.[73] Some countries have extensive policy and regulations in place concerning genetic engineering and research, while for others, non-functional regulatory systems, policy gaps and risk-assessment capacity are major challenges.[74-77]

Attempts have been made to identify, evaluate and address the ethical and biosafety concerns of synthetic biology. The U.S. National Academies of Science, Engineering, and Medicine published a report on gene drives in 2016 highlighting the need for stringent environmental risk assessments and deliberation that charters human values and necessitates rigorous public engagement.[19]

In December 2017, the ad-hoc technical expert group on synthetic biology, established by the Parties to the Convention on Biological Diversity, concluded that organisms – developed or being developed through current methods of synthetic biology, including those containing gene drives – fall under the description of living modified organisms (LMOs), which are regulated under the legally-binding Cartagena Protocol.[78] With 171 Party nations, the Protocol applies the precautionary approach and requires that each Party take all necessary measures to ensure the safe handling, transport and use of the resulting LMOs.[79]

SYNBIOSAFE, an EU-funded research project, was established to identify key issues in safety, security, risk management ethics and, importantly, the science–society interface, which emphasizes public education and dialogue among scientists, businesses, government, and ethicists.[80,81] Some gene-drive developers have also proposed ethical research guidelines that emphasize the need for meaningful public engagement.[82]

Video: Why is this African village letting mosquitoes in?

Video Link: https://www.youtube.com/watch?v=ooYShrGtkUQ *© BBC News*
Photo credit: Dmitry Trashchenko / Shutterstock.com

Video: Could genetically engineered mice reduce Lyme disease?

Video Link: https://www.youtube.com/watch?v=FOCNixYPsf4 *© PBS NewsHour*
Photo credit: Szasz-Fabian Jozsef / Shutterstock.com

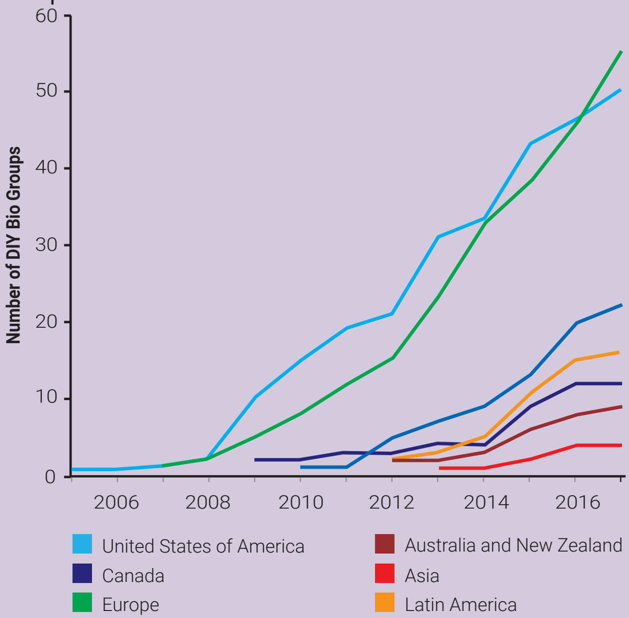
Nevertheless, the intentional release of modified organisms and their potential to permanently transform wild species and cross international borders will likely test the limits of current policy, leading some environmental groups to call for a moratorium on all gene-drive research.[83] Other regulatory concerns focus on the potential use of synthetic biology for military offensive purposes.[84,85]

Current ethical frameworks may not be able to keep pace with the rapid progress of synthetic biology and its inherent complexity, especially concerning wild species.[86] Decisions to release engineered organisms into the wild will be shaped by the pervading environmental ethic, or how a majority of citizens relate to non-human nature.[87] Altering the genetic code of wildlife is seen by some as a gross overstep by humans, echoing concerns about genetically modified crops. Others may feel that there is a moral responsibility to use a technology that could save lives or restore damaged ecosystems.[87] These contrasting value systems require responsible decision-making for resolution.[89] Synthetic biology applications also raise questions of who has ownership of an LMO and its genome, what protection is available for vulnerable communities, and how to ensure those most impacted have a voice. It is crucial that balanced and inclusive deliberative forums steer the field of synthetic biology and ensure that its environmental applications are used to the benefit of all on our shared planet.

Citizen scientists, biohackers and garage labs

Synthetic biology and genome editing have attracted interest not only from companies, but also regular citizens. Do-It-Yourself Biology, also known as "DIY Bio", the movement of "citizen scientists" interested in synthetic biology experiments has become an international phenomenon over the last decade. Often with little prior knowledge of the field, enthusiasts meet in makeshift labs to take crash courses in biotechnology and conduct hands-on experiments.[90,91] Simple protocols found online and specialized kits costing US$150–1,600 have driven the movement's rapid expansion.

DIY Bio labs can be found in most major cities and by 2017 there were about 168 groups worldwide.[92,93] Regulating the use of easily accessible and low-cost technologies like CRISPR and gene editing kits will likely be a challenge for authorities. There is also growing concern that the technology could be misused by terrorists to destroy agricultural crops or turn harmless microbes into biological weapons.[94]



Source: The Brookings Institute[93]

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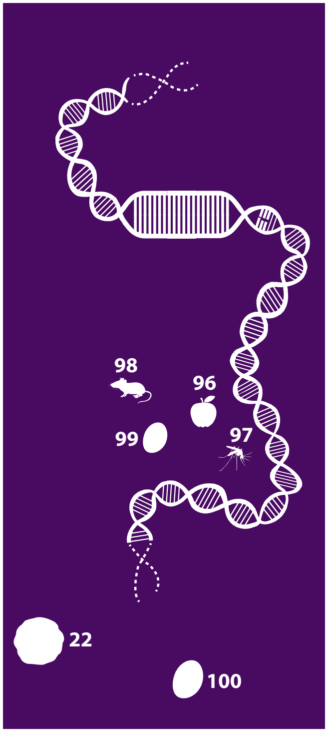

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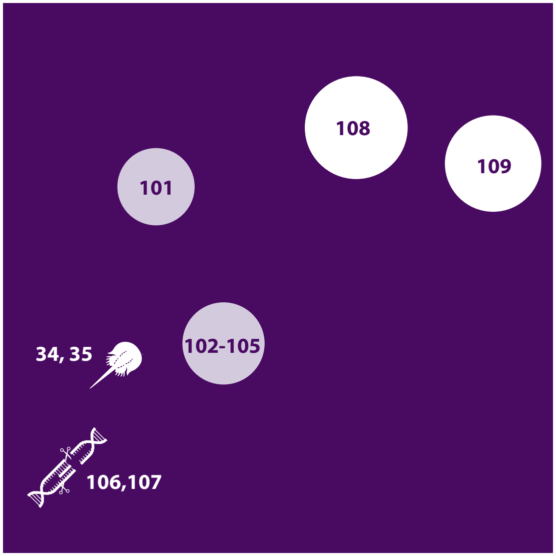

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Ecological Connectivity:
A bridge to preserving biodiversity

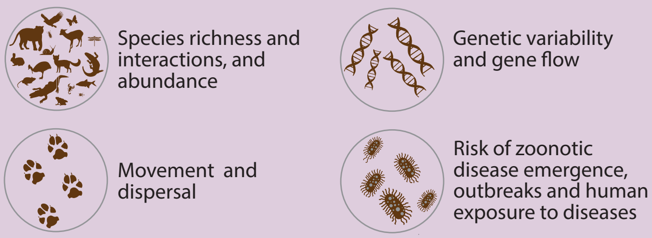
Reconnecting fragmented ecosystems

Nature was once vast and boundless, but in an industrialized, 21st century world, this is no longer the case. Across the globe, landscapes and seascapes are becoming more fragmented. Wildlife has less freedom to roam and free-flowing rivers are increasingly rare. Along tropical coastlines, previously seamless gradients of mangroves, seagrass meadows and coral reefs are now more fractured, undermining essential productivity and ecosystem resilience to natural and anthropogenic disturbances.[1] A consequence of the segmentation of natural landscapes is that mammals and other species are moving less than half the distance they once did.[2] This limited ability to migrate, disperse, mate, feed and thrive means that wild animals are cornered into situations where the threat of extinction looms larger.

Fragmentation is typically a symptom of landscape transformation and destruction. The division of habitat into fragments has three specific effects: a reduction of overall habitat area and quality, increased isolation of small habitat patches, and increased disturbance associated with artificial boundaries of habitat fragments, or 'edge effects'.[3-6] Isolated and smaller patches of habitat mean fewer species and smaller populations in each patch, with restricted interactions among habitat patches. Increased fragment edges expose populations within the patch to external disturbances along the boundaries. Eventually, when a patch becomes too small and isolated, viable populations and species richness can no longer be sustained.[5] Fragmentation ultimately leads to a downward spiral of cascading ecological dysfunctions, from the unravelling of food webs, to the loss of critical ecological processes such as mineral and nutrient flows, to direct extinction of species.[3,5,7-9]

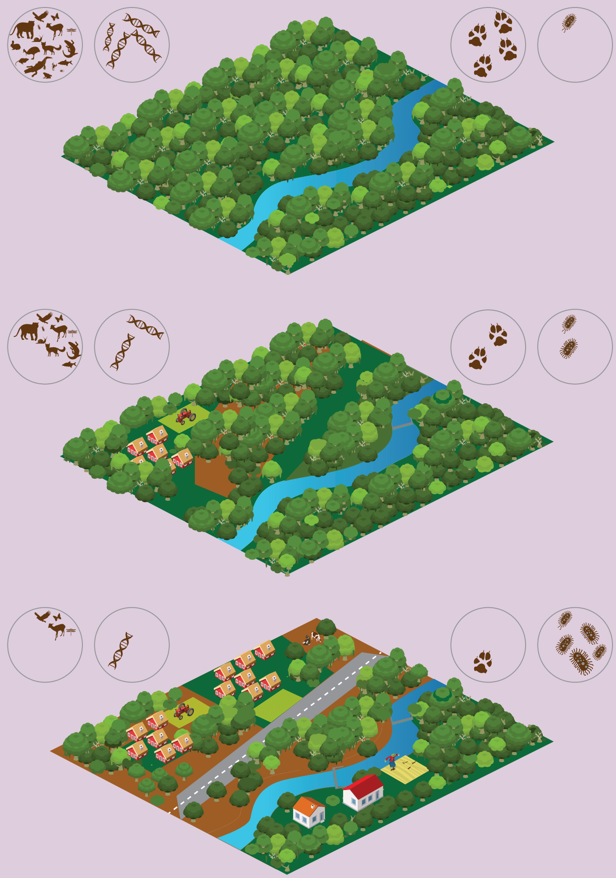
Maintaining or restoring connectivity between fragmented habitats or landscape patches has been identified as the key to counteracting many of the negative impacts of fragmentation.[10] Connectivity can be defined as the degree to which landscapes and seascapes allow species to move freely and ecological processes to function unimpeded. Scientific evidence built on island biogeography research and species meta-populations studies overwhelmingly demonstrates that connected habitats are more effective in preserving species and ecological functions.[11,12] Connected ecological communities and habitat patches sustain vital ecological processes such as pollination, productivity, decomposition, and biochemical and nutrient cycling. Ecological connectivity can also help species adapt to future environmental conditions and buffer changes by bolstering ecological resilience to disruptive threats such as climate change.[13]

Despite the obvious advantages, the world's nations currently lack a consistent approach to implementing connectivity conservation. What are the best measures to assess success for connectivity conservation? How do governments and conservationists create corridors, design ecological networks, or determine the effectiveness of connectivity conservation efforts? The conservation of intact landscapes and seascapes through the designation of more or large-scale protected areas is feasible, but requires making difficult political, social and economic choices.[14,15] Connectivity as a conservation target requires shared goal setting among stakeholders to ensure multidimensional consideration and implementable coordinated action. Public and private sectors must work together for effective outcomes because stopping biodiversity loss and reducing the impact on ecosystems is a shared responsibility of both sectors, from the community level to a global scale. In many instances, connectivity efforts can incorporate local socioeconomic concerns within a larger conservation framework.



Habitat fragmentation

About 40% of terrestrial ecosystems have been converted into agricultural landscapes.[16] Land and river transformation for human use leads to habitat fragmentation. Smaller and more isolated fragments of habitat surrounded by human activities are less likely to maintain the function and survival of animal and plant inhabitants. Habitat fragmentation negatively affects abundance, distribution, movement, species richness and interactions, reproduction and genetic diversity.[5] It impairs the ability of species to adapt to new climatic conditions.[17]



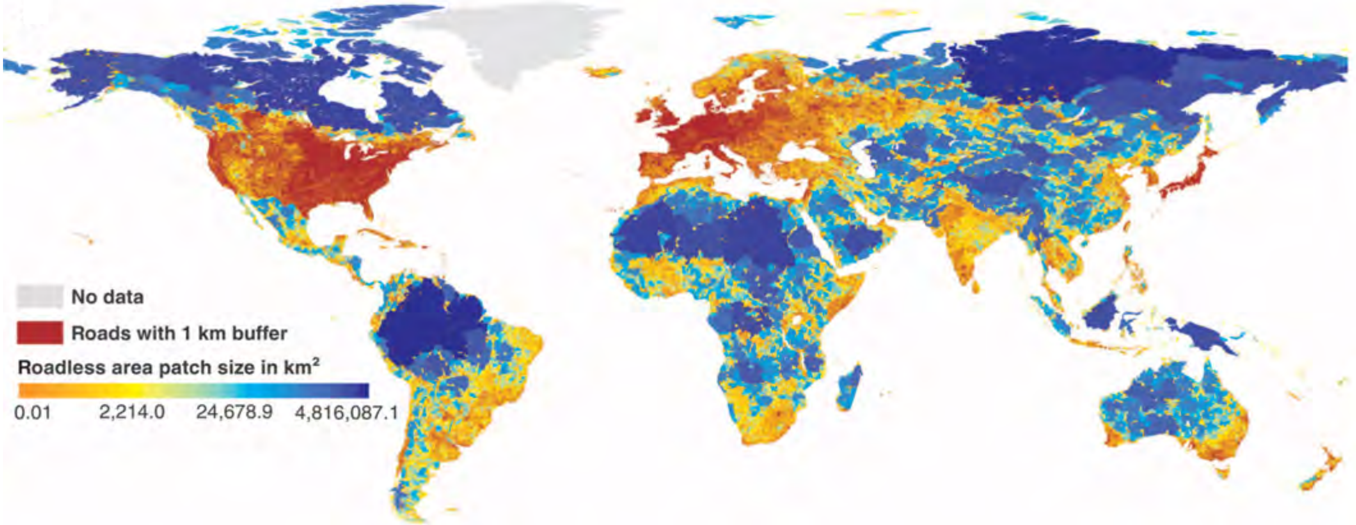
The forces of fragmentation

Societies are transforming the Earth's biosphere and reshaping its ecology in unprecedented ways. The latest research indicates that more than 75 per cent of the planet's land surface has been modified by humanity.[18-21] Human population pressures, growing urbanization, agricultural expansion, pollution, and infrastructure development all work in synergy as fragmentation forces. Some land-use projections estimate that by 2050, roughly one billion hectares of tropical land could be cleared specifically for agricultural needs.[22] The marine environment is even less immune to these trends: new research shows that of the world's oceans, only around 13 per cent is still classified as marine wilderness, much less than many conservationists had expected.[23]

Linear infrastructure is often the tip of the spear of modern development. Roads, rails, pipelines, fences, and canals are being built at record rates, especially in remote, previously undeveloped regions of the tropics. Ninety per cent of all new road construction is expected to occur in developing nations.[24] In India, where nearly 60 per cent of the world's tiger population is found, critical tiger corridors are threatened by 4,300 kilometres of newly planned national and state roads.[25] Globally, over 25 million kilometres of new roads are anticipated by 2050 – a 60 per cent increase in the total length of existing roads in 2010.[26]

Free-flowing rivers, the ecological lifeblood of landscapes and estuaries, are challenged by the fragmentation resulting from the size and scale of the ongoing construction of dams. Large dams divide 59 per cent of global rivers into sections, disrupting the natural flow of 93 per cent of the global river volume, with nearly 28 per cent considered to be under heavy or severe flow regulation.[27] In the Amazon basin alone, there are currently over 400 dam projects being developed, constructed, or planned.[28] Together, dam construction, road building and deforestation work to undermine the ecological integrity of continental river basins, which also has real consequences for other human economic and recreational activities. For example, freshwater connectivity contributes approximately US$200 million per year to the Amazon basin fishing economy that provides employment for roughly 200,000 anglers.[29]

Landscape fragmentation by roads



An analysis of a dataset of 36 million km of roads across the world shows that roads have fragmented the earth landscape into more than 600,000 patches. More than half of these patches are within 1 km range of any road (in red). Moving towards the blue shade are land patches further away from all roads and less influenced by road effects.

Source: Ibisch et al. (2016)[30]

Xingu River in northern Brazil in 2000 and 2017

The construction of the Belo Monte hydroelectric dam project in 2011 has completely reshaped the Xingu River. More than 80% of the river flow has been diverted, causing large areas to dry up and directly affecting indigenous communities and wildlife living in the area.
Photo credit: Joshua Stevens / NASA Earth Observatory

Rivers, landscapes and coastlines are inextricably linked. Connectivity is also a recognition that nature operates as an integrated sum of its parts. Connectivity between aquatic and terrestrial systems is vital to ecological integrity and too often, these elements are managed as separate units. In temperate ecosystems, for example, research has shown that the footprint of gravel-bed river floodplains extends well beyond riparian zones. This influence on sub-surface terrestrial ecology projects beyond visible river channels and their deltas, reaching further into the marine realm. Free-flowing river systems work to connect aquatic, avian, and terrestrial communities – from microbes to grizzly bears – influencing the biogeochemistry of landscapes and seascapes along the way.[31]

Video: Seed dispersal and forest fragmentation

Video link: https://www.youtube.com/watch?v=0m6AjWZ2p8I *© HHMI BioInteractive*
Photo credit: Jess Kraft / Shutterstock

Landscape fragmentation and connectivity

Landscape fragmentation is the subdivision of large, continuous habitats into smaller, more isolated pieces or patches.

Landscape connectivity is a measure of the extent to which a particular landscape allows the free movement of animals and other ecological flows.

As the climate warms, maintaining connectivity between areas of different temperatures could allow organisms to move along **temperature gradients**, permitting species to adapt

Well-connected spaces allow species to migrate to new habitats, especially when they need to **adapt to climate change**

River fragmentation is mostly caused by **dams and reservoirs**, which disconnect upstream and downstream ecosystems, affecting pathways for species dispersal and migration as well as transport of organic and inorganic matters

Globally, the construction of over **3,700 large hydropower dams** is planned

Roads change the behaviour of some species. Studies found animals like hedgehogs, rattlesnake, turtles, red squirrels and snails avoided crossing roads.

Transport infrastructure such as **roads** and **railways** disrupts the movement of wildlife

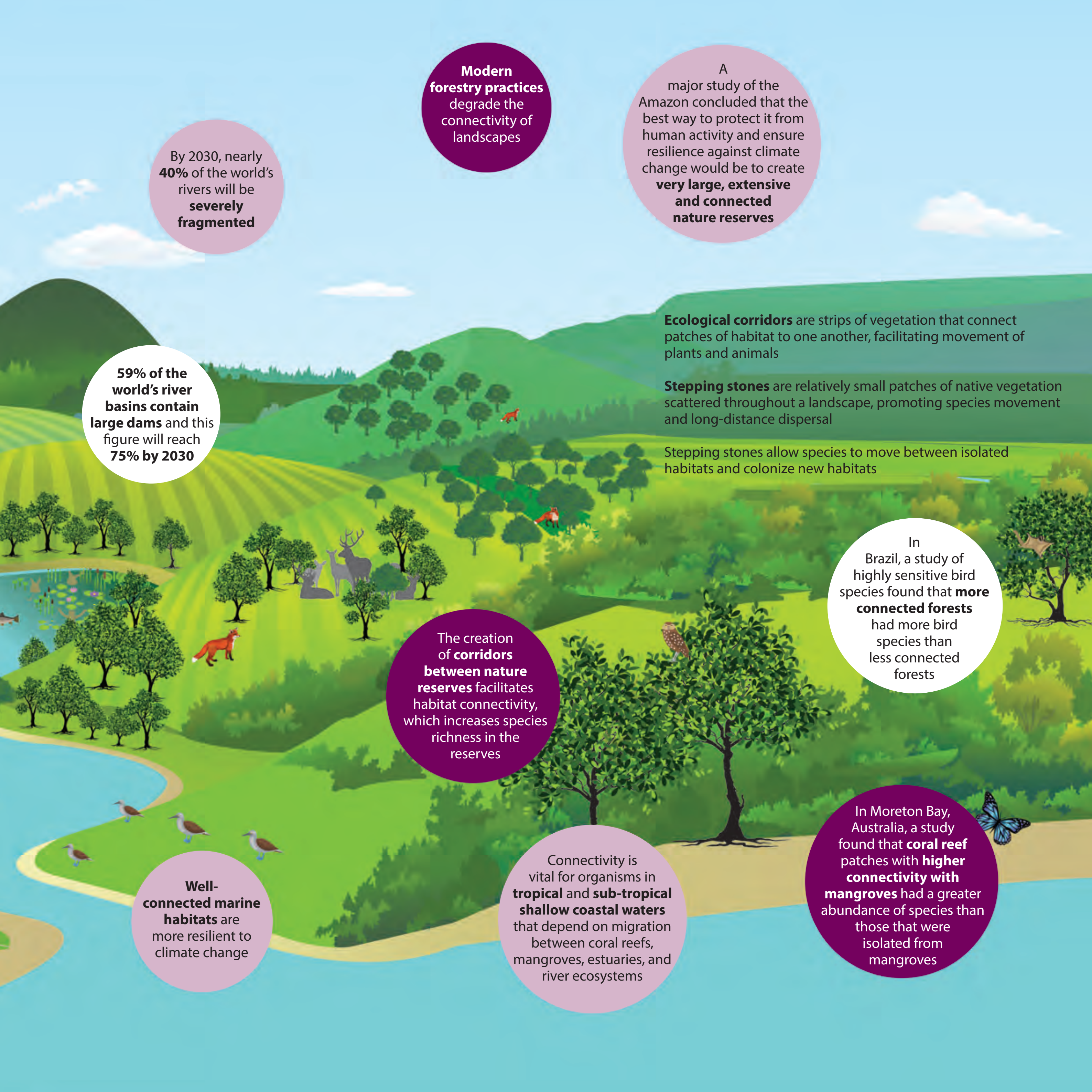
Factors such as **road width**, traffic load, and **curvature of the road** can also influence how many species are killed

Habitat fragmentation has been found to cause a **reduction in the number of top predators**

A global study found that **177 mammalian species** had lost more than **30%** of their geographic ranges and **40%** of these species exhibited huge declines in populations

Land–sea connectivity encompasses biological migration, hydrological cycling, nutrient transport, and other climatic processes, which are vital to both coastal and global ecosystems

Connectivity enhances **plant–animal interactions** such as pollination and seed dispersal. Plants in more connected areas produce more fruit.


Modern **forestry practices** degrade the connectivity of landscapes
A major study of the Amazon concluded that the best way to protect it from human activity and ensure resilience against climate change would be to create **very large, extensive and connected nature reserves**
By 2030, nearly **40%** of the world's rivers will be **severely fragmented**
59% of the world's river basins contain large dams and this figure will reach **75% by 2030**
Ecological corridors are strips of vegetation that connect patches of habitat to one another, facilitating movement of plants and animals
Stepping stones are relatively small patches of native vegetation scattered throughout a landscape, promoting species movement and long-distance dispersal
Stepping stones allow species to move between isolated habitats and colonize new habitats
In Brazil, a study of highly sensitive bird species found that **more connected forests** had more bird species than less connected forests
The creation of **corridors between nature reserves** facilitates habitat connectivity, which increases species richness in the reserves
Well-connected marine habitats are more resilient to climate change
Connectivity is vital for organisms in **tropical** and **sub-tropical shallow coastal waters** that depend on migration between coral reefs, mangroves, estuaries, and river ecosystems
In Moreton Bay, Australia, a study found that **coral reef** patches with **higher connectivity with mangroves** had a greater abundance of species than those that were isolated from mangroves

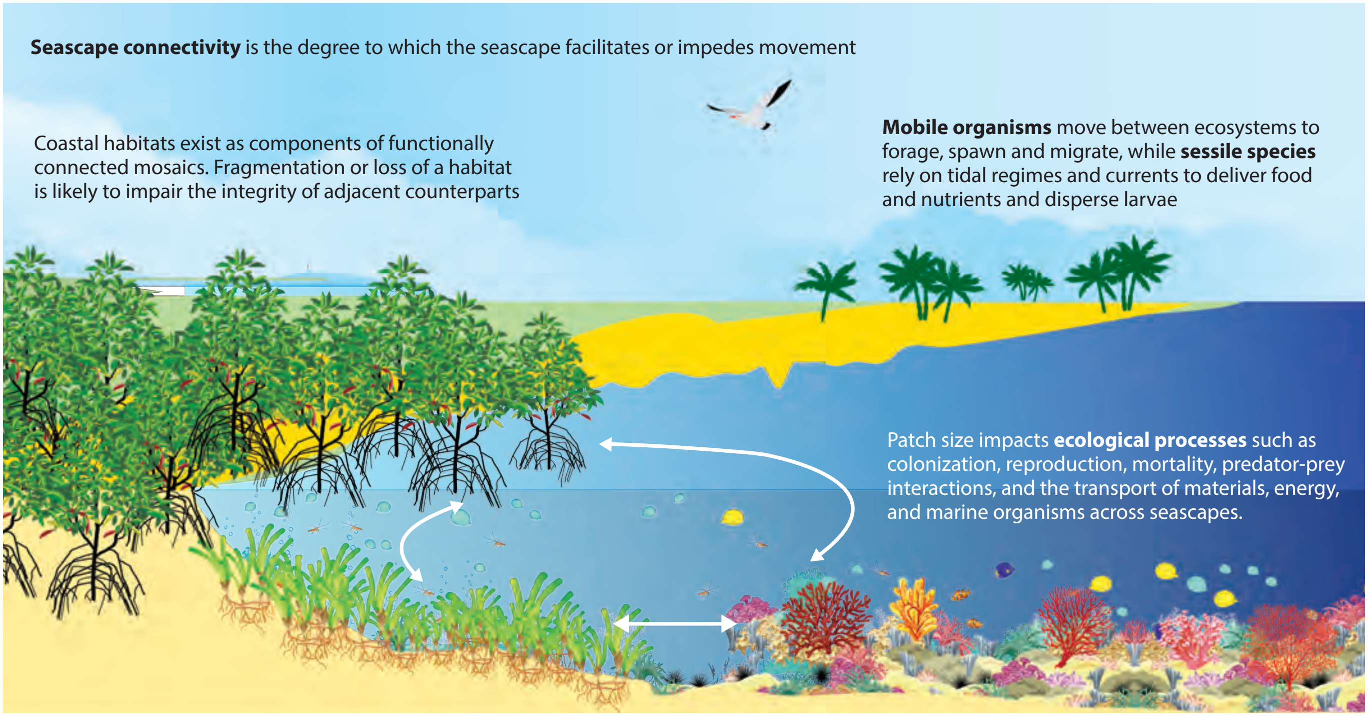
Promoting connectivity solutions

Connectivity conservation is the antidote to fragmentation and in a time when the threats to nature are at scales that stretch both human and financial-response capacity, progressive initiatives are being implemented by some countries. In Brazil, connectivity conservation underlies the country's ambitious efforts to restore viable habitat connections within the heavily fragmented Atlantic rainforest, the Mata Atlantica. Some endangered species have been the focus of restoration projects aiming to connect isolated populations, for example, the golden lion tamarin. Targeted restoration has been shown to reduce species extinction rates in once-fragmented forest blocks.[32] Connectivity is now the stated objective of various Brazilian biodiversity policies. The Brazilian Forest Act and Brazil's Native Vegetation Protection Law specifically highlight connectivity as a critical landscape restoration and habitat conservation strategy. [33,34] The government of El Salvador has recently proposed that the period 2021–2030 be declared the "United Nations Decade of Ecosystem Restoration" with the aim to restore and enhance landscape connectivity and ecological functions.

In Africa, the Government of Tanzania recently passed a new Wildlife Conservation Act that emphasizes the need for greater wildlife corridor conservation among its protected areas. In Kenya, where most wildlife is found outside of protected areas and county-level planning has just begun, the Kenya Wildlife Service has systematically catalogued the nation's key wildlife corridors and dispersal areas, and has crafted a national wildlife corridor policy.[35]

Within the global marine realm, connectivity functions in a three-dimensional way as the water column adds an additional variable to movement ecology. The sea itself is a connecting medium. Thus, marine connectivity is manifested in multiple ways across marine-coastal connections, surface-seafloor interactions, and as part of ocean current dynamics.[36]

Seascape connectivity



It is almost impossible for Marine Protected Areas, the cornerstone of ocean conservation, to function as ecological isolates in this highly connected environment. As such, the sea is conducive in creating ecological networks that connect critical habitats across space and time.

Furthermore, the complex life histories of many marine species have evolved with the movement dynamics of this fluid world. Seagrasses and mangrove swamps are well-known nursery habitats for the young of many marine species, which then often need to travel to coral reefs, seamounts, or other waters to mature. Seascape connectivity is emphasized as a key guiding principle in marine conservation and spatial planning, as well as restoration efforts; however, in practice it is rarely incorporated into the design of marine reserve networks.[36-39] This is largely due to the scarcity of quantitative data on multiple aspects of connectivity in the design phase, for example, the dispersal and movement patterns of key species at different life stages, ecological connectivity within and outside reserves – as well as between habitat types, and genetic connectivity among populations.[10,38-40] Nevertheless, studies of interactions between connectivity and the performance of marine reserves in the Caribbean, Florida Keys, Solomon Islands, Moreton Bay and the Great Barrier Reef in Australia demonstrate the ecological importance of greater connectivity. Positive effects on fish abundance, species richness and composition, recruitment and various ecological processes were observed in these protected areas.[10,41-44]

Efforts have been made by the international community to promote connectivity solutions. In 2016, the International Union for Conservation of Nature (IUCN) established the Connectivity Conservation Specialist Group (CCSG) to catalyze and energize the growing practice of connectivity conservation. Comprising around 900 members from 80 nations, the CCSG is focused on building capacity for the practice of consistent connectivity conservation worldwide by developing networks and providing guidance through a combination of scientific, engineering and policy expertise.

Video: What's marine connectivity?

Video link: https://www.youtube.com/watch?v=MowPR5GYqKM *© Ifremer*
Photo credit: Damsea / Shutterstock

Video: Behind the scenes of the red crab migration—Christmas Island 2012

Video link: https://www.youtube.com/watch?v=n9yl51LQ0sI *© Parks Australia*
Photo credit: David Stanley

Setting targets for future connectivity

The Aichi Biodiversity Targets adopted as part of the implementation of the Strategic Plan for Biodiversity 2011–2020 by the Convention on Biological Diversity (CBD) encompass the issues of landscape and seascape connectivity. The Aichi Biodiversity Target 11 states that at least 17 per cent of terrestrial and inland water areas and 10 per cent of coastal and marine areas are to be protected worldwide in a well-connected system of protected areas. Yet many scientists believe that current biodiversity conservation deserves a more ambitious goal.[45,46] The conservation science community argues that, on average, 50 per cent of all lands and seas need to be managed in order to sustain the ecological processes that maintain nature and critical planetary health thresholds, including ecosystem services that support human livelihoods.[4,14,15] For many areas of global ecological significance, a bolder target is scientifically warranted and politically supported. For instance, the Amazon basin requires greater protection to sustain this vast watershed's regional and global hydrological and climate functions. If the Amazon loses more than 20 per cent of its forests, landscape models predict a threshold flip in conditions that would support tropical savannah rather than forest, resulting in impacts on global climate patterns.[47] In implementing the Aichi Biodiversity Targets, the Brazilian government established its own goal to protect 30 per cent of the Amazon while ensuring that other biomes within its territory would individually meet the 17 per cent target.[48] The next ten-year CBD strategic plan covering 2021–2030 will be negotiated in October 2020 in China. There is enthusiasm among the conservation community that the goals of Aichi Biodiversity Target 11 could be framed more ambitiously and in line with the aspiration of "50% for Nature" by the year 2050.

While much effort has focused on meeting the protection percentages for lands, freshwater and seas, it is also recognized that more could be done on the modifying element of a well-connected system of protected areas, and other effective area-based conservation measures. The science unequivocally demonstrates that connected protected areas are more effective protected areas.[49,50] Connecting fragmented landscapes and seascapes through ecological networks can effectively enhance the functionality of nature and boost more ambitious approaches to conservation.

Wildlife corridors are a widely accepted connectivity strategy for protecting species migrations. Corridors are often designed for and focused on a particular species, such as pronghorn antelope in North America, tigers in Asia, and spotted jaguar in South America. Corridors come in an array of shapes and sizes depending on the species of concern and the constraints of the landscape, ranging from discrete linear trails to series of "stepping stone" habitat patches that facilitate migration of birds or sea turtles.

Linkage zones are larger landscape or seascape areas that serve a wide array of species and ecological processes in order to maintain connectivity. These zones comprise large swathes of land or sea that facilitate dispersal between protected areas, which is critical in places like East Africa where an overwhelming majority of wildlife is found outside of protected areas. Linkage zones also facilitate the movement of animals, biomass, and energy between habitat patches, or among different ecosystems within protected areas.

Permeability areas are the largest-scale concept used by conservationists to protect connectivity values in human-dominated regions outside of protected areas. These areas support the seasonal needs or spatial extent of species movement and/or ecological processes, such as vernal pools or specific freshwater hydrologic flows.

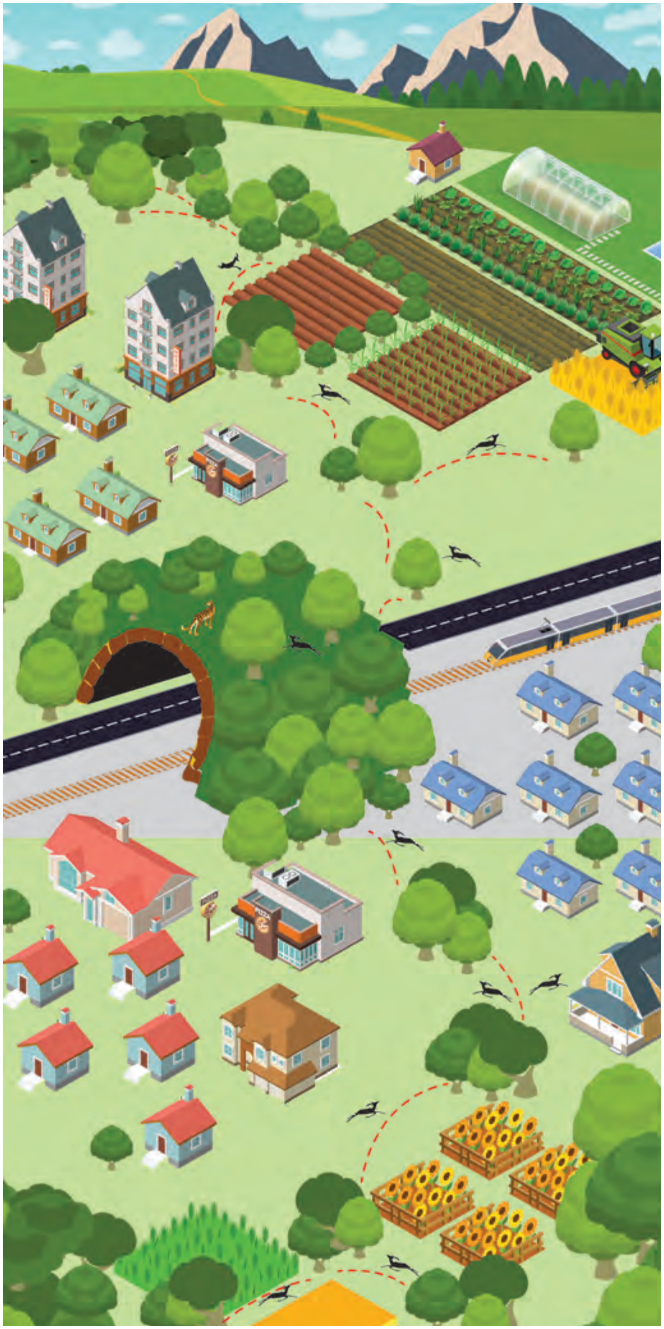
Climate corridors are proposed by scientists as a means to conserve species movements along temperature gradients; these same corridors often serve as 'climate refugia'.[51] Some connectivity conservation efforts explicitly include climate resilience in their objectives, such as the Great Eastern Ranges Initiative in Australia.[52]

Presently 14.7 per cent of land around the world is covered by protected areas and less than half of this coverage is connected.[50] As this statistic suggests, there is much opportunity for improving connectivity between protected areas globally. If the world seeks large-scale conservation action rapidly, connecting protected areas through ecological networks offers hope.

The application of connectivity conservation is still relatively nascent within wider conservation practice, and there is much to learn to perfect best practices.[53,54] As an emergent practice, ecological connectivity conservation faces its greatest implementation challenges outside of protected areas. Limiting impacts from fragmenting forces such as linear infrastructure development is obviously a critical need. Educating policymakers, government agencies, and local community stakeholders about the importance of ecological connectivity is equally crucial. While some nations could introduce regulatory measures to conserve connectivity, the vast majority of ecological connectivity efforts will rely on incentive-based participatory conservation approaches.[55] The adaptation of existing environmental policies could facilitate the wider adoption of connectivity conservation by including connectivity targets within both environmental impact assessments, and various conservation finance and tax incentive programmes.

Protected areas alone cannot save biodiversity or conserve the interconnected ecological functions that sustain life on this planet. Connectivity is the embodiment of ecology, which is the science of interdependence. This is imperative as interconnected lands, freshwater and seas are the lifeblood of intact nature. Thus, connected networks represent the best opportunity to maintain and restore ecological and evolutionary processes, avoid extinctions, and protect terrestrial, freshwater, and marine ecosystems vital to humanity and all life. Connectivity could ensure that ecosystems around the world will be more resilient and adaptable to global change, and will have the ability to sustain the ecological integrity that meets the needs of present and future generations. Until the forces of fragmentation are overcome, connectivity conservation by design creates a safety network for biodiversity conservation – and ultimately, humanity.

Stepping stones and crossing



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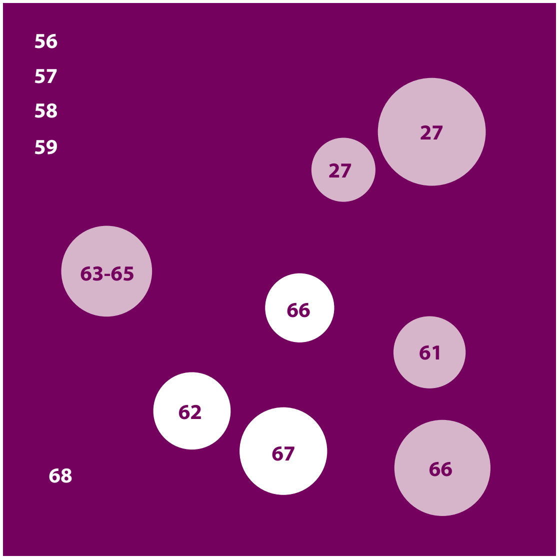
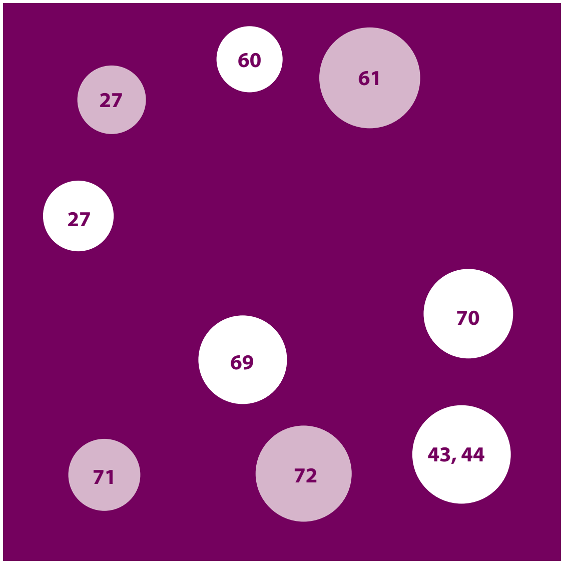
Graphic references





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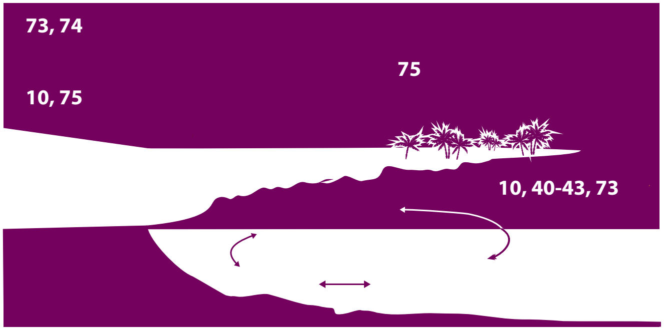

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Permafrost peatlands with numerous lake depressions, Cape Bolvansky, Russia
Photo credit: Hans Joosten

Permafrost Peatlands:
Losing ground in a warming world

Accelerating change in the Arctic

Peatlands located in the tropics receive much attention as global hotspots for their critical role in carbon storage and climate change mitigation. They store nearly 120 gigatons of peat carbon, but this is only about 20 per cent of all carbon locked away in global peatlands.[1] The largest volumes are stored in the northernmost areas of our planet, with the northern circumpolar region holding almost half of the world's soil organic carbon, largely in the form of permanently frozen peat.[2-5]

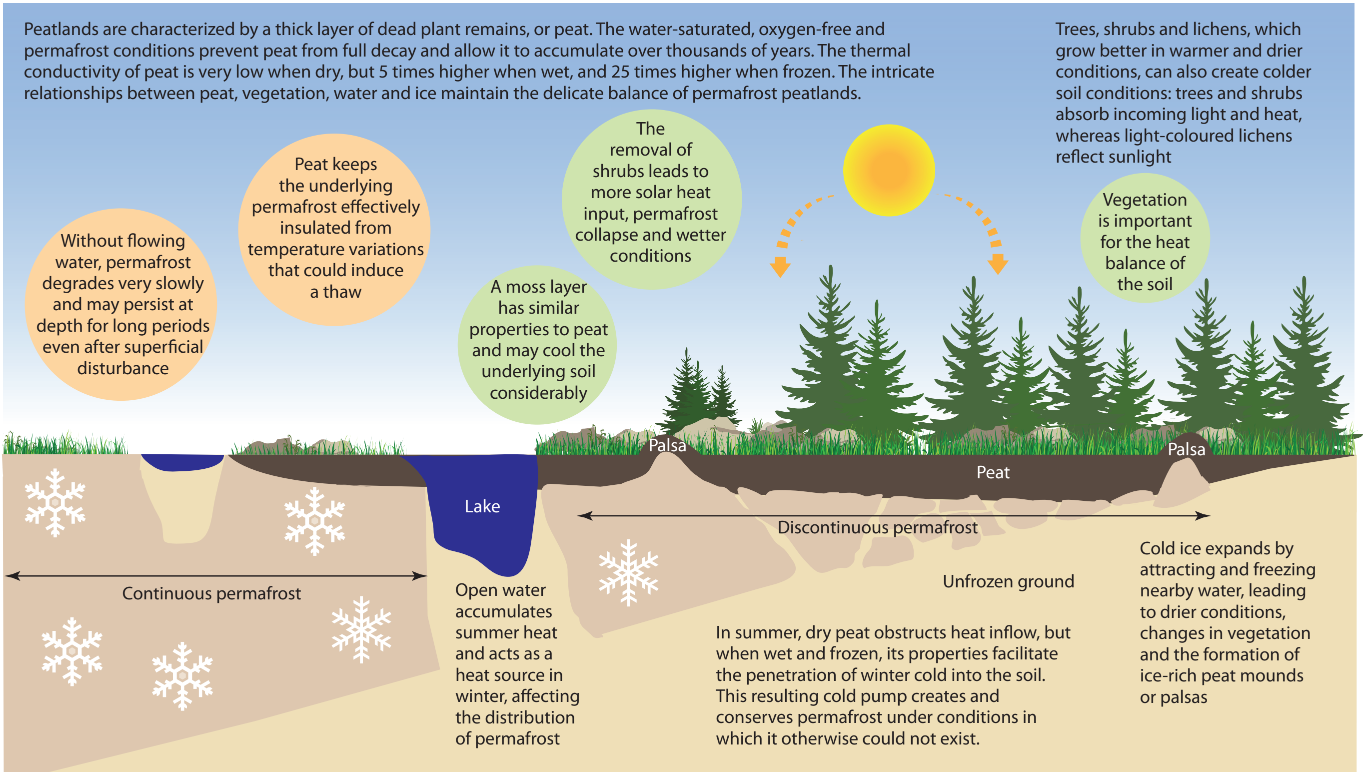
Much of the ground in the northern hemisphere freezes and thaws seasonally, and some stays frozen all year round. Underneath roughly 23 million square kilometres of the north lies permafrost – ground that remains at sub-zero temperatures for at least two consecutive years. Arctic and subarctic peatlands exist within the permafrost zones of Canada, Denmark/Greenland, Finland, Norway, Russia, Sweden and the United States. Permafrost peatlands with a peat layer thicker than 40 centimetres span over 1.4 million square kilometres, and an even larger area has shallower peat.[3,6-8] Extensive permafrost peat deposits can also be found far outside the Arctic and subarctic regions, for instance in Mongolia and on the Qinghai-Tibetan plateau, where mountain ranges prevent warm oceanic air from moving inland, and winter temperatures are very low.[9,10]

Permafrost peatlands are undergoing rapid changes. The Arctic is now warming twice as fast as the global average.[11] In recent decades, the southern permafrost boundaries have receded northwards by 30 to 80 km, a significant loss in coverage.[12-15] The risks associated with permafrost degradation are that the mobilization and microbial decomposition of previously buried, frozen organic matter could lead to the release of significant amounts of carbon dioxide and methane, which could, in turn, strongly reinforce global warming.[16-19] Widespread permafrost degradation would also have enormous direct impacts on the regions' ecosystems, hydrology and infrastructure.

Although permafrost has been intensively studied for over a century, more research on its distribution, characteristics and dynamics is critically needed to better understand how it responds to climate change and human disturbance.[20] In the case of peatlands with permafrost, knowledge is even more incomplete. The way in which permafrost peatlands respond to a warming climate and their collective role in global climate change are neither clearly understood nor straightforward, as the interaction of permafrost, ecosystems and climate is extremely complex.[20-22] For example, although frozen (dry) and thawed (wet) peatland sites may have similar carbon-sequestration rates and act as a carbon sink, they usually have totally different greenhouse-gas flux characteristics and may act as a net source of emissions.[23-25] Moreover, frozen and thawed peatland sites could also rapidly alternate over time and space.[23,26]

Permafrost thaw is seen as one of the most important "tipping elements" that could precipitate a runaway greenhouse effect, or an uncontrollable "Hothouse Earth".[27] To avoid such a destructive scenario, it is critical that the world's permafrost and its peatlands stay frozen and retain their carbon deposits.

Peatlands and permafrost: the role of peat, plants and water



Thawing permafrost, decaying peat and complex interplays

Each year of the past decade has been warmer in the Arctic than the warmest year of the 20th century.[15] Globally, permafrost temperatures have continued to rise in recent decades. The greatest increments in annual mean permafrost temperatures have been observed in the coldest parts of the Arctic, whereas the increases have been much less in "warmer" permafrost and in discontinuous permafrost zones. In some locations, permafrost temperatures have dropped marginally because of recent cold winters.[15,28]

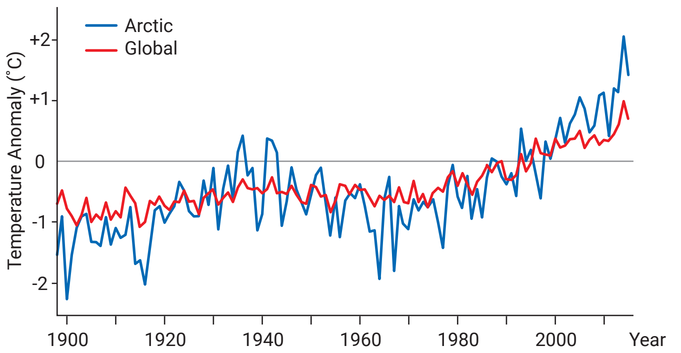
As temperatures rise, the thawing of ice-rich permafrost or the melting of ground ice leads to distinctive depressions in the landscape, known as thermokarst. Over the past decades, thermokarst formation in peatlands seems to have accelerated in the discontinuous permafrost zones.[29-31] However, across the Arctic, long-term observations do not suggest uniform trends in thermokarst development attributable to global warming.[15]

When formerly frozen soil collapses due to a thaw, the subsidence allows the formation of small, new bodies of water that can later evolve into lakes. The formation of thermokarst lakes, in turn, accelerates permafrost thaw even faster and deeper.[19] The spread of these lakes, on the other hand, could also increase the connectivity of drainage networks, supporting lake drainage, vegetation regrowth, peat formation and the re-establishment of permafrost.[32-37] These contrasting dynamics illustrate the greater need for a better understanding of potential impacts of the warming trend.

Climate change and elevated temperatures have dramatically increased the incidence of wildfires in the Arctic, with blazes spreading into tundra and forest–tundra boundary regions. Fuelled by underlying peat deposits, fires release vast amounts of carbon, destroy vegetation and insulating soil layers, and decrease ground albedo, or light reflectance, leading to increased sensitivity to climate change and widespread thermokarst development.[38-44] Even under the most conservative scenarios, the combined impacts of warmer temperatures and wildfires are predicted to be especially severe in discontinuous permafrost zones, with climate conditions becoming unfavourable to permafrost altogether.[31] This could cause changes in the types of vegetation and its productivity, which could in turn result in larger and more frequent wildfires.[45,46]

Another effect of increased warming due to climate change is that permafrost thaw could release significant amounts of methane, a potent greenhouse gas, into the environment. Although there is large variability in Arctic methane-emission estimates, current global climate projection models seem to suggest only slight increases in methane emissions from the northern permafrost region.[47,48] However, most models do not include an adequate representation of thaw processes.[8]

Arctic (60–90°N) and global annual surface air temperature relative to the 1981–2010 average value



Source: Adapted from the Arctic Report Card 2018 of the US National Oceanic and Atmospheric Administration[11]

Video: Permafrost – what is it?

Video link: https://www.youtube.com/watch?v=lxixy1u8GjY *© Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar und Meeresforschung*
Photo: Freshly-drilled core sample of permafrost, Pokhodsk, Russia
Photo credit: Hans Joosten

Thermokarst

Photo credit: Hans Joosten

Thermokarst is a landscape feature that results from the melting of ground ice in regions with underlying permafrost, causing subsidence at the surface. Typical thermokarst formations include thermokarst lakes, sinkholes, pits and troughs in polygonal terrain.[56,57] Thermokarst is widespread in discontinuous permafrost zones.[58,59] It is also frequently found in the much colder zones of continuous permafrost, where ice wedges cause permafrost instability.[60,61]

Water accumulating due to thermokarst initially enhances heat gain and degradation in a positive feedback. Conversely, vegetation growth and the accumulation of organic matter gradually limits further downward thawing. Because of new and rapid peat accumulation in thermokarst depressions, the thawing of permafrost does not necessarily convert the peatland into a carbon source.[22,23,62] However, wet soil conditions will likely cause the release of methane.

A recent modelling study assessed the long-term climatic consequences of permafrost degradation by considering the abrupt thaw processes relating to recently formed thermokarst lakes. The result suggested that within this century, carbon release in the form of methane (CH_4) may account for a small fraction of total carbon release from newly thawed permafrost, yet it could cause up to 40 per cent of the additional warming effect attributable to newly thawed permafrost.[49]

Climate change is only one of many factors directly influencing the changes in permafrost peatlands. Any disturbance to the surface soil can lead to permafrost degradation, including natural processes such as forest or tundra fires, and anthropogenic disturbances, such as industrial and urban infrastructure development and construction activity, mining, tourism, and agriculture.[50,51] These many forms of development in permafrost peatlands often disregard the unique features of the areas, causing landscape fragmentation and disruption of the water cycle.[14,52] In Russia, 15 per cent of the tundra territory has been destroyed by transport activities, resulting in permafrost thawing, erosion, subsidence and thermokarst development.[53] About 45 per cent of the oil and natural gas production fields in the Russian Arctic are located in the most ecologically sensitive areas, often in peatlands, including the Pechora region, Polar Urals and north-west and central Siberia.[54,55] The rising demand for natural resources and increased accessibility to frozen regions due to warmer conditions may in the future result in more industrial and infrastructural activity, escalating disturbance to peatlands and permafrost. The resulting changes will also impact indigenous peoples who have traditionally depended on the use of land such as peatlands for food, reindeer, game, and fish.[14]

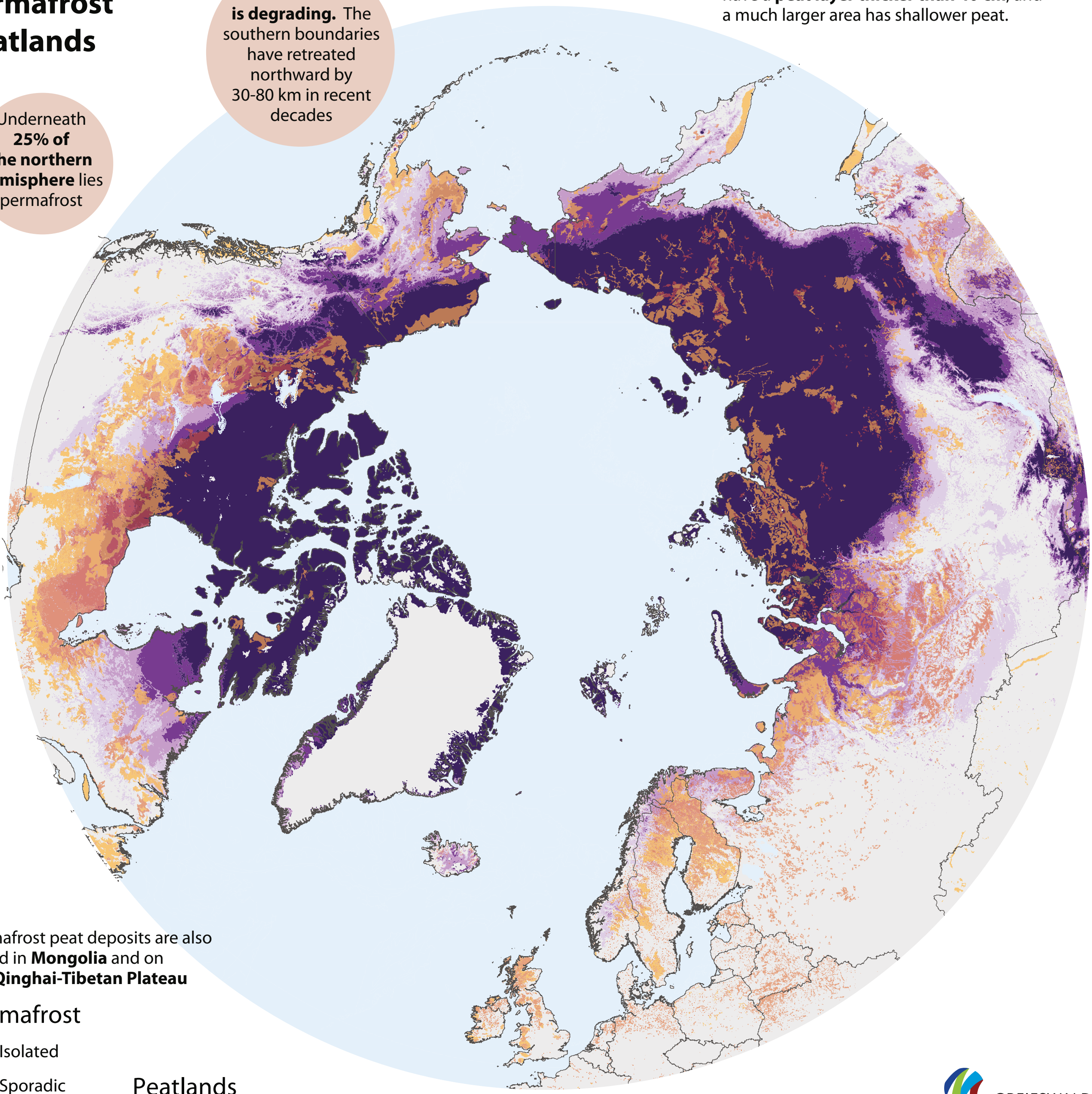
Thawing and collapse of permafrost in Mongolia *Photo credit: Hans Joosten*

Distribution of Permafrost Peatlands

Permafrost is degrading. The southern boundaries have retreated northward by 30-80 km in recent decades

Underneath **25% of the northern hemisphere** lies permafrost

Peatlands span vast areas in the permafrost zones. At least **1.4 million km^2** of permafrost peatlands have a **peat layer thicker than 40 cm**, and a much larger area has shallower peat.



Permafrost peat deposits are also found in **Mongolia** and on the **Qinghai-Tibetan Plateau**

Permafrost

- Isolated
- Sporadic
- Discontinuous
- Continuous

Peatlands

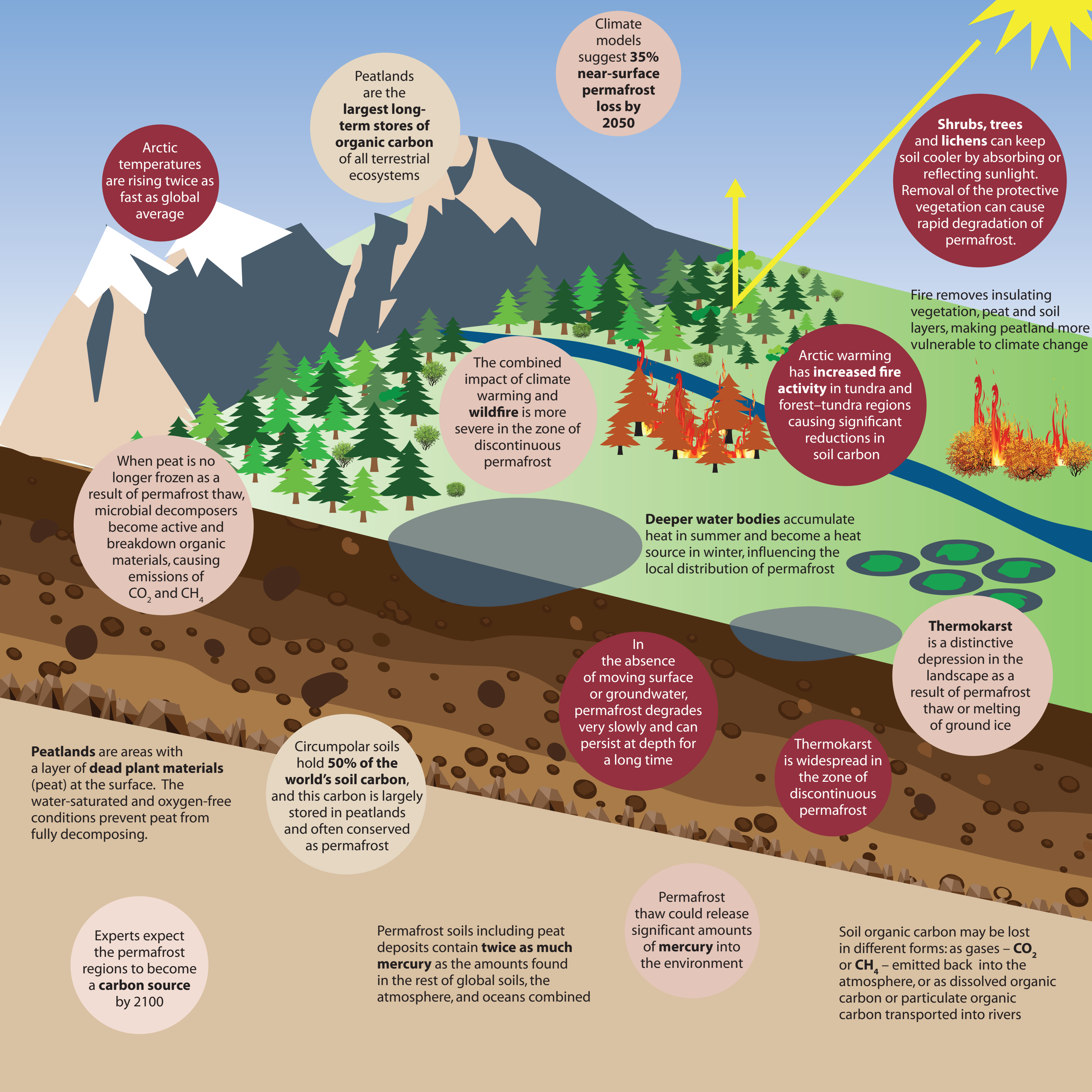
- > 50% cover
- 20-50% cover

GREIFSWALD MIRE CENTRE

Geospatial data sources:

Peatlands data provided by Greifswald Mire Centre, Greifswald, Germany

Permafrost data provided by Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research (AWI), Bremerhaven, Germany[90]



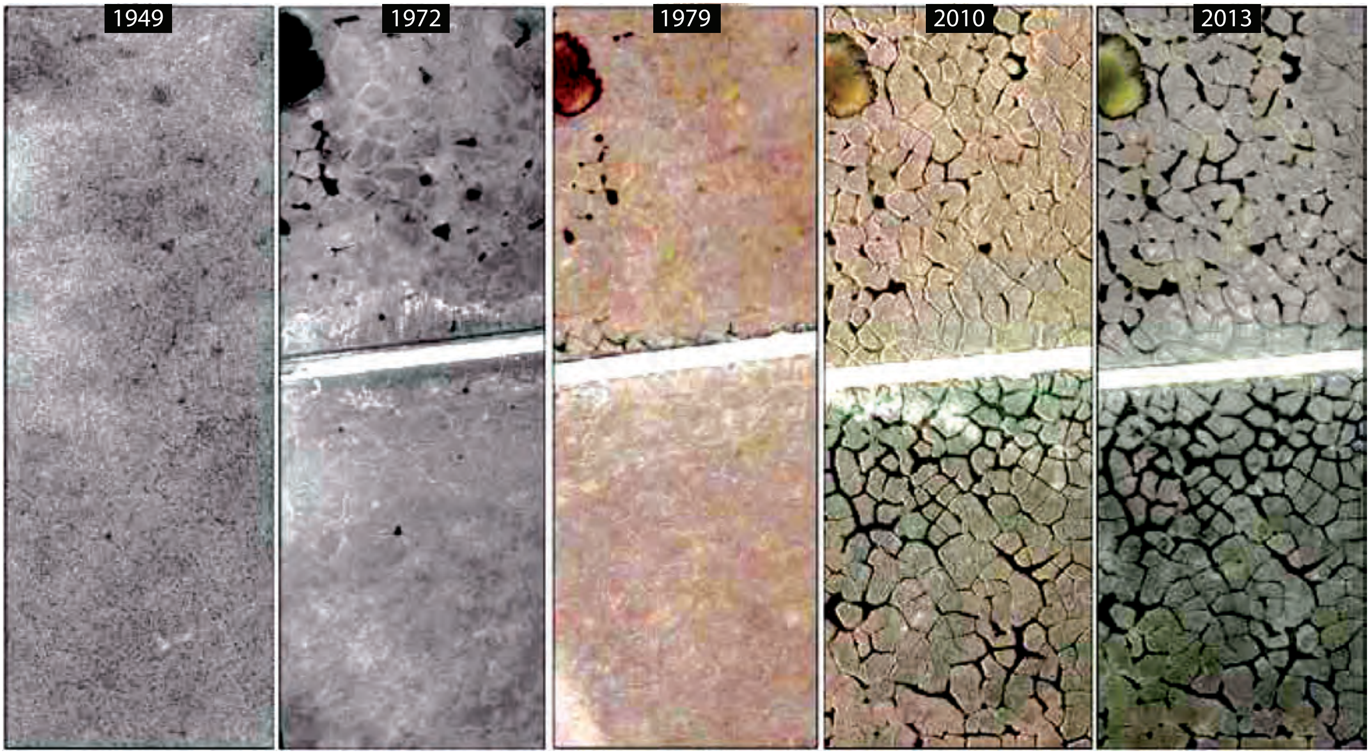
Arctic temperatures are rising twice as fast as global average
Peatlands are the **largest long-term stores of organic carbon** of all terrestrial ecosystems
Climate models suggest **35% near-surface permafrost loss by 2050**
Shrubs, trees and **lichens** can keep soil cooler by absorbing or reflecting sunlight. Removal of the protective vegetation can cause rapid degradation of permafrost.
Fire removes insulating vegetation, peat and soil layers, making peatland more vulnerable to climate change
The combined impact of climate warming and **wildfire** is more severe in the zone of discontinuous permafrost
Arctic warming has **increased fire activity** in tundra and forest–tundra regions causing significant reductions in soil carbon
When peat is no longer frozen as a result of permafrost thaw, microbial decomposers become active and breakdown organic materials, causing emissions of CO_2 and CH_4
Deeper water bodies accumulate heat in summer and become a heat source in winter, influencing the local distribution of permafrost
Thermokarst is a distinctive depression in the landscape as a result of permafrost thaw or melting of ground ice
In the absence of moving surface or groundwater, permafrost degrades very slowly and can persist at depth for a long time
Thermokarst is widespread in the zone of discontinuous permafrost
Peatlands are areas with a layer of **dead plant materials** (peat) at the surface. The water-saturated and oxygen-free conditions prevent peat from fully decomposing.
Circumpolar soils hold **50% of the world's soil carbon**, and this carbon is largely stored in peatlands and often conserved as permafrost
Experts expect the permafrost regions to become a **carbon source** by 2100
Permafrost soils including peat deposits contain **twice as much mercury** as the amounts found in the rest of global soils, the atmosphere, and oceans combined
Permafrost thaw could release significant amounts of **mercury** into the environment
Soil organic carbon may be lost in different forms: as gases – CO_2 or CH_4 – emitted back into the atmosphere, or as dissolved organic carbon or particulate organic carbon transported into rivers

Growing awareness of permafrost peatlands

For more than a century and increasingly over the last decades, permafrost regions have been the subject of research and technology development to address their distinctive scientific and engineering challenges. Despite the efforts of the International Permafrost Association and the Global Terrestrial Network for Permafrost, large gaps in region- and habitat-specific knowledge remain, not least due to extreme climatic conditions, limited accessibility and a complex geopolitical setting. A recent review indicated that 30 per cent of all citations in scientific literature related to field experiments in the Arctic are primarily derived from the direct surroundings of just two research stations: Toolik Lake in Alaska, USA and Abisko in Sweden.[63] This could bias scientific consensus and lead to inaccurate predictions of the impacts of climate change in the Arctic.

With the growing awareness of climate change and Arctic ice melt, recent assessments are increasingly trying to encompass aspects such as social-ecological change, regime shifts, and the role of human action in adaptation and transformation.[64,65] Large-scale research projects are being developed to address the implications of permafrost thaw and degradation. These include the Arctic Development and Adaptation to Permafrost in Transition (ADAPT) initiative, which collaborates with 15 laboratories across Canada and other groups of researchers to develop an integrated Earth systems science framework in the Canadian Arctic. Dedicated laws such as Ontario's 2010 Far North Act are combining with new planning initiatives to open up and protect the Far North through a land-use planning process in consultation with First Nations.[66]

The Arctic Council is an example of strong international cooperation that has been especially instrumental in



Progression of thermokarst development due to permafrost thaw between 1949 and 2013 in a study site located in Prudhoe Bay, Alaska, United States. The white line is the Spine Road constructed in 1969.

Source: Walker et al. (2014)[52]

generating and increasing knowledge for national and international policymaking, such as with its 2017 report on snow, water, ice and permafrost in the Arctic.[15,67] While it is recognized that Arctic states play a key role as stewards of the region, efforts by other actors in the protection and awareness of permafrost peatlands are also needed. A number of international organizations, such as the Intergovernmental Panel on Climate Change – through its IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, the World Meteorological Organization, and the International Science Council through the International Arctic Science Committee, have become increasingly engaged, helping to raise awareness and understanding of the implications of changes in the Arctic.

Permafrost thaw has led to thermokarst formation in peatlands near Naryan-Mar, Nenets autonomous region, Russia

Photo credit: Hans Joosten

Ontario's Far North Act and the role of First Nations in protecting permafrost peatlands

Between 50-57 °N and 79-94 °W lies the **Far North of Ontario**, Canada – a dynamic landscape hosting arctic, boreal, and temperate biomes. Here, peatlands dominate the landscape, covering 47 per cent or 21 million hectares of the Far North area, and storing about 36 gigatons of carbon as peat.[68] This is equivalent to a quarter of the carbon stored in all of Canada's peatlands.

Assented to in October 2010, **Ontario's Far North Act** recognizes the significant role of the Far North in carbon storage and sequestration capacity, and provides for community-based land-use planning as a strategy to fight climate change.[66,69] The Act centres around the significant role of First Nations – aboriginal peoples in Canada who are not Métis or Inuit – in land-use planning that includes cultural, social, ecological and economic considerations.

As required by the Act, the **Far North land use strategy** sets out to help prepare community-based land-use plans while integrating issues beyond the scope of individual planning areas, such as indigenous knowledge. Four objectives outlined in the strategy include:

1. A significant role for First Nations in planning.
2. The protection of ecological systems and areas of cultural value in the Far North by including at least 225,000 km^2 of the region in an interconnected network of protected areas designated in community-based land-use plans.
3. The maintenance of biological diversity, ecological processes and functions, including the storage and sequestration of carbon in the Far North.
4. Enabling sustainable economic development that benefits the First Nations.

The strategy was planned for completion by 2016, but the process is still ongoing, led by interested First Nations working with the Ontario Ministry of Natural Resources and Forestry. Some community-based land-use plans have been approved, some drafted, while others are underway and some have not yet started.[70] Although progress is being made, uncertainty remains on how to achieve some of the Act's objectives, including in areas of governance, and particularly in scientific knowledge. It is imperative to understand how climate change affects carbon sequestration and storage in the Far North peatlands, as well as the related ecological processes, in order to develop appropriate policy and management responses.

Knowledge priorities and network expansion

There remains a great deal of uncertainty about how fast permafrost peatlands will change and what the impacts of those changes will be, both locally and globally. International cooperation is required to fund further research in the long term and devise workable strategies to reduce vulnerabilities. Nations need to collaborate on a range of implementable measures that acknowledge and apply traditional and local knowledge, facilitate engagement with stakeholders, and develop effective observation networks.[15] At the same time, public outreach and education concerning the risks, likely impacts and potential adaptation options will be key to developing informed governance and policy.

Although there is an existing network of observation stations providing information on general trends in permafrost change, the spatial distribution of sites is very uneven. In particular, there are large gaps in the network across the central Canadian and central Siberian Arctic, Greenland, Russian Far North-East, Tibetan Plateau and subarctic region.[30,63] The timely assessment of the global status of permafrost requires the expansion of existing research networks to a more comprehensive monitoring network. This extended network would optimally be designed to be user-friendly for all stakeholders, from climate scientists to the general public, and would include the use of standardized measurements and easily accessible databases.[15,64] Countries with extensive permafrost zones would benefit from preparing adaptation plans that assess the potential risks and include mitigation strategies for the damage and costs of permafrost degradation.[64]

Permafrost peatlands as carbon hotspots represent a special, highly diverse and dynamic environment that encompasses complex relationships between soil carbon, hydrology, permafrost, vegetation, and people. The major knowledge gaps lie in the limited understanding of how the processes interrelate and in the insufficiency of current studies and models. More research is required on the precise location of permafrost peatlands, how they are changing, and what their release potential is. Climate models need to include carbon emissions from the mobilization of permafrost carbon. To better characterize the response and feedback of permafrost peatlands to climate change, it will be critical to advance beyond single-disciplinary investigations. This will require

Satellite image taken on 19 July 2016 showing dense smoke over permafrost peatlands of north-central Russia. Red demarcations indicate high surface temperatures likely caused by peat fires.
Photo credit: NASA Earth Observatory/Jesse Allen and Joshua Stevens

Video: Restoring peatlands in Russia for fire prevention and climate change mitigation

Video link: https://www.youtube.com/watch?v=QZ5qu_nPHYM
Photo: Fire in dwarf birch tundra in Komi Republic, Russia
© Wetlands International
Photo credit: Hans Joosten

Video: Peatlands – climate regulation and biodiversity

Video link: https://www.youtube.com/watch?v=ZcxZ9gvNfSU © Naturstyrelsen

Flat palsas in Komi Republic, Russia

Photo credit: Hans Joosten

a move towards an integration of field observations and retrospective – or palaeoenvironmental – studies, remote sensing, and dynamic modelling.[22,30] The physical complexity of permafrost peatlands and the significant potential risks of their degradation and disruption also demand a more holistic approach to land-use planning and management, requiring better integrated knowledge for planners and policymakers.

The Arctic has already begun to change substantially. Even with the full implementation of the Paris Agreement under the United Nations Framework Convention on Climate Change, it is still likely that by the end of this century the Arctic environment would be quite different from that of today.[15] The near inevitability of accelerating impacts reinforces the urgent need for local and regional adaptation strategies targeting these carbon-dense northern ecosystems. The prudent management of permafrost peatlands will be key to limiting greenhouse-gas emissions, reducing human and ecological vulnerabilities, and to building longer-term climate resilience.

Palsa permafrost mire near Noyabrsk, Western Siberia, Russia

Photo credit: Franziska Tanneberger

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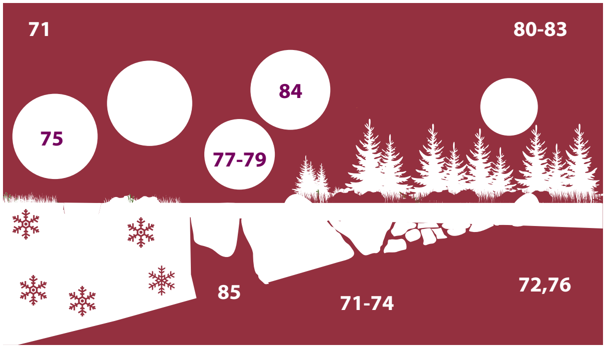
Graphic references



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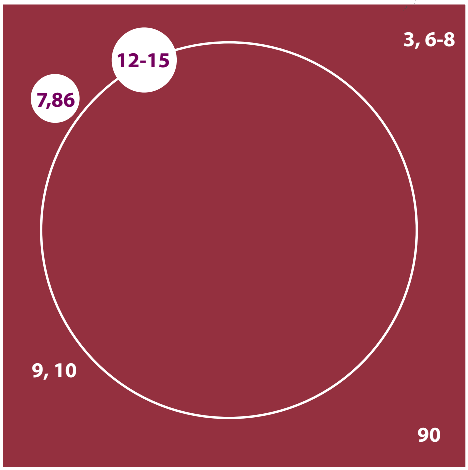

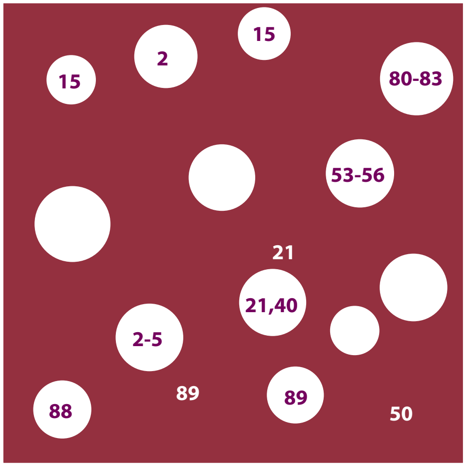

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The Nitrogen Fix:
From nitrogen cycle pollution to nitrogen circular economy

The global nitrogen challenge

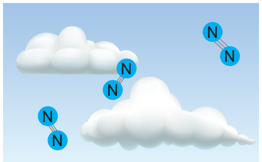
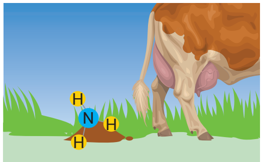
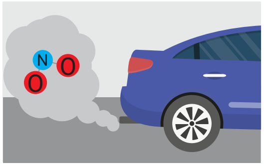
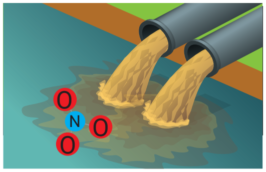
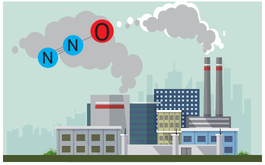
The *UNEP 2014 Year Book* highlighted the importance of excess reactive nitrogen in the environment.[1] Its conclusions are alarming. This is not just because of the magnitude and complexity of nitrogen pollution, but also because so little progress has been made in reducing it. Few of the solutions identified have been scaled up, while the world continues to pump out nitrogen pollution that contributes significantly to declines in air quality, deterioration of terrestrial and aquatic environments, exacerbation of climate change, and depletion of the ozone layer.[2-10] These impacts hinder progress toward the Sustainable Development Goals as they affect human health, resource management, livelihoods and economies.[11-15] Yet there are signs of hope. The past four years have seen a transformation in approaches to managing nitrogen pollution. These include new thinking for both consumption and production in order to seriously address the nitrogen problem.[16-24]

Nitrogen is an extremely abundant element in the Earth's atmosphere. In the form of the N_2 molecule, nitrogen is harmless, making up 78 per cent of every breath we take. The two nitrogen atoms are held together by a strong triple bond ($N{\equiv}N$), making it extremely stable and chemically unreactive. The planet benefits because N_2 allows a safe atmosphere in which life can flourish, while avoiding the flammable consequences of too much oxygen. The environmental interest in nitrogen focuses on the conversion of N_2 into other chemically reactive forms. For simplicity, scientists refer to all other nitrogen forms as "fixed" or "reactive nitrogen" (N_r).[11,25] There are many types of N_r with many different effects –

beneficial and harmful – and this is where the complications arise. Reactive nitrogen is essential for all life on earth. For example, ammonia (NH_3) is the foundation for amino acids, proteins, enzymes and DNA, and thus central to the metabolism of all life forms. Similarly, nitric oxide (NO) acts as a key biological signalling compound, while ammonium (NH_4^+) and nitrate (NO_3^-) are the major nutrient forms of nitrogen essential for plant growth. This points to a primary benefit of N_r compounds in that they help to produce food and animal feed. Using the Haber-Bosch process of artificial nitrogen "fixation", humans have massively scaled up the manufacture of fertilizers – ammonia, urea and nitrates – to sustain a growing world population.[26] In parallel, humans benefit from the natural biological fixation of N_2 to N_r by specialist bacteria found in soil and associated with the roots of legume crops.

Against these benefits must be set the numerous losses of ammonia, nitrate, nitric oxide (NO), nitrous oxide (N_2O) and many other forms of N_r pollution that cause multiple impacts on the environment. These may occur directly following fertilizer use, while animal manure, human excreta and other organic wastes also cause huge losses of N_r to the environment. Although the fraction of N_r lost to the environment from biological nitrogen fixation is thought to be smaller than from many fertilizers, once excreted from animals and humans, both sources contribute to N_r pollution. Reactive nitrogen is also yielded as a by-product of human activities. For instance, fossil fuel and biomass combustion processes release NO and NO_2, collectively called NO_x. While major efforts have been made to reduce NO_x from vehicles and energy generation, emissions are still escalating in rapidly developing parts of the world.[6,12] Altogether, humans are producing a cocktail of reactive nitrogen that threatens health, climate and ecosystems, making nitrogen one of the most important pollution issues facing humanity. Yet the scale of the problem remains largely unknown and unacknowledged outside scientific circles.

Different forms of nitrogen in the environment

	Di-Nitrogen (N_2)	Ammonia (NH_3)	Nitric Oxide (NO) and Nitrogen Dioxide (NO_2)	Nitrate (NO_3^-)	Nitrous Oxide (N_2O)
Source	N_2 makes up 78% of air we breathe	Manure, urine, fertilizers and biomass burning	Combustion from transport, industry and energy sector. NO and NO_2 are collectively known as NO_x.	Wastewater, agriculture and oxidation of NO_x	Agriculture, industry and combustion
Benefits	N_2 maintains stable atmosphere for life on Earth. It makes the sky appear blue.	NH_3 is the foundation for amino acids, protein and enzymes. Ammonia is common used as fertilizer.	NO is essential in human physiology. NO_2 has no known benefit.	Widely used in fertilizers and explosives	Used in rocket propellants and in medical procedure as laughing gas
Effects	N_2 is harmless and chemically unreactive	NH_3 causes eutrophication and affects biodiversity. It forms particulate matter in air which affects health.	NO and NO_2 (or NO_x) are major air pollutants, causing heart disease and respiratory illness.	It forms particulate matter in air and affects health. In water, it causes eutrophication.	N_2O is a greenhouse gas–300 times more powerful than CO_2. It also causes depletion of stratospheric ozone.

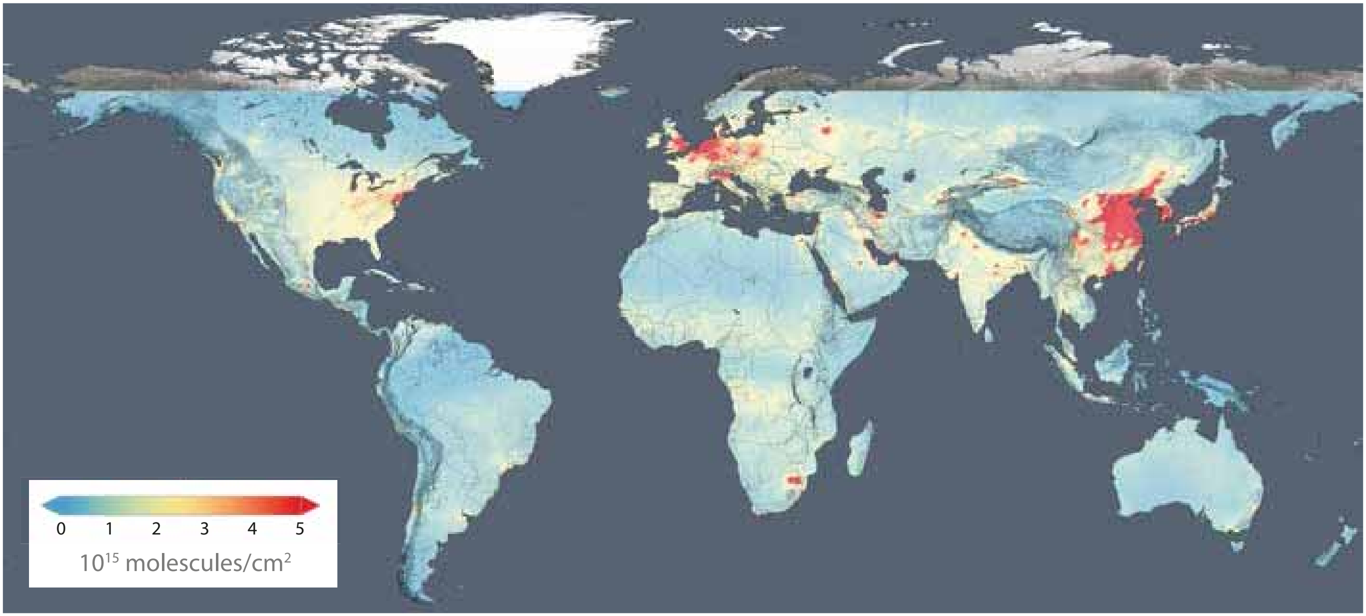
The knowns and known-unknowns of nitrogen

Both the cycling of nitrogen compounds and the human impacts are well documented.[4,12,27,28] Yet compared with the role of carbon in climate change, there has been little public debate about the need to take action on nitrogen. The increased levels of N_r compounds in the air above cities and above agricultural areas are measurable, for example as NO_x, NH_3 and fine particulate matter, or $PM_{2.5}$. Elevated levels of NO_3^- in groundwater under agricultural areas in several regions around the world and in rivers downstream of cities with little or no sewage treatment are equally quantifiable. Atmospheric concentrations of the greenhouse gas N_2O are accumulating at an accelerating rate. The clear message is that humans are massively altering the global nitrogen cycle, causing multiple forms of pollution and impacts, making N_r a key pollutant to tackle, from local to global scales.[22]

The European Nitrogen Assessment identified five key threats of nitrogen pollution: water quality, air quality, greenhouse-gas balance, ecosystems and biodiversity, and soil quality.[4] It highlighted that nitrogen pollution itself is not a new problem, but that nitrogen management needs to be part of the solution to many existing environmental problems. Concerning food production, global nitrogen use is extremely inefficient.[20,29] Considering the whole food chain, only around 20 per cent of the N_r added in farming ends up in human food.[11,17] This implies that a worrying 80 per cent is wasted as pollution and N_2 to the environment, demonstrating that N_r pollution represents a massive loss of valuable resources.

While past efforts have focused on a fragmented approach between different N_r forms, considering them all together has several advantages. First, it allows us to start looking at the synergies and trade-offs between N_r benefits and different types of N_r pollution. Secondly, and just as important, it encourages us to quantify the societal cost of all the impacts of nitrogen pollution in order to inform policy and the general public.[13,30] Cost estimates can help guide mitigation policies, however, the true cost of N_r pollution is really a known-unknown, since

The average concentration of nitrogen dioxide (NO_2) in the troposphere in 2014



NO_2 is a gas emitted mainly from cars, power plants and industrial activity. NO_2 and other NO_x react with other air pollutants to form harmful ground-level ozone, acid rain and particulate matter.

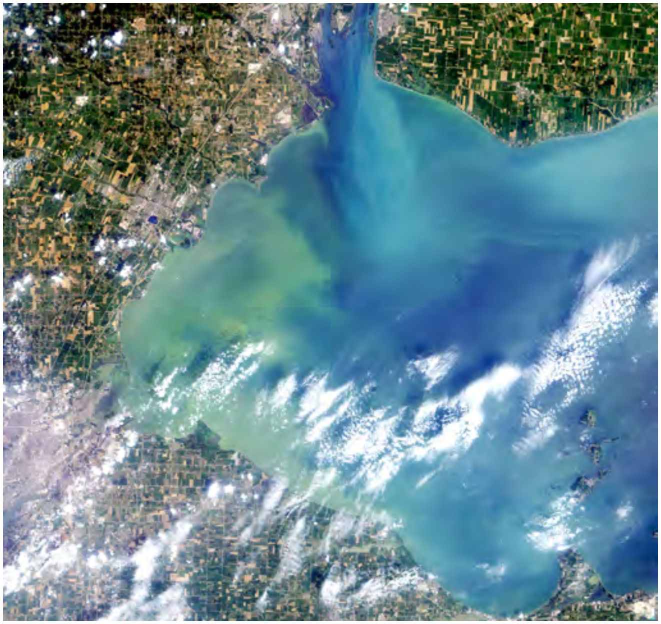
Photo credit: NASA Goddard Space Flight Center

Video: Saving the Great Lakes from toxic algae

Video link: https://www.youtube.com/watch?v=b6JzL4NG26k *© PBS NewsHour*
Photo: Algal bloom in Pelee Island in the southeast of Lake Erie
Photo Credit: Tom Archer / Michigan Sea Grant (www.miseagrant.umich.edu)

impacts tend to be fundamentally "non-commensurable", that is, it is hard to find a common measure. Comparing health, ecosystem and climate costs is like trying to compare apples and oranges. The available estimates, based on the willingness of people to reduce the risks of N_r pollution, or estimates of costs to ecosystems and healthcare services, are nevertheless informative and indicate a global cost of around US$340 billion to US$3,400 billion annually.[11]

A much simpler calculation, however, can be even more powerful. Globally, around 200 million tonnes of N_r resource is lost to the environment per year as N_r and N_2.[11,28] If we multiply this by a nominal fertilizer price of US$1 per kg N, then the total amounts to a cash loss of around US$200 billion per year. This represents a strong motivation for action. This message is also relevant for areas with too little N_r, such as sub-Saharan Africa, where reducing N_r pollution would help limited available N_r sources to go further in supporting food production.[31] The conversion of N_r compounds back to N_2 (termed "denitrification") does not provide a safe way to avoid N_r pollution. Rather, it implies a need for fresh N_r inputs, tending to increase pollution. Indeed, all N_2 and N_r losses need to be reduced if economy-wide nitrogen use efficiency (NUE) is to be increased.



Algal bloom (shown in milky green) in the west of Lake Erie between Canada and the United States on 3 August 2014. Lake Erie's frequent algal blooms are caused by nitrogen and phosphorus loading from agricultural runoff of fertilizers and manure, municipal wastewater effluent and atmospheric deposition.

Photo credit: Jeff Schmaltz / NASA Goddard Space Flight Center

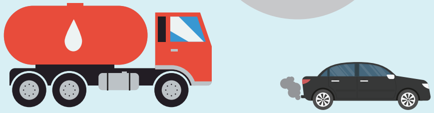
Video: Human fingerprint on global air quality

Video link: https://www.youtube.com/watch?time_continue=7&v=aMnDoXuTGS4 *© NASA Goddard Space Flight Center*
Photo credit: Doin / Shutterstock.com

Fossil fuel combustions in the transport, energy and industrial sectors

High temperature combustion of **coal, petroleum** and **natural gas** releases a large amount of **N_r** in the form of **NO** and **NO_2**, collectively known as **NO_x**

The **transport sector** contributes to more than **65% of NO_x** emissions

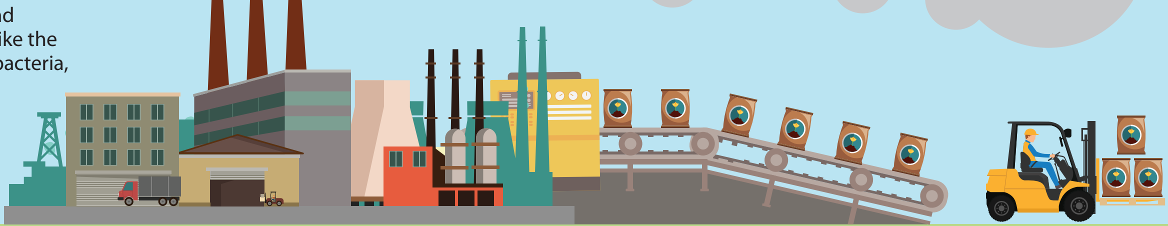


Fossil fuel combustion is responsible for **13%** of the **anthropogenic fixation of N_2 to N_r**

Fertilizer manufacture

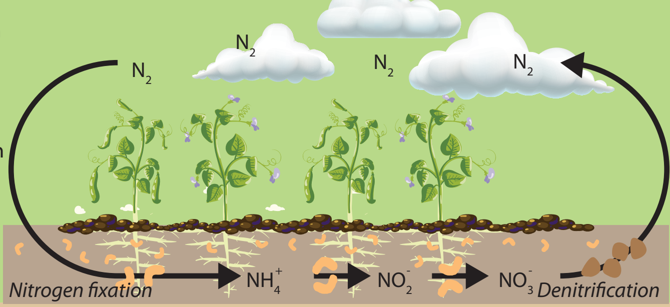
The Haber-Bosch process was invented more than 100 years ago to meet the growing need for mass industrial production of N_r fertilizers and nitrogen-based explosives. Like the natural nitrogen fixation by bacteria, **it artificially fixes atmospheric N_2 into ammonia (NH_3).**

Fertilizer manufacture accounts for **63%** of the anthropogenic fixation of N_2 to N_r



Biological nitrogen fixation in crop cultivation

In nature, N_2 can be converted into N_r through lightning and biological nitrogen fixation by nitrogen-fixing bacteria

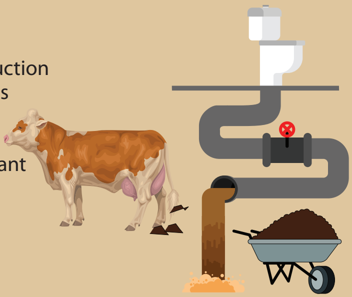


N_r can also be biologically converted back to N_2 through the **denitrification process** by anaerobic bacteria. These natural processes keep a balanced cycle of nitrogen, but increased **cultivation of nitrogen-fixing crops** such as legumes has significantly added N_r inputs and losses into the environment.

Biological nitrogen fixation in crop production is responsible for **24%** of the conversion of N_2 into N_r

Waste

In addition to the food production and combustion of fossil fuels being key to mitigating N_r emissions, the **role of waste management** is also significant in preventing more N_r from cascading through the environment

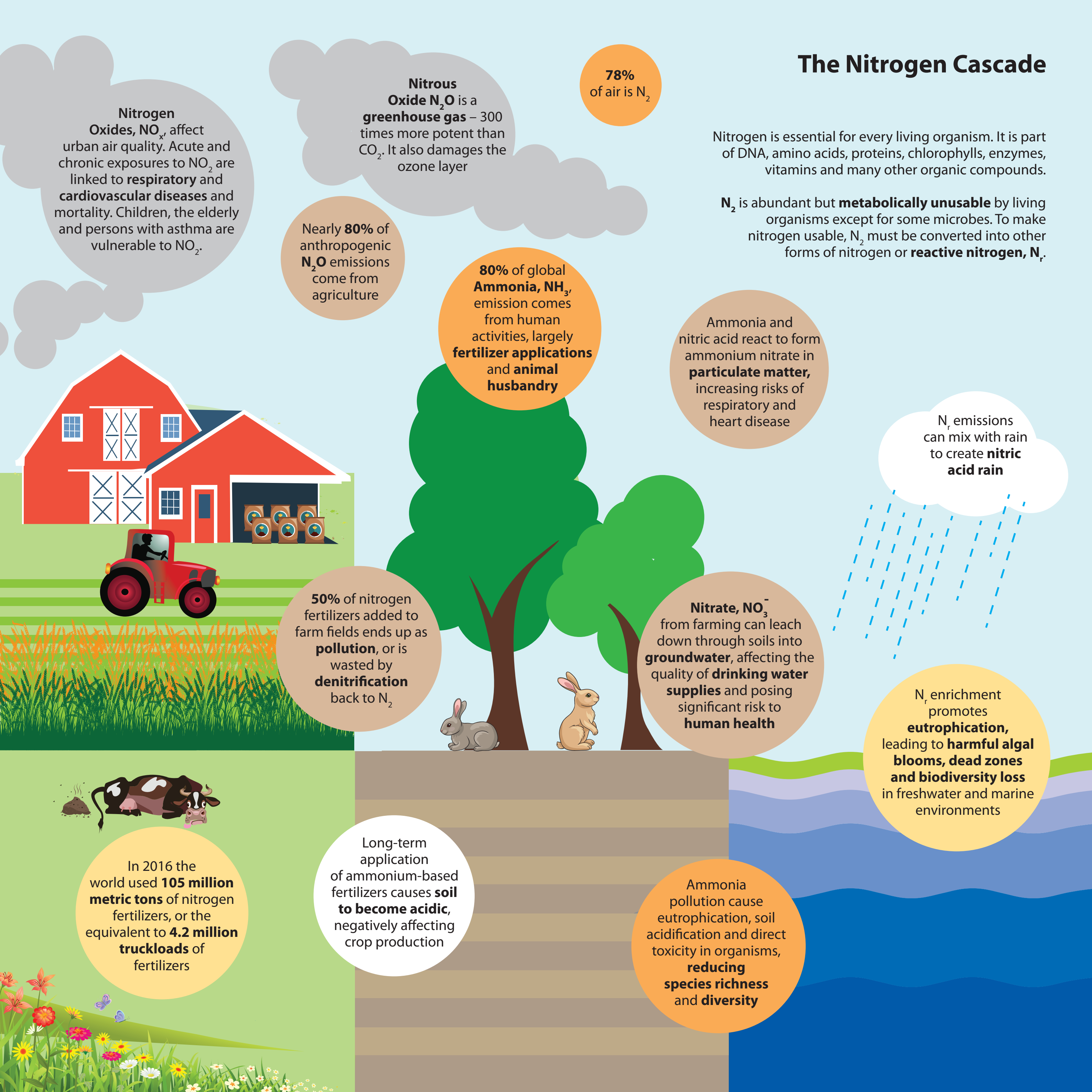


Sewage, wastewater and food waste contain proteins. About **16%** of **protein** is **nitrogen**

Unlike sewage and wastewater, a large amount of **food waste is avoidable**

Cereals, fruits, vegetables, roots and **tubers** make up the largest volumes of food losses and waste

Every year about **1/3 of the food produced** globally for human consumption is **lost or wasted**


The Nitrogen Cascade
Nitrogen is essential for every living organism. It is part of DNA, amino acids, proteins, chlorophylls, enzymes, vitamins and many other organic compounds.
N_2 is abundant but **metabolically unusable** by living organisms except for some microbes. To make nitrogen usable, N_2 must be converted into other forms of nitrogen or **reactive nitrogen, N_r**.
78% of air is N_2
Nitrogen Oxides, NO_x, affect urban air quality. Acute and chronic exposures to NO_2 are linked to **respiratory** and **cardiovascular diseases** and mortality. Children, the elderly and persons with asthma are vulnerable to NO_2.
Nitrous Oxide N_2O is a **greenhouse gas** – 300 times more potent than CO_2. It also damages the ozone layer
Nearly **80%** of anthropogenic **N_2O** emissions come from agriculture
80% of global **Ammonia, NH_3**, emission comes from human activities, largely **fertilizer applications** and **animal husbandry**
Ammonia and nitric acid react to form ammonium nitrate in **particulate matter,** increasing risks of respiratory and heart disease
N_r emissions can mix with rain to create **nitric acid rain**
50% of nitrogen fertilizers added to farm fields ends up as **pollution**, or is wasted by **denitrification** back to N_2
Nitrate, NO_3^- from farming can leach down through soils into **groundwater**, affecting the quality of **drinking water supplies** and posing significant risk to **human health**
N_r enrichment promotes **eutrophication,** leading to **harmful algal blooms, dead zones and biodiversity loss** in freshwater and marine environments
In 2016 the world used **105 million metric tons** of nitrogen fertilizers, or the equivalent to **4.2 million truckloads** of fertilizers
Long-term application of ammonium-based fertilizers causes **soil to become acidic**, negatively affecting crop production
Ammonia pollution cause eutrophication, soil acidification and direct toxicity in organisms, **reducing species richness** and **diversity**

Policy fragmentation and circular economy solutions

Just as nitrogen science has become fragmented between environmental compartments and N_r forms, the same is true of nitrogen policies. The impacts of N_r cross multiple policy domains, such as air pollution, climate, freshwater and marine policy, biodiversity, health and food security. While this fragmentation is widely seen in the domestic policies of many countries, it is equally apparent in the Sustainable Development Goals (SDGs). Examination of the SDGs and the underlying indicators shows that nitrogen is relevant almost everywhere, but almost equally invisible. Only in the proposed indicator for SDG 14.1 on life below water is a nitrogen-related indicator currently being developed.[32] Proposals to include NUE or nitrogen losses in the set of SDG indicators have not been adopted thus far.[20,33]

The consequences of this policy fragmentation across the nitrogen cycle can easily be seen in policy trade-offs. For example, policies to reduce NO_3^- pollution of water in the European Union led to the prohibition of manure application to land in winter "closed periods". However, this led to an increase in spring-summer manure application, which in turn resulted in an increased peak in atmospheric ammonia concentrations.[34] This temporal effect was only partly avoided in a few EU countries, by requiring low NH_3^- emission application of manure.[35] Another example concerns the recommendation to bring cattle indoors to reduce climate-relevant emissions of N_2O. However, even with the best technical measures to moderate emissions, this would generally lead to increased NH_3 emissions.[36] Such trade-offs are also relevant for combustion sources. For example, the introduction of catalysts to reduce NO_X emissions in the 1990s increased N_2O and NH_3 emissions.

These examples illustrate the urgent need to bring nitrogen science and policies together across multiple threats.[11,30,37] For example, the Chinese Government's 2015 "Action Plan for the Zero Increase of Fertilizer Use" aimed to prevent the growth in synthetic fertilizer use by 2020 without reducing food production, which would limit all forms of N_r pollution. It has been suggested that a next step should focus on socioeconomic barriers associated with farm size, innovation and information transfer.[38]

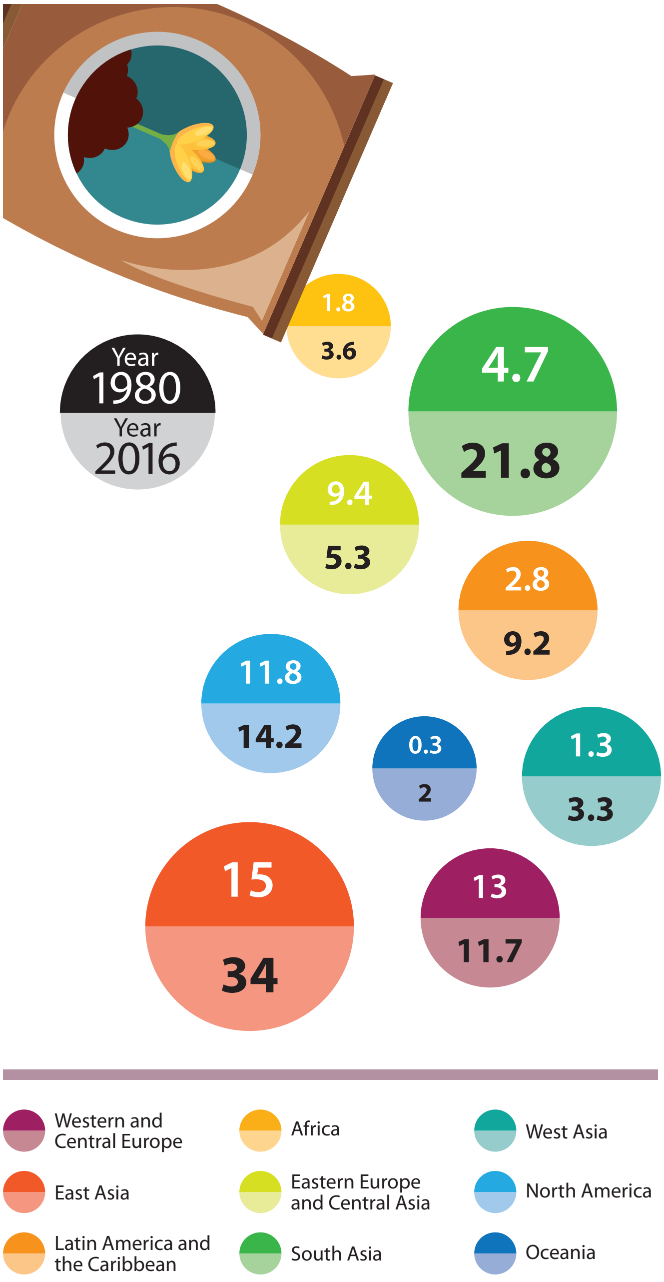
Nitrogen, nutrients and the circular economy

The Circular Economy Package adopted by the European Union in 2015 aims to maximize the efficiency of resource use in all steps of the value chain – production, consumption, waste management and recycling of secondary raw materials.[42,43] The plan recognizes the management and trade of organic and waste-based fertilizers as key in the recovery and recycling of bio-nutrients, such as nitrogen and phosphorus, back in the EU's economy. The new regulation encourages the sustainable and innovative production of organic fertilizers using domestically available bio-waste, animal by-products such as dried or digested manure, and other agricultural residues. Currently, only 5 per cent of organic waste material is recycled and applied as fertilizer within the EU. Enabling free cross-border movement of the bio-based fertilizers would lead to the creation of a new market space and supply chain for secondary raw materials within the EU. It is estimated that around 120,000 jobs would be created as a result. The recovery of nitrogen from bio-waste is expected to reduce or substitute the need for synthetic or inorganic nitrogen fertilizers, the production of which has high carbon and energy footprints. At the same time, this will further help to reduce losses of reactive nitrogen into the environment.

Mobilization of the circular economy for nitrogen and other nutrients starts on farms, where reducing losses allows a more effective delivery of nutrients to support crop growth. A major need here is the provision of practical tools to guide farmers on reducing nitrogen inputs to account for reduced nitrogen pollution losses, achieved by implementing mitigation methods. These should be supported by appropriate soil testing to give farmers confidence in fine-tuning nutrient levels.

However, there is also massive potential for scaling up reuse of nitrogen and other nutrients for the production of value-added, marketable products. Just as major investment is transforming society for a "low-carbon economy" (e.g. through renewable energy sources), the value of nitrogen implies a major economic opportunity through investment toward a "nitrogen circular economy".

Regional consumptions of all types of nitrogen fertilizers in 1980 and 2016 (in million metric tonnes)



Data source: International Fertilizer Association (https://www.ifastat.org/databases/plant-nutrition)

It is also easy to envisage transforming the nitrogen cycle in agriculture into a model of the circular economy for nitrogen. Here improvements in efficiency and reduced losses from fertilizers, biological nitrogen fixation, urine and dung allow more of the fresh nitrogen to reach intended food and bio-energy products. At the same time, reprocessing of livestock and human excreta into new fertilizers offers the opportunity to market recycled fertilizer products.

The situation has been very different when it comes to combustion sources of NO_x, since all available technologies, for instance, catalytic and non-catalytic reduction, focus on denitrification of NO_x back to N_2. Yet this represents a massive loss of resources. Multiplying global NO_x emissions by the fertilizer price of N_r would give an annual resource of US$50 billion globally, pointing to the need for technologies to recapture NO_x as NO_3^-.[11,39]

In India, a financial perspective also informs the government's policy from 2016 requiring all urea fertilizer to be coated with neem oil, in order to reduce both environmental losses of N_r and financial leakage of the subsidy to non-agricultural urea applications. The same principle underlies the Indian Prime Minister's call in November 2017 for farmers to halve fertilizer use by 2020, as well as governmental backing for Zero Budget Natural Farming (ZBNF) in some Indian states. The ZBNF movement focuses on avoiding costly external inputs of fertilizers and pesticides, helping farmers avoid debt, while promoting organic opportunities to improve soil organic matter, soil biology and fertility. In Andra Pradesh, a rapid upscaling of ZBNF to thousands of enthusiastic farmers is being supported by partnership between BNP Paribas, United Nations Environment Programme (UNEP) and the World Agroforestry Centre ICRAF, through the Sustainable India Finance Facility (SIFF). This innovative approach is based on loans to support investment and expansion being paid back by the government, since much less fertilizer subsidy will be needed when the fertilizer use reduces.[40,41]

Towards a holistic international approach for nitrogen

The encouraging news is that a few countries are piloting more integrated approaches to nitrogen management. For example, Germany quickly responded to the European Nitrogen Assessment by working on an integrated nitrogen strategy.[23,44] The difficulty for many countries is that a response to address nitrogen threats is split across multiple ministries, making it difficult to coordinate action. For example, in Brazil, agriculture is still expanding over large areas and the need for better decoupling of crop and animal production with environmental impacts has not been expressly addressed.[45] Internationally, the transboundary impacts of N_r also require clear legislation and policy actions.

The members of the International Nitrogen Initiative (INI) have given considerable thought to these challenges. The first step has been to work with the United Nations Environment Programme to establish a coordinated approach to scientific support for international policy development, in the form of the "International Nitrogen Management System" (INMS).

With the support of the Global Environment Facility and 80 partner organisations, INMS is developing guidance on the management of nitrogen, the integration of flows

Video: Air pollution from agriculture

Video Link: https://www.youtube.com/watch?v=07P_wXTTusI *© European Union*
Photo credit: gillmar / Shutterstock.com

Video: Why fertilizer matters to the environment and your bottom line

Video Link: https://www.youtube.com/watch?v=5TzzPOy1T3g *© Environmental Defense Fund*
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and impacts, cost-benefit valuation, and future nitrogen scenarios. INMS is also developing regional multi-country demonstrations to show how holistic nitrogen management can help. A key outcome will be the first Global Nitrogen Assessment, due for publication in 2022.

The next challenge is to develop a more coherent policy framework for the nitrogen cycle. The need for this can clearly be seen in the multitude of the United Nations Environment Assembly resolutions relevant to nitrogen: 2/6 (Paris Agreement), 2/7 (Chemicals & Waste), 2/8 (Sustainable Consumption & Production), 2/9 (Food Waste), 2/10 (Oceans), 2/12 (Coral Reefs), 2/24 (Land Degradation), 3/4 (Environment & Health), 3/6 (Soil), 3/8 (Air Quality) and 3/10 (Water Pollution).[46,47] The point is well made by Resolution 3/8, which encourages governments "to take advantage of synergistic effects of efficient nitrogen management on reducing air, marine and water pollution".

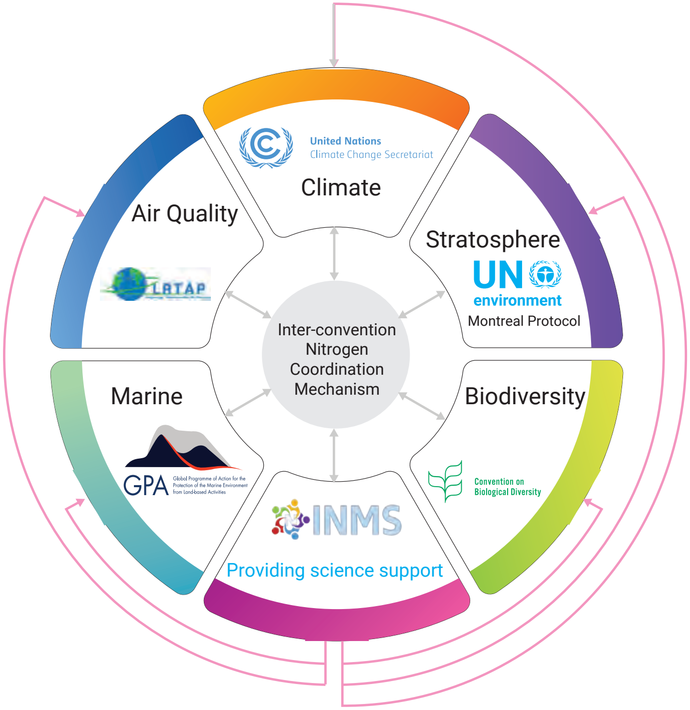
Recent discussions in the scientific and policy communities have explored how to coordinate nitrogen policy engagement more effectively.[48] Some possibilities include:

Option 1: Nitrogen fragmentation across policy frameworks – the status quo
Option 2: Nitrogen leadership under one existing policy framework. This provides a challenge to the mandate of each since existing Multilateral Environmental Agreements (MEAs) address only parts of the challenge.
Option 3: A new international convention to address the nitrogen challenge. There is currently little readiness for this approach.
Option 4: An "Inter-Convention Nitrogen Coordination Mechanism", providing an intergovernmental forum for inter-institutional cooperation on nitrogen, perhaps under the mandate of the United Nations Environment Assembly.

At present the Coordination Mechanism is lacking, which limits the extent to which the existing MEAs learn from each other, while also being inefficient in requiring that INMS work individually with multiple MEAs. The Coordination Mechanism would serve to actively engage Member States and relevant MEAs. The Major Groups and Stakeholders to the United Nations Environment Programme already facilitate involvement of business and civil society. It should be noted that Option 4 remains just that – an option. It is for national goverments to discuss which approach would be the most agile, efficient and cost-effective.

Nevertheless, this discussion points to another benefit. It is becoming increasingly obvious that global society needs a holistic approach for nitrogen science and policy. First, the multi-source, multi-sector perspective allows synergies and trade-offs to be considered. This would benefit agriculture and industry by providing a more coherent basis for business decision-making. Secondly, the holistic approach provides the foundation to develop the circular economy perspective that is vital to mobilizing change. In addition to these, such an approach for nitrogen becomes an illustration of how future environmental policy could coordinate more effectively between issues. As the United Nations Environment Programme works towards its strategy for a "Pollution-Free Planet", the lessons are likely to be all the more important across the realms of interacting pollution issues.

Inter-convention Nitrogen Coordination Mechanism



Video: The agricultural ammonia challenge

Video Link: https://www.youtube.com/watch?v=y0lG5mOWyAs *© CAFREtv*
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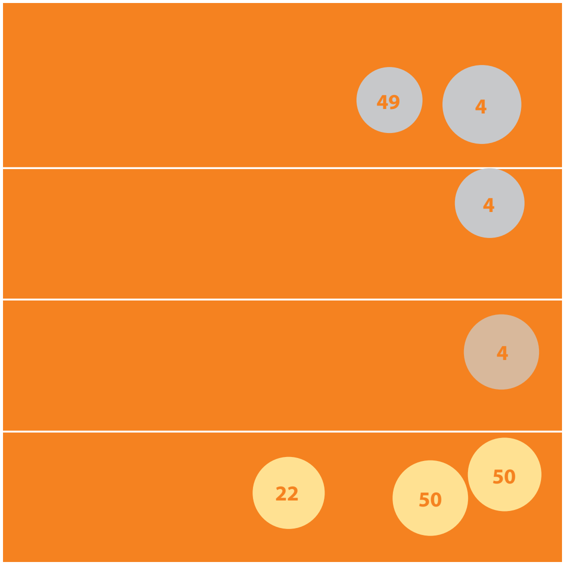
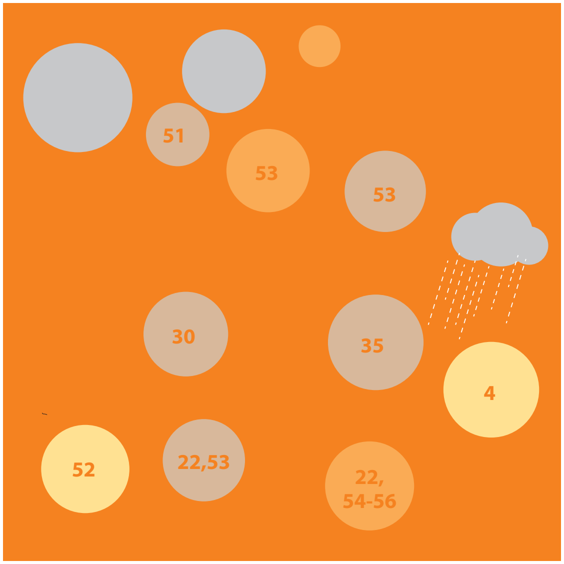
Graphic references





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The 2011 flood in Bangkok, Thailand
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Maladaptation to Climate Change:
Avoiding pitfalls on the evolvability pathway

Defining adaptation and maladaptation for the climate change context

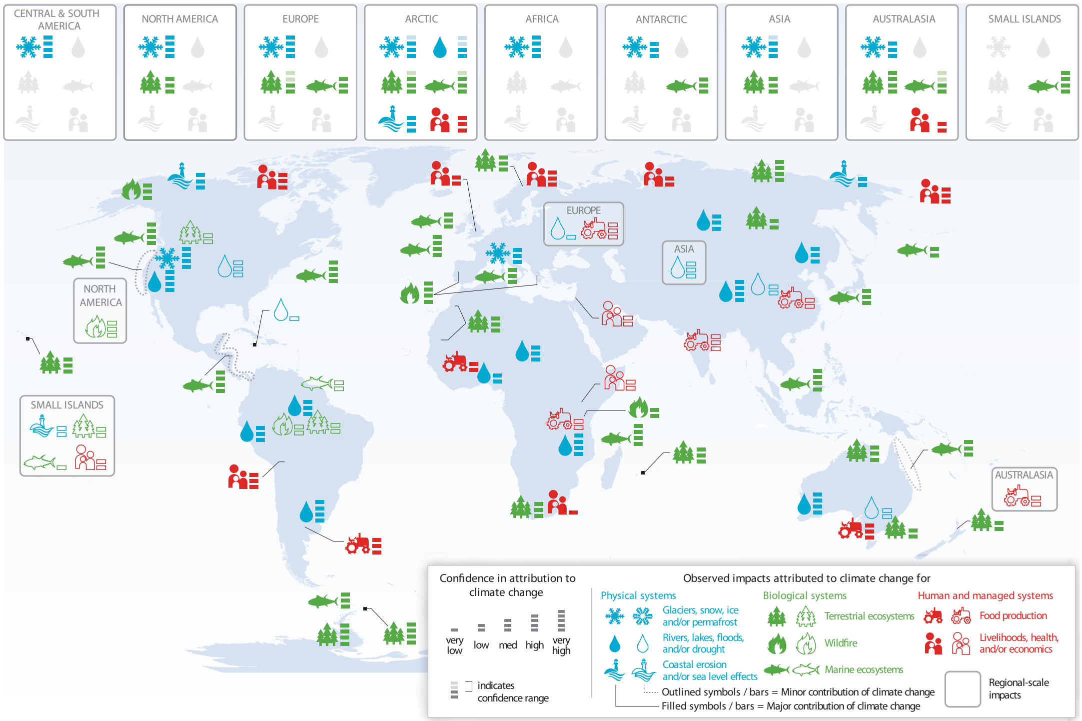
Metaphors are essential to logical thinking. As used for climate change research and policy, the terms adaptation and maladaptation originate from evolutionary biology.[1] Basically, genetic mutations spontaneously appear in every generation of a species and a natural selection process, imposed by the external environment, determines the success or failure both of those mutations and, as a consequence, of species. The idea can be applied to bacteria, to plants and animals, to ecosystems, and even to human behaviour. An important characteristic of successful adaptation is evolvability, the capacity to continue evolving through further adaptation as surrounding conditions continue to change.[2] In evolutionary biology, an identifying characteristic of a maladaptation is the absence of evolvability. It is a dead end.

While the origins of adaptation come from evolutionary biology, adoption of the term for successful human responses to environmental change started with disaster management. In that field, all human responses to a disaster are adaptations to the changed condition, including efforts to abate, or cut off, the source of the disaster.[3] The separation of what was called abatement from adaptation materialized in negotiations around the United Nations Framework Convention on Climate Change. One rationale for separating them was that negotiators would be distracted from agreement on pathways for abatement, or mitigation, if adaptation were available as an easier option.[4] Another explanation is that developed countries would only support efforts that had global outcomes, such as reduced carbon dioxide in the atmosphere, rather than locally focused adaptation objectives.[5]

As climate change negotiations progressed, researchers examined how and why some adaptation actions go awry, particularly those actions that waste substantial amounts of human, natural, or financial resources.[6] As these opinions developed, the United Nations Intergovernmental Panel on Climate Change (IPCC) realized the importance of precise, unambiguous terminology. In 2001, the panel suggested a nuanced definition of maladaptation, one that differs from its usage in biology or behavioural science, in the form of "… an adaptation that does not succeed in reducing vulnerability but increases it instead".[7] Discussions further focused on differences between a maladaptation and an unsuccessful adaptation. An unsuccessful adaptation may be neutral – it may simply mean an action did not work. But when an intended adaptation results in increased vulnerability for other groups and sectors, even in the future, that is a maladaptation.[8] At the same time, neither unsuccessful adaptation nor maladaptation should be confused with sham adaptation: wasteful projects presented as adaptation, such as expensive infrastructure serving only the interests of a small group, without actually improving resilience or reducing vulnerability to climate change.[9]

Maladaptation thinking continues to advance, and one influential study considered the problem according to the outcomes, identifying five categories of maladaptation when compared to alternative choices. According to this analysis, maladaptations are actions that increase greenhouse gas emissions, burden the most vulnerable disproportionately, incur high opportunity costs, reduce incentives to adapt, or set paths that limit the choices available to future generations.[8] These parameters were further articulated and broadened by the IPCC in their 2014 Fifth Assessment Report.[10] As the concept of adaptation versus maladaptation becomes clearer and we are better able to distinguish between them, managing the consequences of climate change should become less intimidating.

Global patterns of observed climate change impacts



Each filled symbol in the top panels indicates a class of systems for which climate change has played a major role in observed changes in at least one system within that class across the respective region, with the range of confidence in attribution for those region-wide impacts indicated by the bars. Regional-scale impacts where climate change has played a minor role are shown by outlined symbols in a box in the respective region. Sub-regional impacts are indicated with symbols on the map, placed in the approximate area of their occurrence. The impacted area can vary from specific locations to broad areas such as a major river basin. Impacts on physical (blue), biological (green), and human (red) systems are differentiated by colour. Absence of climate change impacts from this figure does not imply that such impacts have not occurred.

Graphic and caption source: The fifth assessment report of the Intergovernmental Panel on Climate Change[11]

Maladaptation at scale

In the face of climate change, the concept of maladaptation has developed from adaptation that does not work to adaptive actions that damage resources, narrow future options, worsen the problem for vulnerable populations, or pass on responsibility for solutions to future generations. If an adaptation action violates sustainable development, social equity and poverty eradication goals, particularly in the sense of disproportionately burdening the vulnerable, that action is maladaptive.[12] Efforts to avoid maladaptation at larger scales include research to identify major risks and responsible adaptation strategies throughout the infrastructure asset lifecycle that can inform the decisions, and the actions, of planners and regulators, designers, constructors, operators, investors and insurers.[13] Threats from maladaptation would likely escalate as the scale of the action increases. Recalling the characteristic of evolvability from biology could provide a preliminary screen for maladaptive actions, while prioritizing preservation of evolvability could forestall serious mistakes.

Limiting future options at the scale of installing a seawall along a domestic property may be considered a maladaptation as it will cause problems and limit options for neighbours, but such consequences are usually limited to the local vicinity. However, if a poorly considered action aggravates the original problems or limits future choices at a regional or global scale, then it becomes a much more dangerous maladaptation. At a larger scale, such maladaptations may not only constrain evolvability, but could also threaten the resilience of ecosystems, ways of life, and whole societies. This scale of maladaptive actions, especially those that increase greenhouse gas emissions or intensify ecosystem degradation, could contribute to the biogeophysical feedbacks to drive Earth system functions towards global tipping elements. Many of these tipping elements are irreversible – such as losses of permafrost, coral reefs or the Amazon rainforest – and that irreversibility could usher us over planetary thresholds.[14]

The IPCC's Global Warming of 1.5°C report of 2018 identifies multiple requirements for effective adaptation, demonstrating the importance of climate-smart planning and implementation during the transition to an acceptable

Abridgement of maladaptation in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change[10]

In the IPCC's 2014 Fifth Assessment Report, Working Group II on the Impacts, Vulnerability and Adaptation (WGII) defined maladaptation as "…actions that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future". It also offered a summary table of twelve broad categories for maladaptation.

Two of the WGII categories describe actions that deliberately ignore what is known: failure to anticipate expected climate change, and failure to take wider implications into account. Other categories concern trading off long–term vulnerability for short–terms benefits, including resource depletion that leads to later vulnerability; procrastination versus impetuous action; installation of infrastructure that cannot last; and engaging in moral hazard, where risk-taking is encouraged by various schemes offering payouts.

Further categories emphasize actions that promote one group, often an elite, over other groups, warning that perpetuating privilege may lead to conflict, as well as actions that ignore local knowledge, traditions and relationships. However, persisting with traditional but inappropriate responses is also considered maladaptation.

WGII also warns against actions that set path dependencies that cannot be easily corrected, and actions, especially engineering defences and solutions, that preclude alternative approaches, such as ecosystem-based adaptation. Finally, migration may be appropriate adaptation or maladaptation – or both – depending on the context and outcome.

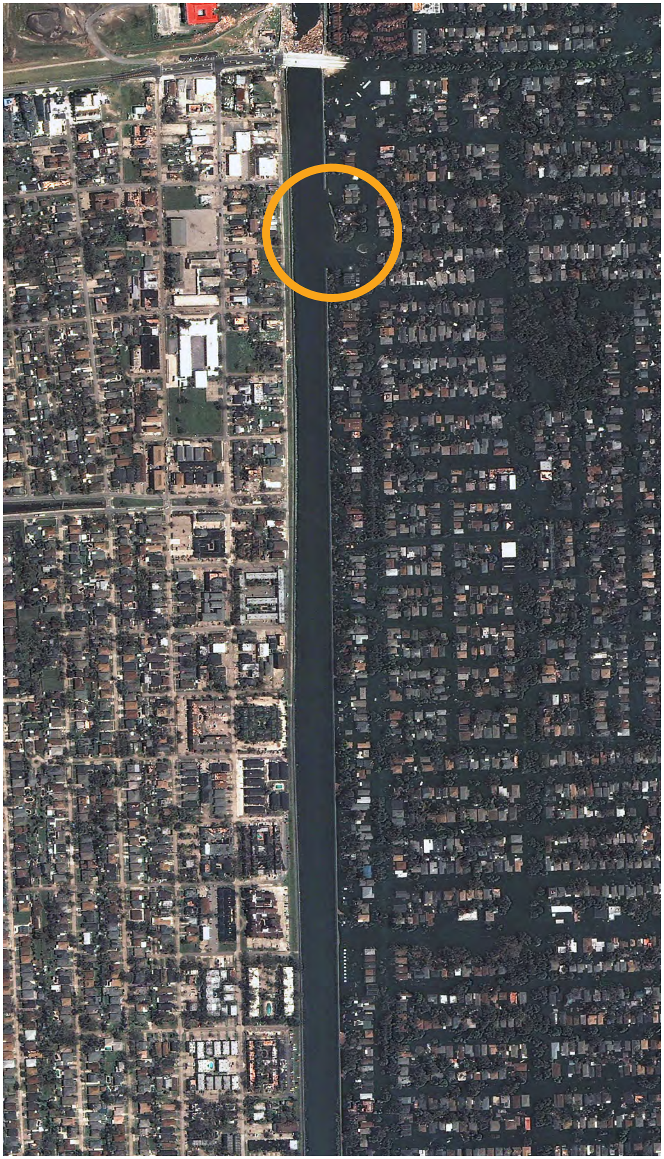
temperature increase.[15] Avoiding maladaptation is a crucial component of this transition. A number of regional-scale cases, self-identifying or not as climate change response, can serve as examples for useful inquiry as we face a future disrupted by climate change. These cases are quick samples of categories presented by the IPCC's Fifth Assessment Report and other distillations of current literature.

Balancing short–term demand against planning for long–term resilience

As an example of the balance between shorter- and longer-term benefits, the Coastal Climate-Resilient Infrastructure Project in southwest Bangladesh has already been presented as a case study of a possible maladaptation.[16] Conditions that frame the question are the adaptation benefits over the next two decades versus the longer-term maladaptive costs that will dominate by 2050 as rising sea level inundates the region.[16] Potential maladaptive outcomes include complex issues for migration, both out of and into the region. Investors expect that the new markets and better roads, bridges, drainage, and cyclone shelters will encourage the coastal populations to stay, when perhaps they should migrate inland. There is a significant likelihood that these facilities will lure newcomers, possibly including some of Dhaka's informal settlement population who have already been displaced by environmental disasters.[19]

Burdening the most vulnerable disproportionately

In some cases, attempts to adapt to changing conditions on multiple fronts can become maladaptations for particular population groups. After 2005's Hurricane Katrina devastated New Orleans and the surrounding region in the USA, initial plans for new green areas to build urban resilience against future floods appeared to concentrate acquisition in the low-lying land that traditionally belonged to poor African-Americans, rather than to other groups.[12,19] That particular urban-renewal proposal was not accepted. However, more than a decade later, studies show that many of the city's poorest and most marginalized people never regained what little they did possess, and a significant proportion of them had to migrate out of the region.[12,20]



Hurricane Katrina of August 2005 damaged many sections of the levee system designed to protect the low-lying city of New Orleans against floods and storm surges. The satellite image shows how a levee breach (yellow circle) allowed flood water from the 17th Street Canal to inundate neighborhoods on the east side of the canals, causing billions of dollars in property damage, while the west side remained dry.

Photo credit: Digital Globe (www.digitalglobe.com)

Maladaptation to Climate Change

The case studies presented in the infographic demonstrate a range of actions to adapt to changing climate at different scales. Some cases are maladaptive given the unintended consequences or will become maladaptations in the near future. Others are actions taken after consideration of many factors to avoid maladaptation.

Maladaptation, defined by the IPCC, is an intended adaptation that instead increases risk of climate-related damages, increases vulnerability to climate change, or diminishes welfare, now or in the future.

Maldaptations are poor choices among alternatives, choices that increase greenhouse gases, unfairly burden the most vulnerable, incur unjustifiable costs, reduce incentives to adapt, or limit choices available to future generations.

Decision-making that **ignores science**, wider implications, or likely consequences

Actions favouring one interest group over another, laying ground for **future conflict and damage**

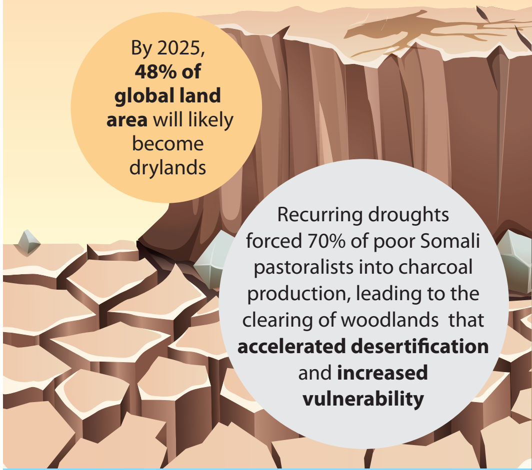
Unwise trade-offs: short vs long term benefits, risk vs reward (moral hazard), too short vs too long consideration period

Actions that determine **path dependency** and lock in or that eliminate choices of future generations

Relocation that puts populations in even **more threatening conditions**

Drought

Climate change disrupts the hydrological cycle. Drought will become more intense, frequent and persistent, threatening all human uses and ecological functioning. Extended drought conditions lead to groundwater overexploitation and aquifers are seldom recharged sufficiently once rains arrive.



By 2025, **48% of global land area** will likely become drylands

Recurring droughts forced 70% of poor Somali pastoralists into charcoal production, leading to the clearing of woodlands that **accelerated desertification** and **increased vulnerability**

Water scarcity

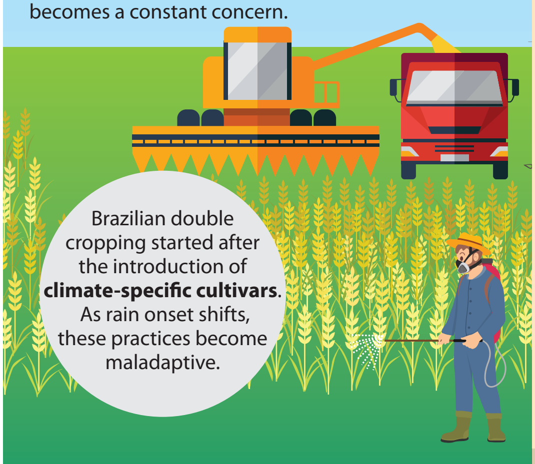
By 2050, 5.7 billion people could be living in water scarce areas. Regions are already adapting to water scarcity through groundwater exploitation, water rationing, or desalination. Such measures may be maladaptive in the long term.

Mexico City faces water scarcity. Exploiting distant groundwater sources is a short-term solution. Actual adaptation invests in longer-term solutions, such as rainwater harvesting and greywater treatment and reuse.

Agriculture

Persistent climate change extremes threaten agricultural production systems. Farmers pride themselves on their adaptive capacities, but these extremes arrive so frequently and persist so unpredictably that adaptation becomes a constant concern.

Some Zimbabwean farmers offset climate uncertainty by increasing pesticide use. Too often, beneficial insects are also eliminated, making conditions worse.



Brazilian double cropping started after the introduction of **climate-specific cultivars**. As rain onset shifts, these practices become maladaptive.

Health

Shifting climatic zones and increases in frequency and intensity of climate extremes produce health consequences. This variability causes crop losses and expanded ranges for disease vectors threatening critical plant and animal species, as well as human populations.

Antibiotics are overused and misused for both preventing and treating veterinary challenges. This maladaptation to **vector-borne diseases** exacerbates threats of antibiotic resistance.

A study showed that the dung from cattle treated with antibiotics **emitted more methane** than antibiotic-free dung. Antibiotic residues also altered dung beetles' gut microbes.

Sea level rise

Sea levels continue to rise globally, threatening infrastructure, groundwater resources, natural barrier islands and coastal communities. An existential threat to low-lying nations and small island states extends to a way of life for millions of people.

Florida canal water levels are used to recharge and maintain pressure against **saltwater intrusion** into groundwater. Raising canal water levels to counter the intrusion inadvertently increases flood threat.

State law guarantees coastal access to native Hawaiians for cultural purposes and subsistence fishing. Sea level rise curtails public access, disproportionately affecting the poor, while development for private profit persists.

Flood

Flooding is one of the most common climate change impacts experienced worldwide. Flood and water management systems suited to the past no longer suffice. As climate continues to change, adaptive management and wide-ranging stakeholder buy-in are required to avoid maladaptations.

Bangkok's metropolitan region is flood-prone due to the lack of planning and investment. Unplanned and uncoordinated **autonomous adaptation** leads to flooding downstream and weakens the entire public drainage system. In 2011, official responses to flood protected the wealthy and burdened vulnerable groups.

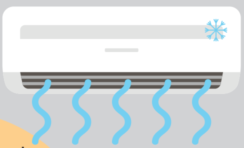
Wildfire

Globally, the length of the fire season increased by 19% from 1979 to 2013. Wildfires play important roles in ecosystems worldwide, but their destruction can ruin socioeconomic systems. In some regions, standard management strategies exacerbate conditions.

After decades of fire suppression and five years of climate–related drought, Californian forests are full of **wildfire fuel**. With transformation in mind, the State is initiating ***prescribed burning*** to manage that threat.

Cities

By 2050, 70% of the global population will live in cities. Around the world, cities already experience changing climate in the form of heatwaves, floods, and adaptation failure. Urban adaptations can be policies, infrastructure development, or technological fixes. Remedies seldom benefit all, and they can threaten some marginalized groups.



Warming temperatures and water shortages prompted Melbourne, Australia to increase air-conditioning and desalination. These are maladaptations: b-y increasing GHG emissions, they compound vulnerability in other systems, sectors and communities.

Societal vulnerability

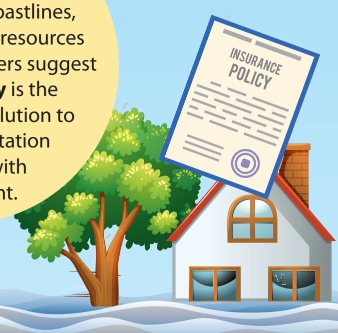
Around the world, people have adapted to climate impacts in various ways: water supply rethinking, insurance schemes, livelihood strategy changes, voluntary or forced migration, and resettlement projects. When these well-intentioned methods are ill-suited to local conditions, or do not consider multiple facets of the issue, vulnerability may increase.

Some farmers seek protection from climatic extremes through **crop insurance** that can inhibit further adaptation strategies.

Insurance policies are maladaptive when they support risky behaviour, such as rebuilding in dangerous locations, or they promote replacement rather than redesign according to changing conditions. As climate threats intensify, insurance may provide a **false sense of security**.

China's climate adaptation resettlement projects offered financial incentives and improved living standards. They also produced **disproportionately heavier burdens** on those left behind, those already displaced, and the poor.

On small island states, increasingly rising tides wash over coastlines, ruining freshwater resources and crops. Researchers suggest **labour mobility** is the best long-term solution to avoid maladaptation associated with resettlement.

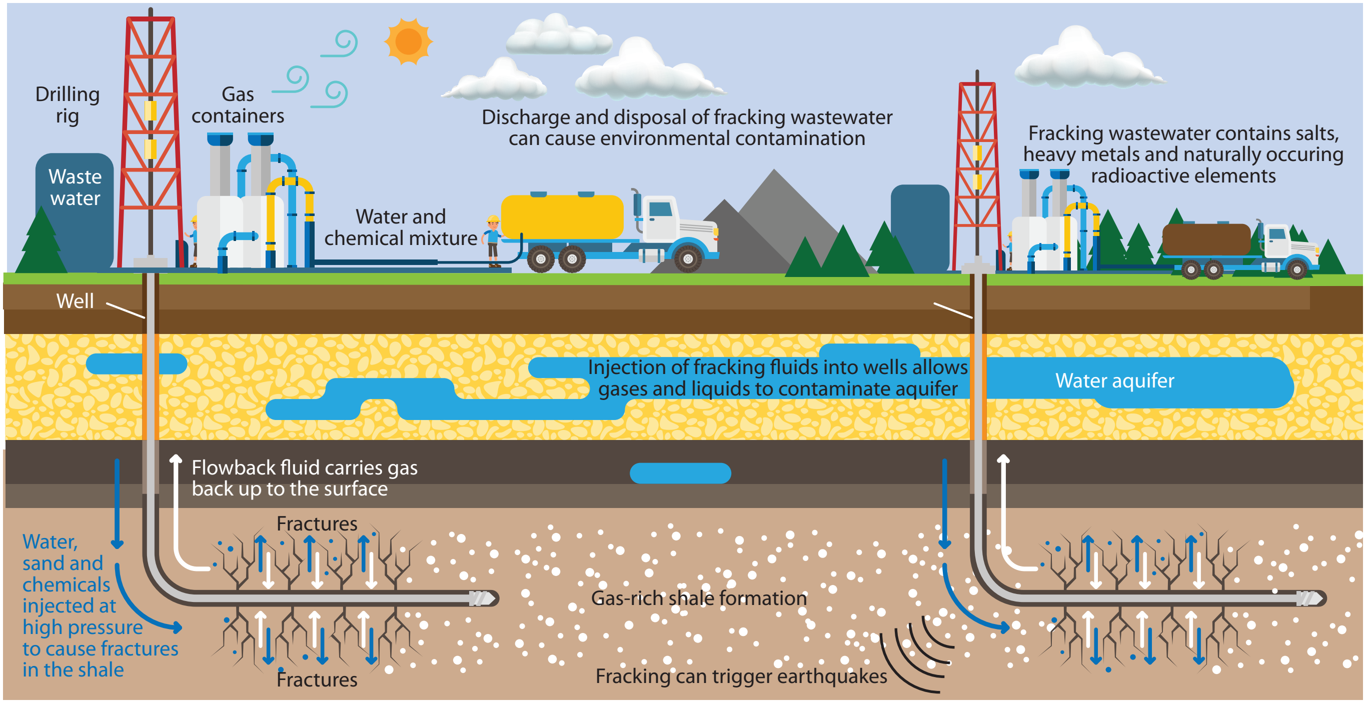


Limiting options for future action

Petroleum geologists and engineers developed the capacity to extract oil and gas from deep earth reservoirs sealed by the caprock formations.[21] Some of the depleted reservoirs are considered well suited to sequester carbon dioxide over centuries and longer.[22] Their suitability is due to our understanding of reservoir permeability and the quality of the caprock layer that seals the reservoir.[21,23] When natural gas was promoted as a mitigation strategy, that is, a bridging fuel from coal and oil to renewables, investment grew and the technology evolved.[24] However, there are more problems with that bridge than had originally been anticipated. Much of it was related to the evolution of an extraction technique called hydraulic fracturing, or fracking.[25,26] This technology injects a mix of water, sand and chemicals at high pressure to deliberately force fissures and cracks in the reservoir to release the natural gas. A number of environmental challenges arise from fracking, including aquifer depletion and contamination from chemicals used in drilling and injection, leakage of methane into the environment, and increased seismicity.[27-30] Further, some suggest that hydraulic fracturing may destroy the caprock seal that makes the depleted reservoirs valuable for carbon sequestration.[31,32]

The IPCC Global Warming of 1.5˚C report details two pathways of emission reduction and atmospheric greenhouse gas limitation that will achieve the goal of keeping the global average temperature increase above pre-industrial levels at 1.5˚C. Both pathways rely heavily on the promise of sequestering carbon in geological formations.[15] This hydraulic fracturing industrial policy demonstrates maladaptation on two fronts: the possibility of foregoing long–term benefits for short–term gains and locking into path dependency by damaging future resources. At the same time, fracking increases greenhouse gas emissions by leaking methane throughout its production cycle.[26,33-35]

Hydraulic fracturing or fracking



Jonah gas field, Wyoming, United States

Photo credit: EcoFlight

Avoiding maladaptation in a 1.5°C constrained future

The vision offered by the IPCC's Global Warming of 1.5°C report, and the wisdom of keeping temperature increase to that mark, suggests that climate change consequences need to be more widely considered in decisions made by public and private sector actors, as well as by civil society.[14] Rather than narrowing the concept of maladaptation to unfortunate and complicating outcomes of actions formally labelled as adaptation, policy advisers and decision makers at various levels and in a broad range of institutions could be widening their deliberation to avoid climate change maladaptations in their planning.

The 1.5°C report also emphasizes the United Nations Agenda 2030 and its sustainable development goals, particularly those concerning equality and equity.[14] This vision for meeting the climate challenges ahead focuses on a future that is worth living in, that is better than the one experienced by too many people today. Reducing the root causes of conflicts, wars, insecurities, poverty, and migrations is a vital component of this vision. The human species has always adjusted to changing conditions and we are by nature adaptable creatures. Learning by trial and error is a dependable methodology to guide our adaptations. But we are also a species that uses foresight and that plans ahead. We can design our future. Avoiding maladaptations means we learn not only from our own errors, but also from those experienced by individuals and communities around the world. Using foresight is not limited to each group's suspicions, presumptions, or even aspirations, but needs to be based on scientific evidence and realistic probabilities.

Evidence indicates that maladaptation can be avoided by evaluating all costs and benefits, including co-benefits, for all groups in society, and by being explicit about who the winners and losers will be, and how the burdens could be better shared. Entrenched habits of dismissing the interests of future generations are not appropriate along either of the IPCC 1.5°C pathways that will keep the global average temperatures within that manageable range. We are now living in the future that was overly discounted when the Framework Convention on Climate Change was agreed in 1992. Avoiding maladaptation means evading lock-ins and path dependence, and optimizing evolvability instead. Otherwise, in biological terms, we will find we are at a dead end.

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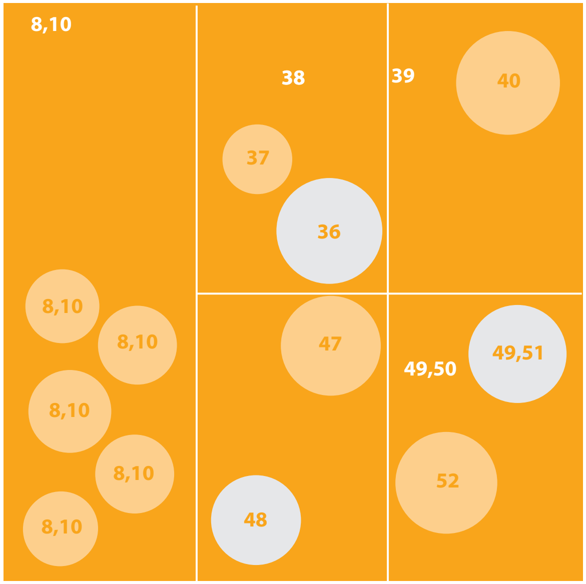
Graphic references



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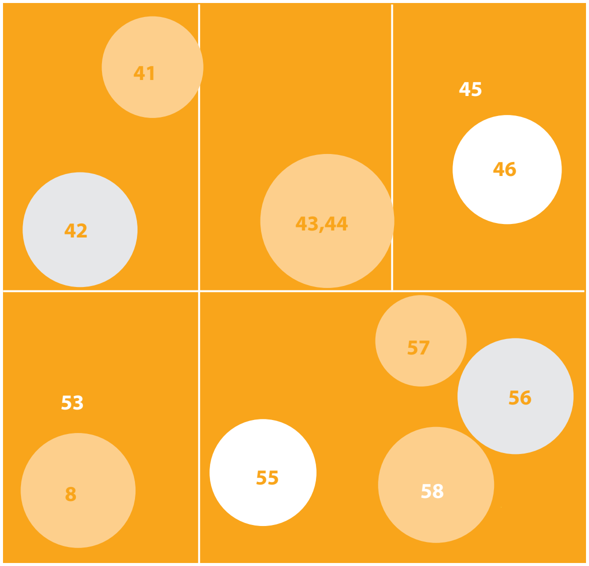

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Sunset Crater Volcano National Monument near the Coconino National Forest
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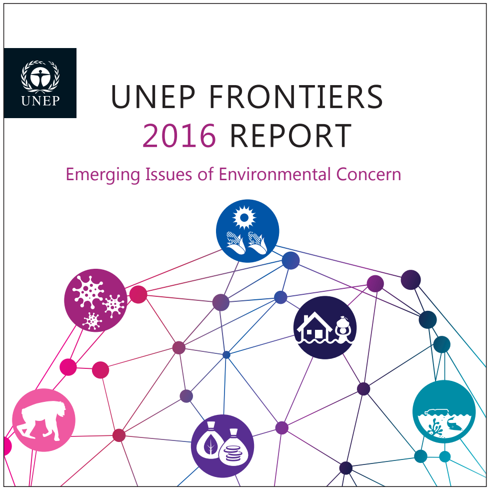

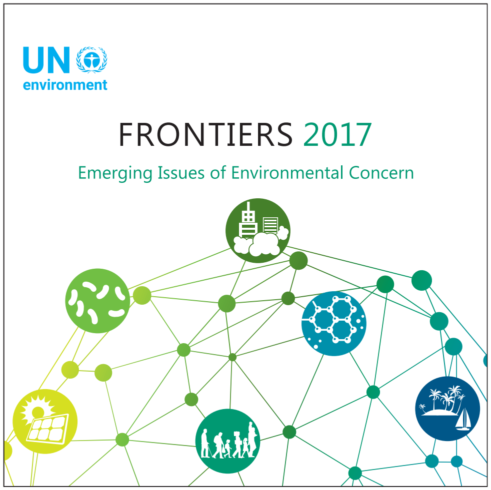

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