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ECONOMIC
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10 Emerging Technology Solutions for Planetary Health

INSIGHT REPORT

OCTOBER 2025

Images: Midjourney, Studio Miko. All images in this report were generated using artificial intelligence.

Contents

Foreword

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With humans putting continued pressure on our natural systems, we are seeing critical Earth processes that regulate the stability and resilience of our planet pushed beyond safe limits. The planetary boundaries framework is a scientific analysis of the stability of Earth's natural systems, offering a clear understanding of the interrelated Earth processes that underpin life and keep our planet healthy. When acting within the safe operating space, these systems are in balance and provide the stable conditions necessary for human development and well-being.

As of 2025, however, seven of the nine planetary boundaries have been breached, with greenhouse gas concentrations rising, synthetic chemicals released into nature, overuse of nutrients, shifts in freshwater, deforestation, ocean acidity and biodiversity all reaching levels that are unsustainable for our planet and will have reverberating negative impacts that we cannot fully predict yet.

Addressing these transgressions calls for a deliberate and swift collective response. By designing policies that prioritize planetary health and mitigate destructive human imprint on our planet and by evolving our business models to account for environmental limits, we can chart a path back towards a safe operating space for humanity, which is a necessary (but far from sufficient) condition for justice.

Advancements in technology have a crucial role to play in efforts to transform the world economy back within the safe operating space of planetary boundaries. They can substitute planet-damaging technologies (such as transitioning away from fossil-fuel-based energy and moving to green electric solutions), enable more effective monitoring of environmental changes, mitigate damaging impacts and have the potential to help restore the integrity of some of our planet's vital systems. The technologies in this report offer promising tools as part of the broader transformation needed to move back towards a safe operating space within planetary boundaries.

From breakthroughs in clean energy and resource efficiency to innovations in materials, agriculture and ecosystem restoration, these solutions have the potential to address and mitigate key drivers of planetary boundary transgressions. While relying on emerging technologies instead of using well-tested and scalable established options would certainly not be a wise choice, and while no single technology can solve the complex challenges we face, emerging technologies do offer, collectively, a contribution to new pathways for interacting with our planet in a way that is mindful of its limits. By supporting the responsible deployment of these technologies, we can help accelerate the transition towards a more sustainable and balanced relationship with our planet.

Introduction

Addressing planetary boundary breaches will require rapidly and equitably scaling emerging technology solutions.

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In 2024, the global average temperature remained 1.5°C above pre-industrial levels for the entire year. 1.3°C of this warming can be attributed to human activity.[1] Current mitigation approaches are not on track to limit warming to this threshold. In fact, many trusted projections show that current policies and commitments will lead to 3°C warming by 2100, setting in motion catastrophic consequences for life on Earth.

In the face of this escalating crisis, technology – and its speedy rollout at scale – has a vital role to play to help humanity build a more sustainable future, adapt to the consequences of the changing climate and repair the harm already done to the Earth and its ecosystems. While the role of technology in addressing the climate crisis must be approached with caution – particularly as advancing technology can also put a strain on global natural resources – it is equally critical to recognize that there is no viable path to a sustainable future that does not depend heavily on both existing and emerging technologies.[2]

For over a decade, the World Economic Forum has highlighted the most cutting-edge technologies poised to make an impact in our societies through our annual Top 10 Emerging Technologies report. This special edition is the first of its kind, focusing on emerging technologies that can specifically address and respond to the current state of our planet.

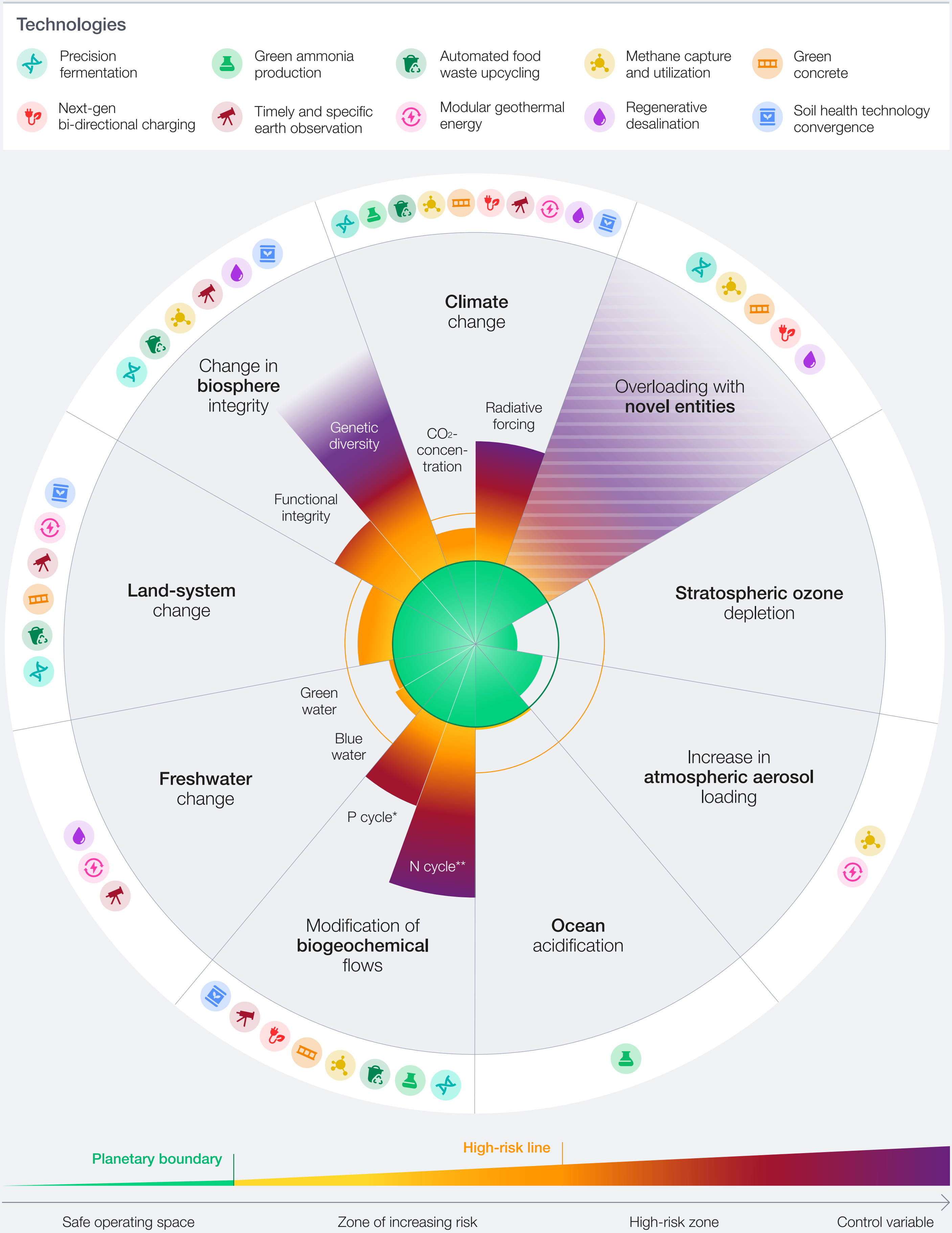
With mounting evidence that we have already exceeded Earth's "safe operating space" and breached seven of the nine planetary boundaries (see Figure 1), there is an urgent need for solutions that mitigate greenhouse gas emissions, maintain biosphere integrity, enable resource efficiency and even repair our Earth systems.

This report spotlights technologies with significant potential to respond to the most pressing environmental challenges of our time. Some – like green concrete, green ammonia production and methane capture and utilization – focus on advances in material and chemical processes to reduce emissions and decarbonize key sectors. Others – like next-generation (next-gen) bi-directional charging and modular geothermal – offer innovative ways to consider energy systems for greater efficiency, flexibility and resilience. Advances in biotechnology have also led to precision fermentation for alternative proteins and microbiome engineering for soil health, which can enhance food security, reduce agricultural emissions and restore ecosystem function. When different advances in technology converge, they enable breakthroughs like automated food waste upcycling, timely and specific Earth observation and regenerative desalination.

To scale, these technologies require an enabling policy environment, robust financial investment and coordinated action across sectors. Ensuring the technologies are developed and deployed in an equitable way is also essential to maximize their impact and ensure benefits are shared broadly across the globe. Each technology in this report has been assessed with these crucial policy, finance and equity lenses in mind.

While technology alone is not a panacea for our planetary health crisis, climate projections make it clear that remaining within the 1.5°C threshold will demand unprecedented technological innovation and rapid adoption. The technologies outlined in this report represent a starting point for collective action – offering approaches with the potential to accelerate progress, inspire collaboration and help secure a sustainable future.

FIGURE 1 | **Alignment with planetary boundaries**



Notes: For a full explanation of each planetary boundary, please refer to the Appendix of this report; *phosphorus cycle; **nitrogen cycle.
Source: Adapted from: Potsdam Institute for Climate Impact Research. (n.d.). *Planetary Boundaries Science (PBScience) Lab*. https://www.pik-potsdam.de/en/institute/labs/pbscience/pbscience.

Methodology

Technologies were nominated, analysed and shortlisted through expert surveys, AI trend analysis and committee review.

Following the established methodology for technology selection developed through the World Economic Forum's Top 10 Emerging Technologies reports over 13 years, the technologies featured in this report were nominated through a survey of experts. This process included input from World Economic Forum partners and Global Future Council members, the Frontiers network of chief editors, and the Frontiers Planet Prize National Champions and Jury of 100 members, inviting a diverse selection of innovations with the greatest potential to address planetary health challenges.

Survey respondents provided information about the technology nominated, including the technology name, description, key breakthroughs, case studies and how it will impact the environment, economy and society, as well as potential risks that accompany the technology. Survey responses were combined with previous submissions for the Frontiers Planet Prize to include the latest technological advances in research and practice. In total, 123 technologies were collected.

To assess the relevance of the emerging technologies, an AI Trend Analyzer – developed by Frontiers – mapped nominations and their frequency in academic articles over a 10-year period. From this analysis, an average "trendiness" score was established, indicating each technology's growing presence and momentum in research literature.

This refined shortlist of 20 technologies was then assessed by a steering committee of experts, who applied the following guiding principles:

- **Novelty**: Early adoption is emerging, but widespread use is not yet achieved.
- **Impact**: Potential for significant planetary boundary response, weighted against potential harm.
- **Depth**: Developed across multiple entities, with broad and sustained interest.

This thorough, multi-phase selection process enables a comprehensive evaluation of each technology's readiness and transformative potential.

In preparing this report, artificial intelligence (AI) tools were used to support elements of writing and background research. Consistent with the World Economic Forum's guidelines for responsible AI use, these tools were treated as collaborators rather than replacements. Subject-matter experts reviewed, fact-checked and revised all outputs to ensure accuracy, integrity and compliance with Forum guidelines on security, transparency and ethical use.

01

Precision fermentation

Producing animal-free proteins to transform food, materials and medicine.

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Over one-third of the world's protein consumption comes from animal sources,[3] making animal agriculture a major driver of land conversion, freshwater use, greenhouse gas emissions and nutrient pollution. Precision fermentation can generate identical or near-identical proteins without animals, using microbes that have been optimized to produce them.[4] By mitigating the need to harvest nutritionally relevant proteins from animals, this approach could help reduce pressure on planetary boundaries related to climate change, land-system change, freshwater use, biogeochemical cycles and biodiversity loss.

In precision fermentation, microbes such as yeast, fungi or bacteria are optimized through DNA modification to produce specific proteins and other high-value target molecules. Optimized microbes are grown on a large scale in steel tanks called bioreactors, where, under tightly controlled conditions, they convert simple feedstocks like sugar into useful products through fermentation – a natural microbial process that breaks down nutrients and releases energy. After fermentation, the desired ingredients are separated and refined. Independent life cycle assessments suggest that precision fermentation, when coupled with renewable energy inputs and sustainable feedstock sourcing, can reduce greenhouse gas emissions by 72-97%, cut water use by 81-99%, and lower land use by up to 99% compared to conventional dairy protein production.[5,6]

“ Precision fermentation can reduce greenhouse gas emissions by 72-97%, cut water use by 81-99%, and lower land use by up to 99%.

Precision fermentation has expanded rapidly in the food sector, through companies like Perfect Day,[7] and is currently being used to produce dairy proteins like casein and whey for cheeses and yoghurts, egg proteins like ovalbumin for baked goods and emulsifiers, and meat-like molecules that replicate colour, flavour and texture in plant-based meats, among many others.[8] This method is also reducing reliance on low-yield, fossil fuel-intensive chemical synthesis for many substances, including vitamins, pigments, flavours, cosmetic ingredients, biodegradable textile coatings and pharmaceutical compounds such as insulin and monoclonal antibodies.[9] In the food industry, the first commercial, animal-free whey protein was approved by the US Food and Drug Administration (FDA) in 2020.[10] Commercial facilities are now scaling up production in multiple regions, with food-grade products approved by authorities in jurisdictions including the European Union, Israel, the US and Singapore.[11]

Wider adoption of precision fermentation could affect not only the environmental impacts of animal agriculture, but also bolster the economic systems and supply chains connected to food, cosmetics and materials. Environmentally, it could reduce demand for feed crops, easing the planetary boundary related to land-system change; lower water and energy use, supporting freshwater sustainability; cut methane emissions from livestock, addressing climate change; and curb fertilizer runoff, improving biogeochemical cycles. However, high energy requirements and the need for refined sugar inputs may limit climate benefits unless these systems are powered by renewables and coupled with sustainable feedstocks. Economically, precision fermentation is already changing how dairy proteins and speciality ingredients are used and sourced, with broader impacts likely across food, cosmetics, pharmaceutical and materials industries. As costs fall and infrastructure expands, new job opportunities may emerge in biomanufacturing, process engineering, food innovation and microbial design. By investing in modular microbial manufacturing, regional strain development and accessible inputs, governments and industry could ensure that precision fermentation supports broader participation in ingredient production – reducing dependence on animal agriculture and helping low- and middle-income regions build climate-resilient food systems.

Make or break

The success of precision fermentation may depend on adaptive regulation, inclusive financing models and equitable access to tools and markets.

Policy lens

Adaptive regulatory frameworks for food safety, labelling and intellectual property can support public trust and market access. While precision fermentation produces proteins similar to their animal-derived counterparts, the final product may lack certain components (e.g. fats, sugars, micronutrients). Clear guidance is needed to ensure accurate labelling and prevent consumer confusion. Fragmented oversight or delays in approval may limit adoption and increase monopolization risk.

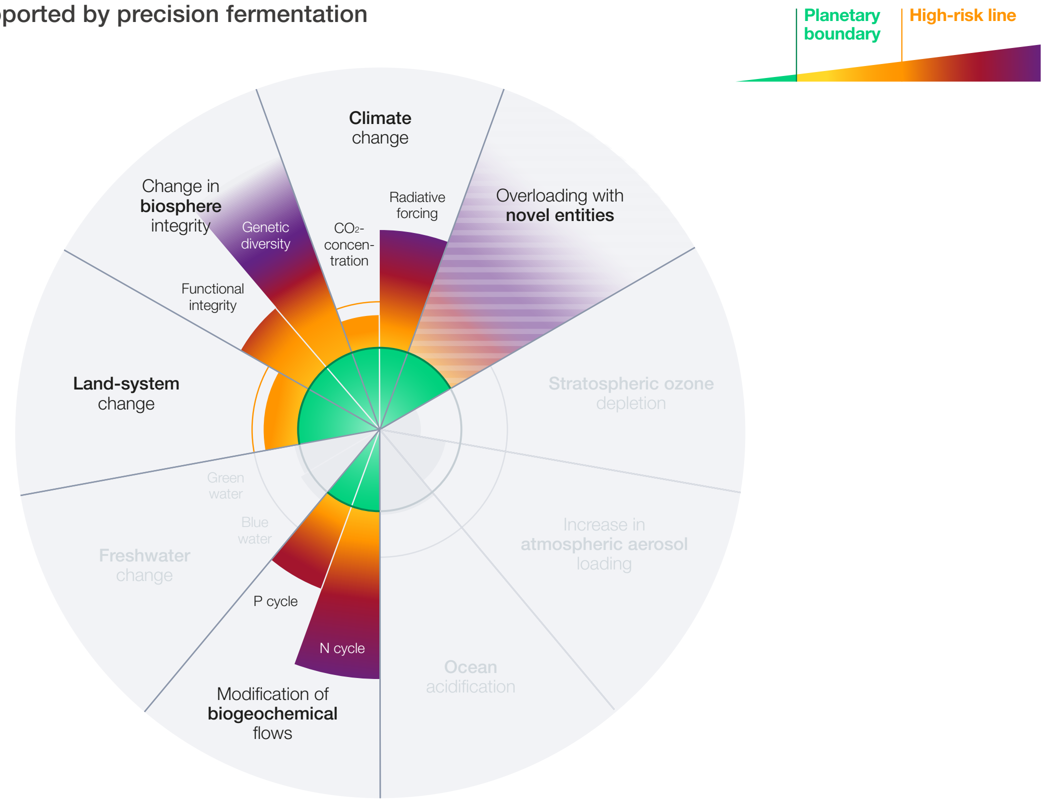
Finance lens

Blended finance approaches, modular infrastructure and open-access strain libraries may expand participation by smaller firms and regional producers. High capital costs and centralized production models could constrain broader access; however, practical scale-up routes – such as business-to-business integration into manufacturing, public procurement and shared manufacturing hubs – can help facilitate adoption and diversify market entry.

Equity lens

Equitable outcomes are more likely where production is affordable, culturally relevant and accessible to diverse stakeholders, including those in low-resource or agriculturally vulnerable settings – including workers, farmers, ranchers and communities affected by shifts away from traditional animal-based production systems. Without inclusive models, benefits may remain concentrated in high-income regions.

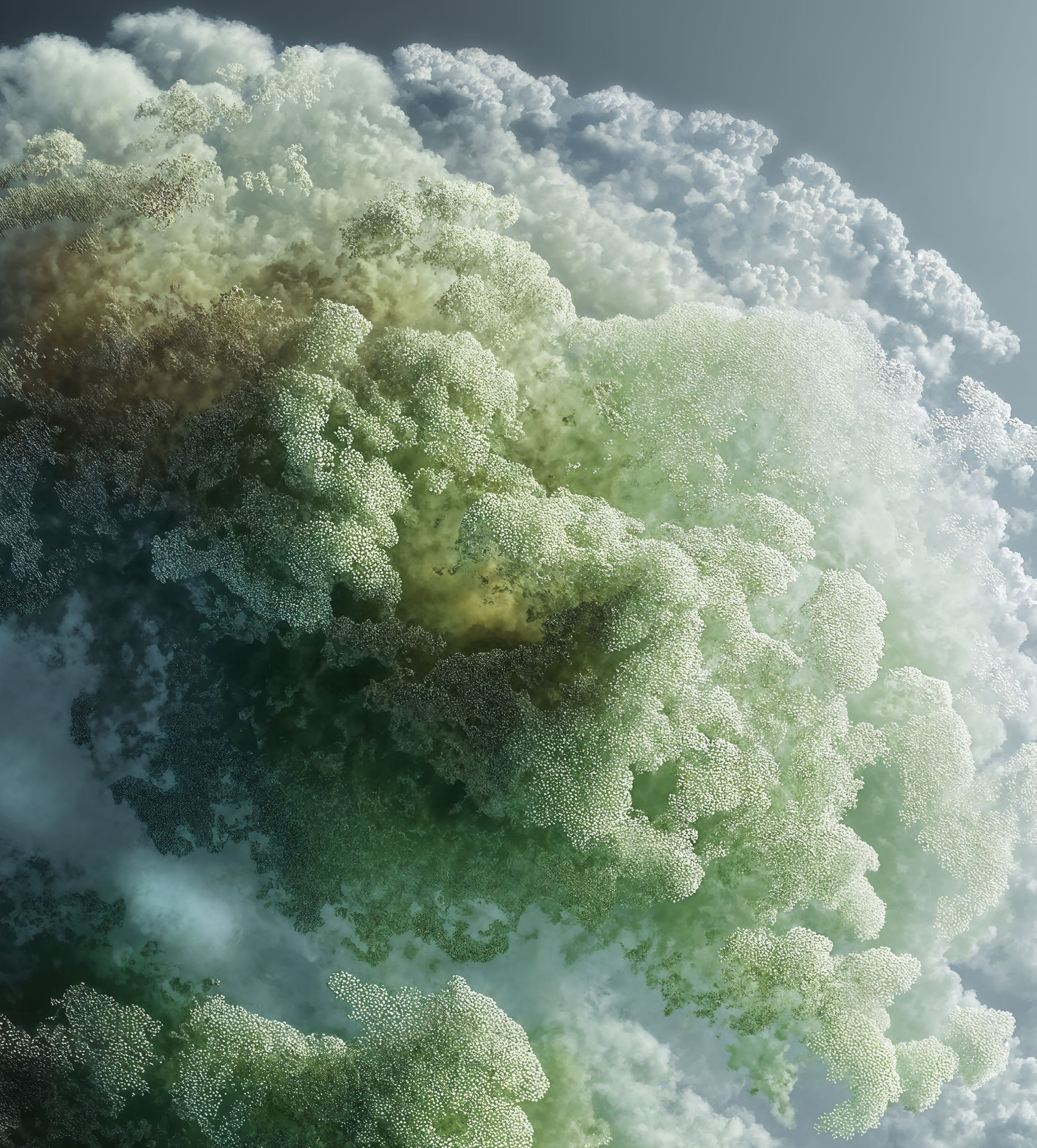
Planetary boundaries supported by precision fermentation



- **Climate change**: Reduces methane and carbon dioxide (CO_2) emissions by replacing ruminant livestock and energy-intensive production systems.
- **Land-system change**: Decreases land needed for pasture and animal feed crops, freeing space for conservation or regenerative land use.
- **Biosphere integrity**: Reduces biodiversity loss by limiting habitat conversion and reliance on animal-derived products.
- **Nutrient cycles**: Minimizes nitrogen and phosphorus pollution by reducing fertilizer use tied to conventional feed production.
- **Novel entities (chemical pollution)**: Avoids harmful byproducts and reduces reliance on synthetic additives and agrichemicals.

02 Green ammonia production

Decarbonizing fertilizer and fuel with renewable-powered nitrogen synthesis.



Hailong Li
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“ Green ammonia could drive investment in electrolysers, storage systems and retrofitted plants – creating jobs across hydrogen production, facilities upgrades and transport logistics.

Modern agriculture depends on ammonia-based fertilizers, but conventional ammonia synthesis consumes up to 2% of global energy and generates more emissions than any other chemical process.[12] Green ammonia production – synthesizing ammonia sustainably using renewable energy – is addressing this environmental burden through cleaner methods that can produce ammonia with much-reduced fossil fuel use. By replacing fossil inputs in fertilizer, industrial feedstocks and transport fuels, green ammonia technologies help reduce pressure on planetary boundaries related to climate change, biogeochemical flows and ocean acidification.

All ammonia production methods rely on nitrogen fixation, which is the chemical process of converting dinitrogen (N_2) from the air into more accessible forms, such as ammonia (NH_3). The traditional approach, called the Haber-Bosch process, uses heat, high pressure and methane-derived hydrogen to convert nitrogen. Haber-Bosch is heavily fossil-fuelled, highly energy-intensive and emits large quantities of CO_2. Green ammonia production uses cleaner methods to reduce energy demands and emissions. Some green approaches retain the Haber-Bosch process but replace fossil-based hydrogen with green hydrogen – produced by splitting water with renewable electricity.[13] Others bypass Haber-Bosch entirely, using electricity, sunlight or microbes to convert nitrogen directly. These emerging methods are known as “green nitrogen fixation”,[14] and they combine energy and hydrogen inputs within a single step – offering a more streamlined, low-emission route to ammonia.

Green ammonia systems are currently being piloted in more than 15 countries, including Morocco, Chile, Japan and Australia.[15] Ports are evaluating how to store and deliver ammonia as a clean marine fuel, and the first ammonia-powered engines are now undergoing operational testing in real-world environments.[16,17] Additional projects are being developed to enable on-site fertilizer production in regions with intermittent power or limited infrastructure, including parts of Africa and rural India.[18,19]

Widespread deployment of green ammonia could bring climate benefits along with economic and social opportunities. Environmentally, green ammonia technologies can reduce greenhouse gas emissions by eliminating fossil fuel use in hydrogen production and high-temperature synthesis. Economically, green ammonia could drive investment in electrolysers, storage systems and retrofitted plants – creating jobs across hydrogen production, facilities upgrades and transport logistics. Still, high upfront costs and the need for port, transport, bioproduction and safety infrastructure remain significant barriers, especially outside major export hubs. Local green ammonia production using desalinated water and renewables could reduce price volatility and improve fertilizer access in countries currently dependent on imported ammonia. If deployed strategically, green ammonia could do more than decarbonize existing supply chains – it could shift where and how fertilizer and energy are produced, expanding access, strengthening regional self-reliance and reducing dependence on fossil-based imports.

Make or break

The success of green ammonia may depend on supportive policy frameworks, targeted investment in infrastructure and equitable access to locally beneficial production.

Policy lens

National strategies, procurement standards and permitting frameworks can support green ammonia as a decarbonization tool. Without clear safeguards, conventional, fossil-fuelled ammonia production with partial carbon capture may be promoted as "low-carbon", limiting support for truly green alternatives.

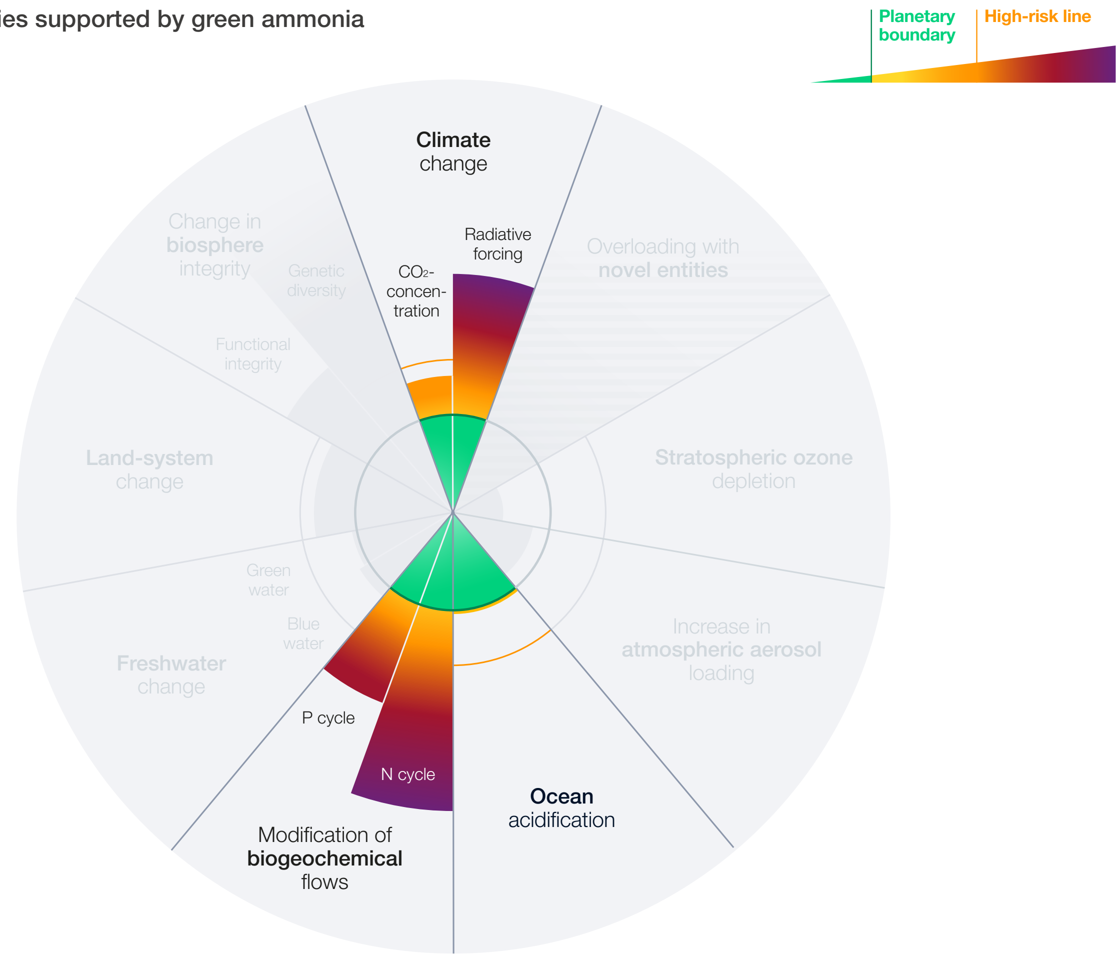
Finance lens

Investment in electrolysers, pilot projects and infrastructure could lower long-term costs and expand regional capacity; however, without targeted incentives, high capital costs may limit adoption to export hubs. Falling prices for conventional Haber-Bosch ammonia further delay adoption, especially in agriculture, where farmers face tight margins and price remains a critical factor.

Equity lens

Local production using renewables and desalinated water could improve fertilizer access in import-dependent regions. If deployment favours global shipping routes over local needs, benefits may bypass the communities most affected by fertilizer price shocks.

Planetary boundaries supported by green ammonia



→ **Climate change**: Eliminates fossil fuel use in hydrogen production and synthesis, reducing greenhouse gas emissions from one of the world's most energy- and carbon-intensive chemical processes.

→ **Ocean acidification**: Avoids CO_2 emissions from conventional ammonia production, helping reduce the absorption of carbon dioxide in oceans.

→ **Biogeochemical flows**: Supports more distributed, on-demand fertilizer production, reducing nitrogen waste associated with transport and overapplication.

03 Automated food waste upcycling

Turning scraps into resources with AI-driven sorting and recovery.

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In 2022 alone, households generated more than one billion tonnes of food waste, much of it ending up in landfills or other unsustainable disposal routes.[20] Recent progress in automation and robotics – driven by advances in AI, machine learning and computer vision – is making it easier to separate food from other waste streams, enabling large-scale recovery for composting, biogas production or upcycling.[21] By scaling up diversion and reuse, food waste automation technologies reduce landfill emissions, lower demand for newly sourced agricultural inputs and strengthen circular food systems. This helps to protect planetary boundaries related to climate change, land-system change, biogeochemical flows and biosphere integrity.

Recent improvements in image recognition and waste classification algorithms enable automated sorting systems to identify food waste even under challenging, real-world conditions – including spoiled, processed or partially hidden items.[22] These systems often combine advanced imaging techniques (e.g. near-infrared and hyperspectral imaging) with robotic arms, with companies like ZenRobotics using real-time data to separate food from packaging or other contaminants with minimal human input[23] – producing cleaner waste streams suitable for composting, anaerobic digestion or upcycling.

95%

of food scraps in Seoul are diverted from landfill or incineration through a citywide food waste programme powered by automation.

Once limited to large recycling plants and agricultural processors, advances in sensor design and energy efficiency have made the technology more compact and affordable, allowing broader deployment in municipal waste facilities. In Seoul, automation supports a citywide food waste programme that diverts over 95% of food scraps from landfill or incineration.[24] The Netherlands are testing AI-driven sorting lines to separate food from packaging at centralized composting hubs.[25] The US and Europe are piloting modular units in grocery stores, university campuses and commercial kitchens to recover waste at the point of generation with companies like Orbisk.[26,27] Growing demand for upcycled products – including animal feed, compost blends, bioplastics and even food ingredients – is increasing the economic viability of these systems. A recent estimate valued the global market for upcycled food products at over $50 billion, with strong growth expected over the next decade.[28]

Automated sorting systems may transform waste management industries, with wide-ranging environmental, economic and societal impact. Environmentally, these systems reduce methane emissions from landfills and support nutrient recycling through composting and anaerobic digestion, helping to protect planetary boundaries related to climate change and biogeochemical flows. Economically, automation could open new markets for upcycled food waste products such as animal feed, compost blends and bioplastics – while creating new roles in sensor maintenance, robotics integration and circular product development. However, high capital costs may limit adoption in low-income regions or small-scale facilities, slowing widespread impact. Societally, expanded recovery infrastructure could reduce environmental burdens in low-income communities disproportionately affected by landfills, while strengthening city-level efforts to meet zero-waste and climate targets. In doing so, food waste automation could help close a critical gap between growing waste volumes and limited capacity for sustainable disposal.

Make or break

The success of automated food waste sorting may depend on regulatory clarity, investment in decentralized systems and attention to equitable access across diverse waste infrastructures.

Policy lens

National and municipal mandates for food waste diversion – paired with contamination standards and procurement support for sorted organics – can accelerate adoption. Promoting interministerial and cross-boundary cooperation is also critical to maintaining processing standards. Without consistent policies, automated systems may remain limited to pilot programmes or high-income municipalities.

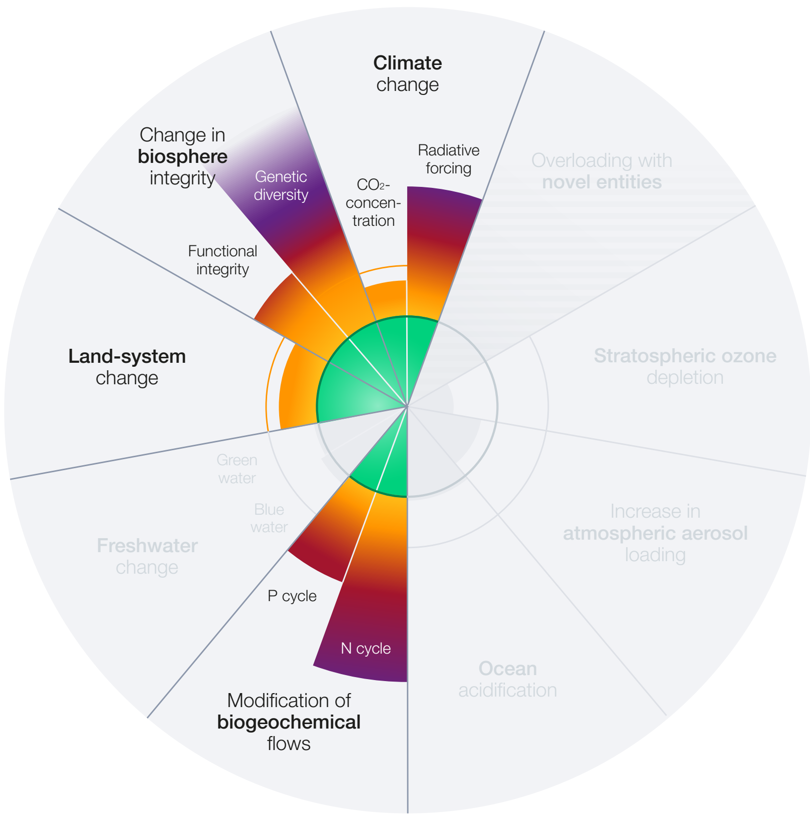
Finance lens

Public funding, climate bonds and outcome-based incentives can reduce the risk of investing in automated recovery infrastructure. Without support for smaller operators, the technology may remain confined to large, centralized facilities.

Equity lens

Locally adapted systems and workforce development can expand recovery capacity in underserved areas while reducing landfill burdens – especially in middle-income countries, where growing waste volumes and demand for upcycled products present clear opportunities. Yet feasibility remains uneven: infrastructure gaps, limited capital and competing priorities may slow adoption.

Planetary boundaries supported by automated food waste upcycling



- **Climate change**: Reduces methane emissions by diverting food waste from anaerobic decomposition in landfills and enabling recovery through composting and biogas systems.
- **Biogeochemical flows**: Supports nutrient cycling by enabling food waste (organic matter and plant nutrients) to be returned to soil systems rather than lost through disposal, reducing the need for synthetic fertilizers and increasing soil organic carbon.
- **Land-system change**: Lowers demand for new agricultural production and landfill space by recovering value from discarded food and reducing organic contamination in landfills.
- **Biosphere integrity**: Limits the spread of landfill-related pollutants that harm ecosystems and supports regenerative practices through compost and soil amendments derived from sorted food waste.

04

Methane capture and utilization

Converting a potent greenhouse gas into valuable energy and products for near-term climate impact.

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Methane capture and utilization technologies aim to intercept this potent greenhouse gas before it reaches the atmosphere and convert it into useful products or energy.

On a 20-year time scale, methane traps roughly 80 times as much heat in the atmosphere as carbon dioxide.[29] Curbing methane emissions is critical to slowing global warming in the near term; yet many methane sources, including landfills, agriculture and fossil fuel systems, remain uncontrolled.[30,31] Methane capture and utilization technologies aim to intercept this potent greenhouse gas before it reaches the atmosphere and convert it into useful products or energy. New systems for detecting, collecting and repurposing methane would ease pressure on planetary boundaries related to climate change, air quality and biogeochemical flows.

Methane capture technologies are advancing to detect and recover emissions from a broad range of sources, including wastewater treatment plants, manure lagoons, landfills, coal mines, and oil and gas infrastructure.[32,33] Compact sensors and low-cost imaging tools now support leak detection at small or remote sites, enabling recovery where it was not previously cost-effective. Researchers are exploring direct air capture approaches that might be able to extract even trace amounts of methane from the atmosphere. Meanwhile, emerging catalytic technologies operate under milder conditions than traditional energy-intensive processes, enabling the conversion of captured methane into useful products.[34,35]

Captured methane is already widely used for energy in many regions, with landfill gas and manure from dairy farms routinely converted into electricity, heat or renewable natural gas.[36,37] Pilot projects are also testing methane-to-chemical pathways to generate low-carbon industrial inputs. Examples include the transformation of biogas into green methanol, direct photocatalytic methane-to-methanol systems[38] and capturing methane from large-scale dairy operations, landfills and abandoned coal mines – currently offered by companies like Frost Methane Labs.[39]

As additional methane capture and utilization technologies move from pilot to deployment, they could present environmental, public health and economic benefits. Environmentally, catalytic conversion systems may reduce reliance on flaring, helping to limit aerosols and chemical byproducts that contribute to novel entities. Intercepting methane before it escapes into the atmosphere reduces greenhouse gas emissions and surface ozone, easing pressure on planetary boundaries related to climate change and atmospheric aerosol loading. Reducing methane and associated emissions could lessen respiratory health risks in nearby communities. In the energy sector, however, there is concern that methane capture could be used as a stopgap solution – focusing on mitigation rather than accelerating the phaseout of fossil fuel use. Economically, the use of methane to generate power provides value and can increase energy security. Emerging agricultural practices such as altering livestock diets and management can increase profits, while converting methane into industrial inputs or the use of black soldier flies in the waste sector could create new markets and job opportunities across agriculture, waste management and industrial chemistry.[40] Methane capture and utilization can serve as a practical tool for near-term climate action – delivering measurable, near-term benefits from otherwise hard-to-abate sectors and methane-intensive industries.

Make or break

The success of methane capture and utilization may depend on clear regulatory direction, balanced investment across sectors and inclusive access to mitigation technologies.

Policy lens

Policy frameworks that direct methane capture towards existing emissions – such as those from landfills, farms or ageing fossil infrastructure – could support long-term climate goals. In the energy sector, if used to justify ongoing fossil fuel development, these technologies could delay broader transitions away from fossil energy.

Finance lens

Targeted investment could accelerate the deployment of catalytic conversion and capture technologies – especially for hard-to-abate sectors. While the fossil fuel industry is hugely profitable, outside capital is likely needed in the waste and agriculture sectors, as well as for some hard-to-abate industries.

Equity lens

Widespread methane mitigation could bring air quality and health benefits to communities near landfills, farms and industrial sites. Without support for technology transfer and deployment in low-income regions, many of the highest-emitting sources may remain unaddressed.

Planetary boundaries supported by methane capture and utilization

- → **Climate change**: Intercepts methane to limit near-term warming and slow long-term climate disruption.
- → **Atmospheric aerosol loading**: Some measures to reduce methane, such as methane capture instead of flaring, lower the emission of associated aerosols that damage air quality and ecosystems.
- → **Biosphere integrity**: Protects vegetation and ecosystem productivity by reducing ground-level ozone from methane emissions, helping to curb biodiversity loss.
- → **Novel entities**: Limits industrial pollutants by converting methane through catalytic processes instead of flaring or uncontrolled release.

05

Green concrete

Transforming construction to cut emissions, lock in carbon and protect resources.

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Green concrete can not only eliminate emissions from traditional cement production but also create a permanent storage route for captured CO_2.

Concrete is the most widely used construction material on Earth. Production of its key binding ingredient, Portland cement, contributes approximately 8% of global CO_2 emissions and drives unsustainable demand for sand, stripping riverbeds and coastlines and damaging ecosystems.[41,42] Novel cement-free green concrete technologies offer an alternative by eliminating Portland cement altogether and instead using binders derived from industrial byproducts or construction and demolition waste (CDW).[43,44] Some of these technologies also enable CO_2 mineralization during curing, where CO_2 is actively introduced and sequestered into the concrete matrix. This process not only eliminates emissions from traditional cement production but also creates a permanent storage route for captured CO_2.[45] Together, these advances cut demand for extracted raw materials and ease pressure on planetary boundaries related to climate change, land-system change, biogeochemical flows and novel entities.

Geopolymer binders, a key example of cement-free systems, are produced by chemically activating aluminosilicate-rich materials such as fly ash, blast furnace slag or milled CDW. Use of these waste materials displaces the use of virgin limestone, sand and gravel, thereby avoiding the energy-intensive, high-temperature, high-emission reactions required to make Portland cement. Geopolymers divert waste from landfills and circumvent resource extraction, which supports circular, lower-impact construction practices. When coupled with CO_2-curing techniques, the result is a durable, lower-carbon concrete that stores captured CO_2 while meeting performance needs.

Sublime Systems uses electricity and non-carbonate materials to produce low-emissions cement, reducing CO_2 emissions by 90% compared to ordinary portland cement, without compromising strength.[46] Experimental methods have mineralized up to 45% of the injected CO_2 – permanently storing it without compromising structural performance.[47] In one demonstration, researchers constructed a full-scale, one-story home using prefabricated components made entirely from CDW and CO_2-enhanced materials.[48] Structural and life cycle assessments indicated durability, high reuse potential and significantly reduced emissions. These approaches have gained regulatory approval in multiple countries, including Germany, Canada and the US.[49]

As continued innovation brings green concrete into mainstream building practices, it is reducing environmental impacts, generating new jobs in low-carbon construction and highlighting persistent barriers to equitable adoption. By reducing emissions and storing carbon, green curing reduces the pressure on the climate change boundary. Geopolymers ease pressure on land systems and limit novel entities. When paired with recycled aggregates, both approaches reduce demand for raw materials and thus help address land-system change and biogeochemical flows. Industry-wide adoption could create new jobs in demolition recovery, CO_2 utilization, recycled binder production and circular construction. Although these technologies can enable distributed, modular concrete production and reduce reliance on centralized cement infrastructure, equity challenges remain – particularly in regions with limited access to technical expertise, financing or procurement flexibility.[50] Procurement standards, workforce development and investment in regional recycling and manufacturing capacity could help ensure green concrete technologies deliver environmental and economic benefits where they are most needed – enabling essential infrastructure to be built faster, cleaner and with far less environmental impact.

Make or break

The success of green concrete may depend on supportive policy frameworks, market-aligned investment tools and equitable access to low-carbon construction materials.

Policy lens

Supportive building codes, procurement policies and infrastructure linking emitters to concrete producers can speed adoption of CO_2-cured and geopolymer products. Consistent standards and third-party verification are essential to build trust in durability, safety and carbon storage claims.

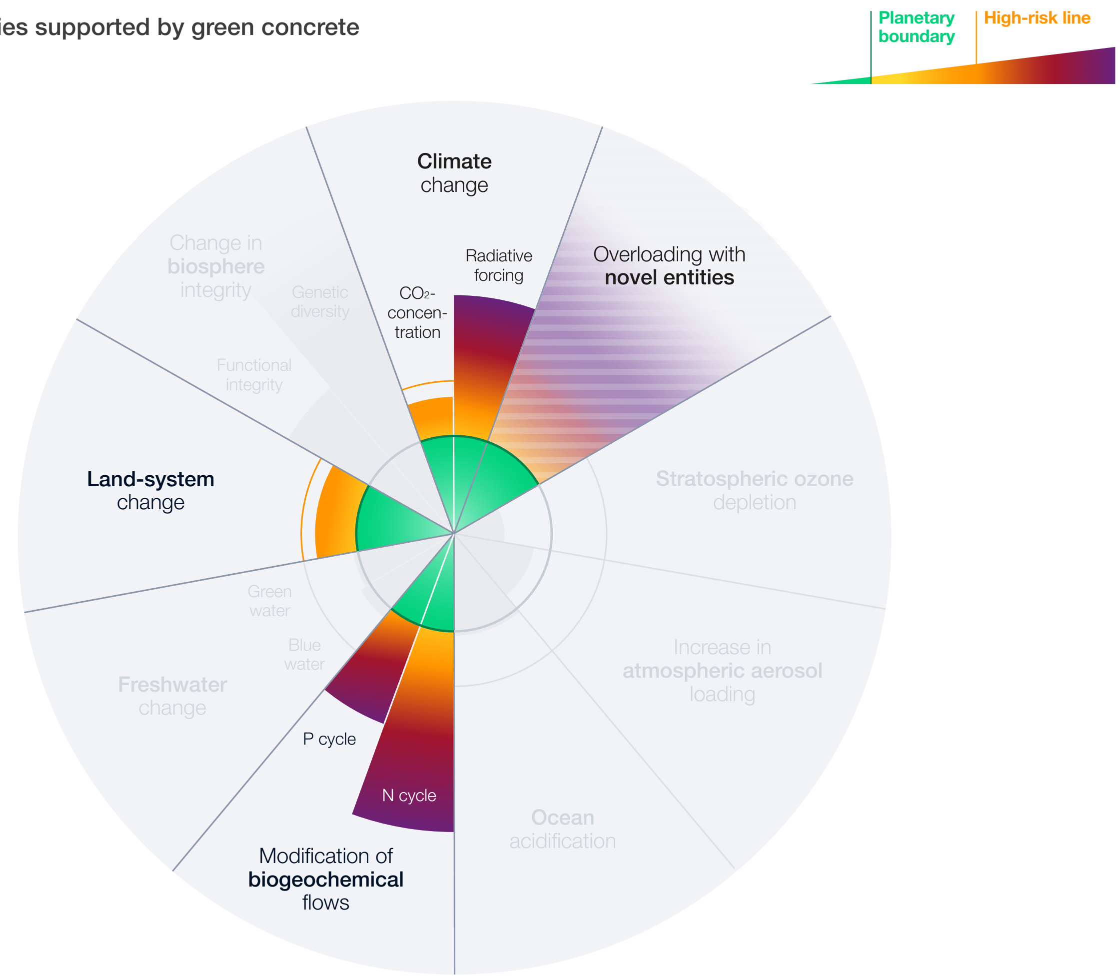
Finance lens

Blended finance, green bonds and major buyer commitments can strengthen market confidence and attract investment. Clear demand signals and tools like environmental attribute certificates (EACs) can help offset high upfront costs and reduce investor risk.

Equity lens

When paired with local manufacturing and reuse of mineral waste (including CDW), green concrete can support circular economies and reduce construction costs. Yet, without attention to affordability, labour practices and access to training and recycled feedstocks, benefits may remain concentrated in wealthier markets.

Planetary boundaries supported by green concrete

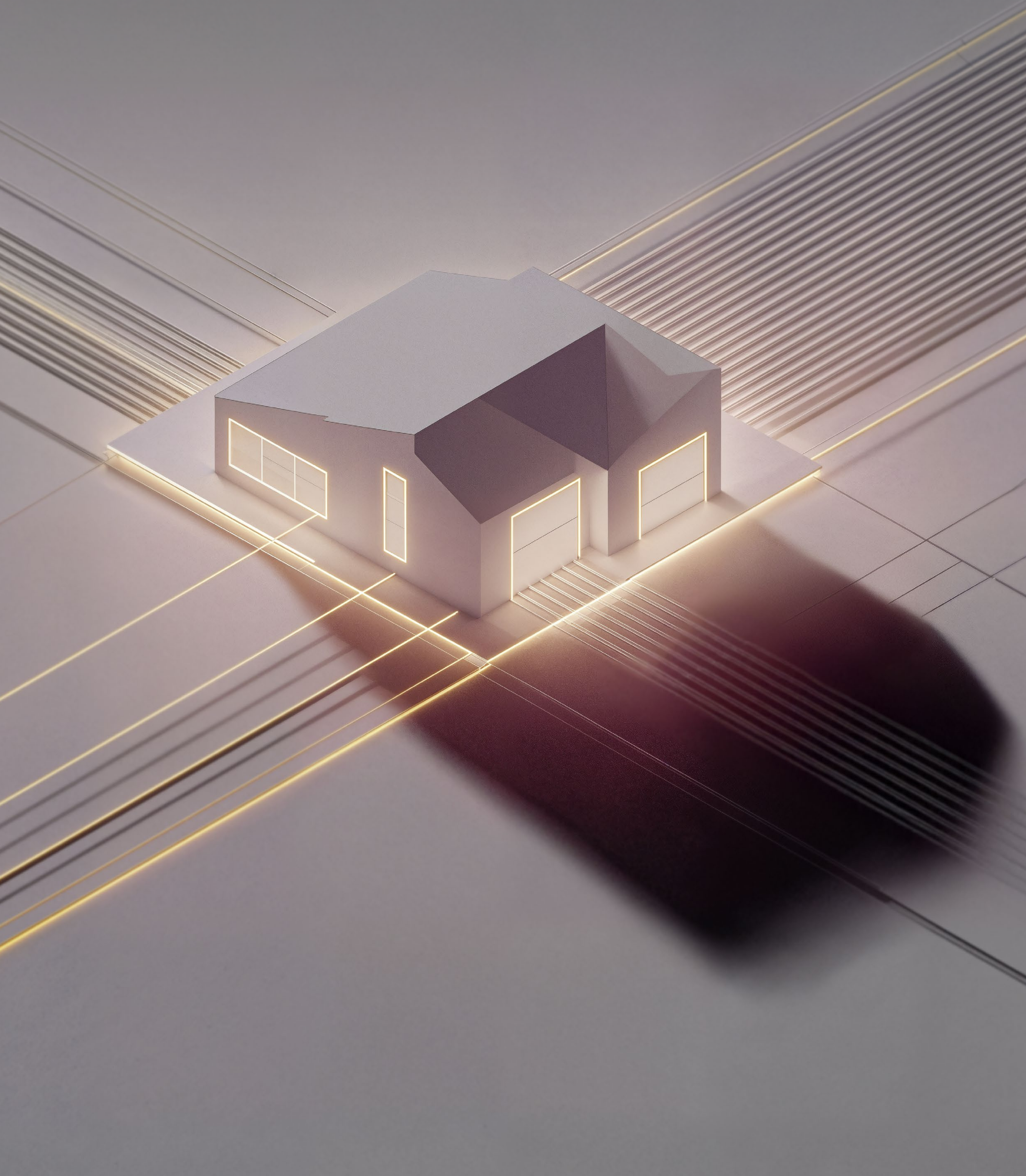


- → **Climate change**: Avoids emissions from high-temperature cement production through geopolymer binders and stores captured CO_2 through mineralization in curing processes.
- → **Biogeochemical flows**: Reduces reliance on limestone and other virgin materials, lowering disruption to habitats and hydrologic cycles associated with large-scale aggregate removal.
- → **Land-system change**: Limits land degradation and habitat loss by reducing demand for virgin aggregate mining, including sand, the most-extracted solid material on Earth, and enabling the reuse of construction and demolition waste.
- → **Novel entities**: Diverts CDW from landfills and immobilizes metal-rich fly ash, slag and CDW in concrete, which then limits releases to the environment.

06

Next-gen bi-directional charging

Turning stored battery power into flexible, renewable-ready energy sources.



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> Well-designed systems could expand access to backup power, reduce energy costs through local energy sharing and support the efficient redistribution of renewable energy.

Electric vehicles (EVs) reached a global fleet of nearly 58 million in 2024,[51] and they are just one example of a rapidly expanding range of devices and technologies equipped with rechargeable batteries. As battery technology continues to improve, stored energy is emerging as a potential asset for powering homes, buildings and even urban and remote power grids. Bi-directional charging allows electricity to move both into and out of batteries, enabling stored energy to be redirected based on use needs.[52] Ongoing innovations in these technologies could support a cleaner, more flexible energy system, supporting the drive towards net-zero greenhouse gas emissions and easing pressure on planetary boundaries related to climate change, biogeochemical flows and "novel entities" such as air pollution and environmental toxicity.

To permit two-way energy flow, bi-directional charging relies on advanced inverters to convert electricity between direct current stored in batteries and alternating current transmitted through power grids. Traditional inverters are limited by heat loss, size and conversion inefficiencies, but next-gen devices – often built with wide bandgap semiconductors such as silicon carbide – can handle higher temperatures, improve conversion efficiency and regulate power flows more precisely.[53]

Bi-directional charging technologies are currently being piloted across a range of real-world settings. In the US, electric school buses equipped with vehicle-to-grid (V2G) systems are supplying stored energy back to the grid during periods of high demand.[54] Residential programmes, such as the University of California, San Diego's INVENT pilot with Nuvve and the Austin SHINES project in Texas with Pecan Street, have tested home-based bi-directional charging installations. These pilots have allowed personal EVs to supply electricity for local energy management, such as campus microgrids and peak demand response in homes.[55,56] In Australia, a bi-directional-capable electric vehicle was used to power critical medical equipment during a blackout in 2024, demonstrating how the technology can support emergency response in real-world conditions.[57]

In Canada, bi-directional charging has been coupled with smart grid technology, renewable energy sources and hydrogen production.[58] If similar integration can be scaled up elsewhere, broad environmental, economic and societal benefits could result. Decreased urban emissions and air pollution from efficient load balancing and reduced reliance on fossil-fuelled backup generators support climate change and novel entities boundaries.[59] However, if battery charging occurs when fossil fuels dominate the grid mix or if batteries are cycled inefficiently, emissions may rise rather than fall – undermining environmental benefits. Expansion of bi-directional charging could transform energy service industries and open new roles in battery health analytics, power systems coordination and decentralized energy management – particularly in regions vulnerable to blackouts or extreme weather. As adoption grows, a key challenge will be managing battery wear from frequent charging/discharging cycles – but well-designed systems could expand access to backup power, reduce energy costs through local energy sharing and support the efficient redistribution of renewable energy to exactly where it is needed.

Make or break

The success of bi-directional charging may depend on coordinated regulation, targeted incentives and equitable integration into homes, fleets and communities.

Policy lens

Regulatory clarity around grid participation, compensation schemes and equipment standards can accelerate adoption. Pairing an economic framework to address costs with market mechanisms that incentivize participation would further support uptake. Without consistent frameworks, deployment may remain fragmented and inaccessible to most consumers.

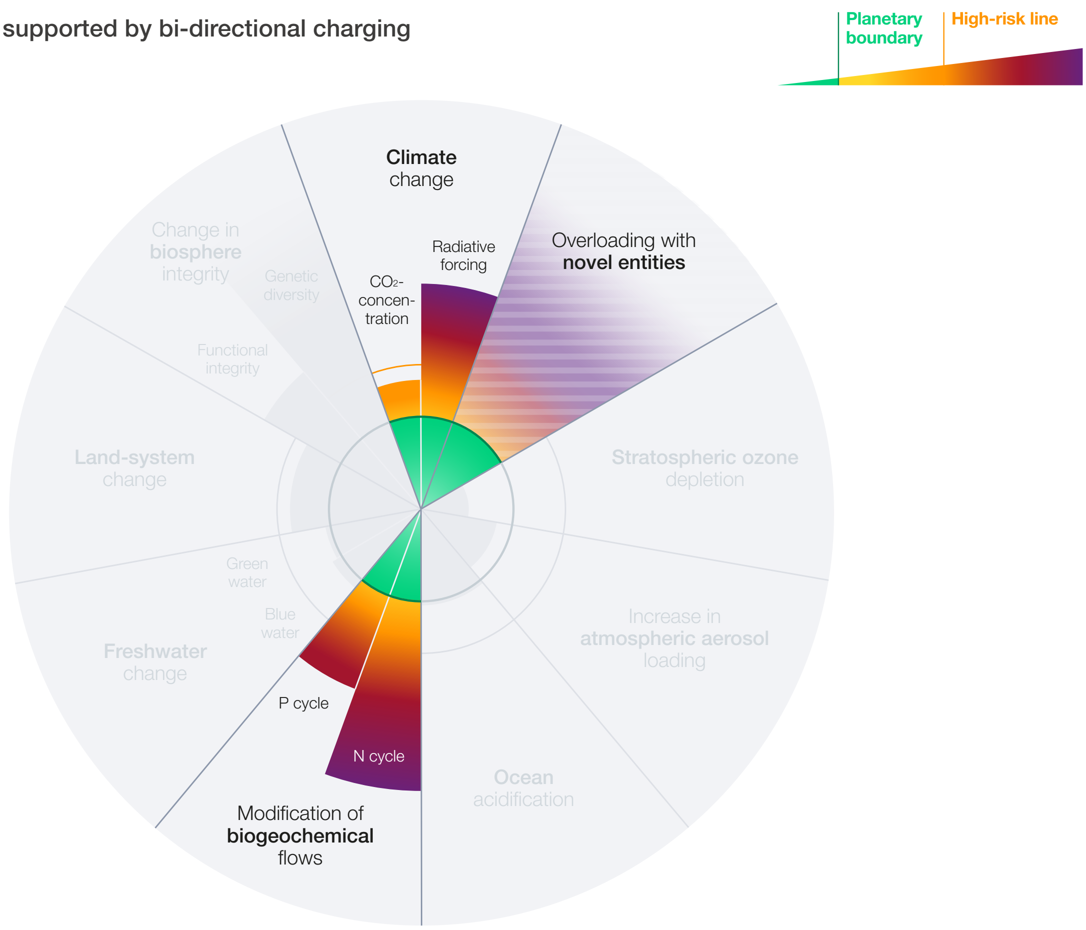
Finance lens

Incentives for bi-directional-ready vehicles, smart inverters and distributed energy programmes can help scale the technology. Without mechanisms to defray battery degradation costs, uptake may be limited to wealthier markets or EV fleets with dedicated energy managers.

Equity lens

Bi-directional systems could enhance energy resilience and reduce peak costs in underserved communities if integrated into affordable housing, public infrastructure or microgrid programmes. If left to market forces alone, however, benefits may concentrate among private EV owners and high-income users.

Planetary boundaries supported by bi-directional charging



→ **Climate change**: Lowers greenhouse gas emissions by reducing demand for fossil-fuelled backup generators and enabling more flexible, higher renewable energy uptake through increased grid capacity and ancillary services for short- to medium-term storage.

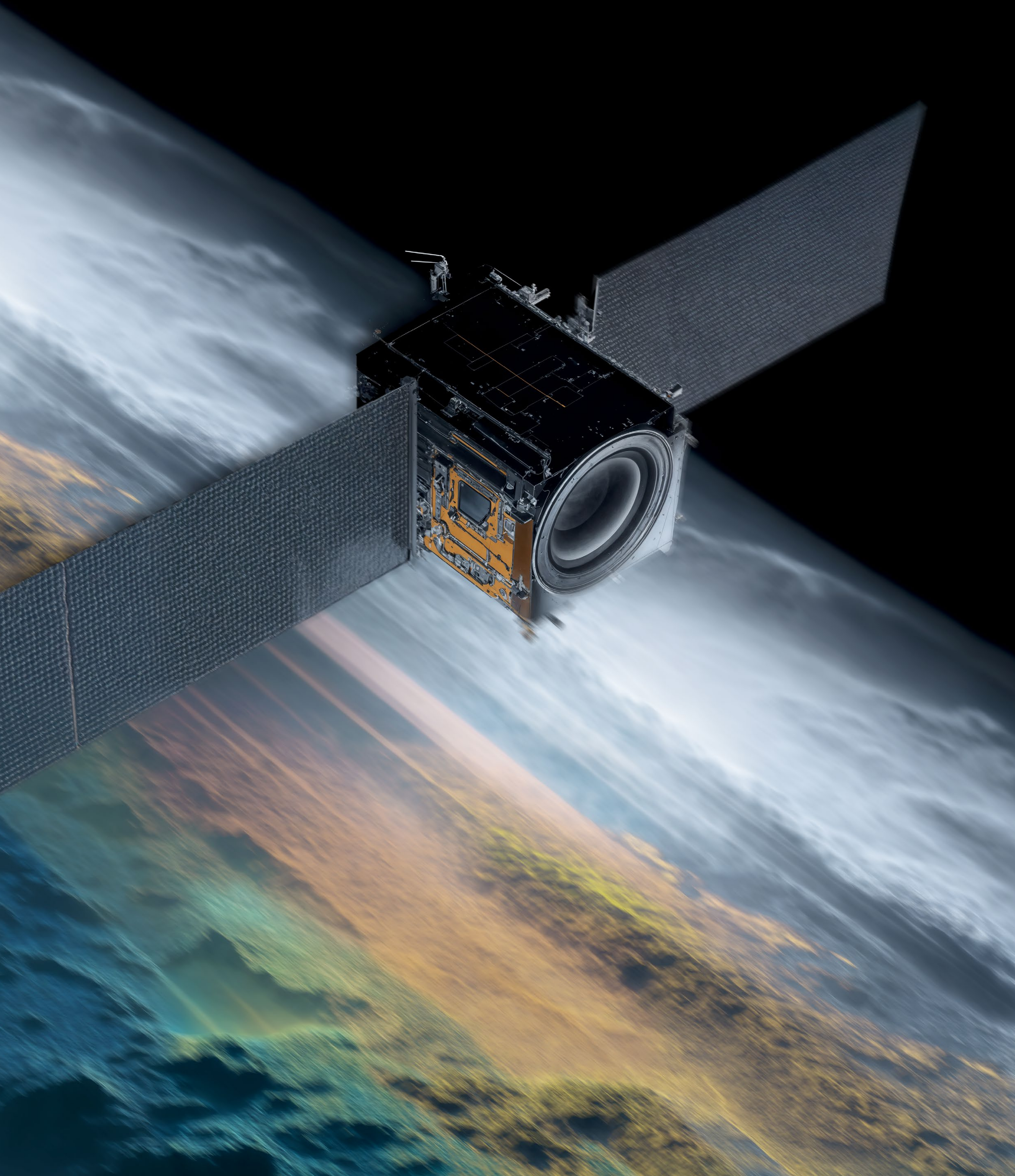
→ **Novel entities**: Minimizes air pollution and toxic byproducts by limiting fossil fuel combustion during peak demand and emergency power use.

→ **Biogeochemical flows**: Eases pressure on nutrient cycles by reducing reliance on centralized fossil infrastructure, fuel transport and associated land and water impacts.

07

Timely and specific Earth observation

From orbit to on-site, tracking change as it happens.



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From flooding to drought and deforestation, environmental conditions are shifting faster than they can be tracked. A new wave of Earth observation (EO) tools is closing that gap – moving beyond coarse snapshots to offer high-resolution, near real-time views of planetary change.[60] These tools give us the unprecedented ability to measure key variables across multiple orders of magnitude, from satellite-based whole-Earth observations to micro-local, tree-by-tree health evaluations and periodic changes in individual city demographics. By fusing satellite, drone and ground-based data with AI-powered analytics, EO systems now provide metre-scale insights (or finer) on key environmental and human-driven impacts such as precipitation, soil moisture, vegetation health and land-use dynamics. These conditions directly affect planetary boundaries, including climate change, land-system change, freshwater use, biosphere integrity and biogeochemical flows.

Multi-spectral and multi-sensor remote measurements, from satellites to drones to local app-based reporting systems, have all begun to enable a vast network of zoomed-in and zoomed-out data parameters to be measured with increasing time regularity and spatial density around the Earth. Combined with computational techniques, including computer vision and image classification, these advances enable vaster quantities of visual and spectral data to be interpreted in near-real-time, transforming data into information that is shareable and actionable for policy and public understanding of science. In addition, open-source visualization platforms enable relevant data and scientific information – both conclusory and predictive – to be shared openly across public engagements and educational venues, dramatically increasing common ground globally.

EO foundation models are another technological advancement set to transform how the public engages with Earth data. Large-scale foundation modals trained on extensive geospatial information allow users to explore that data through natural language, much like large language models (LLMs) do with written text. Once these models reach market maturity, anyone with an internet connection will be able to easily access critical information about Earth systems, from changes in land use over time to the location of urban heat islands or levels of atmospheric CO_2.

Supported by these latest advances, the European Commission's ambitious Destination Earth initiative aims to develop a digital twin of the entire planet.[61,62] The European Space Agency's Digital Twin Earth programme merges EO data with high-resolution hydrological models to simulate and forecast flood, drought and wildfire risks, helping governments prepare for extreme events.[63] Other systems use AI to map surface water loss, monitor deforestation and identify hotspots of land degradation, even under cloud cover – enhancing the local relevance of EO for land restoration, agriculture, climate monitoring and disaster response.[64,65]

If AI-enhanced EO scales in the coming years, it could reduce response time to environmental pressures while altering how governments, industries and communities monitor planetary changes. Frequent and granular environmental monitoring would improve tracking of freshwater depletion, land degradation and biodiversity loss – thus enabling earlier interventions. In industry, EO systems could assess supply chain impacts with greater specificity, helping companies identify deforestation, water stress or emissions hotspots tied to sourcing and production. Broader adoption could generate new roles in satellite operations, environmental analytics and local land-use planning – but high costs, infrastructure demands, and limited internet access may still constrain uptake in low-resource regions. Societally, EO could improve access to actionable environmental data in communities facing climate risk, which could guide decisions on agriculture, relocation or disaster response. Expanding access to EO tools and training could allow local governments and civil society actors to respond more effectively to environmental threats – especially in regions including Africa, South America and South-East Asia, where timely data can guide life-saving decisions.

“By fusing satellite, drone and ground-based data with AI-powered analytics, EO systems now provide metre-scale insights (or finer) on key environmental and human-driven impacts.

Make or break

The success of AI-powered EO may depend on transparent governance, inclusive infrastructure investment and equitable access to data and decision-making tools.

Policy lens

Governance frameworks that promote transparency and accountability, including ensuring data accuracy and validation, as well as being clear that forecasting is fallible and has multiple potential outcomes based on human behaviour, can help maintain trusted insights and protect against misinformation. Without safeguards, environmental EO data may be repurposed for surveillance or military/political use, further undermining public trust and local engagement.

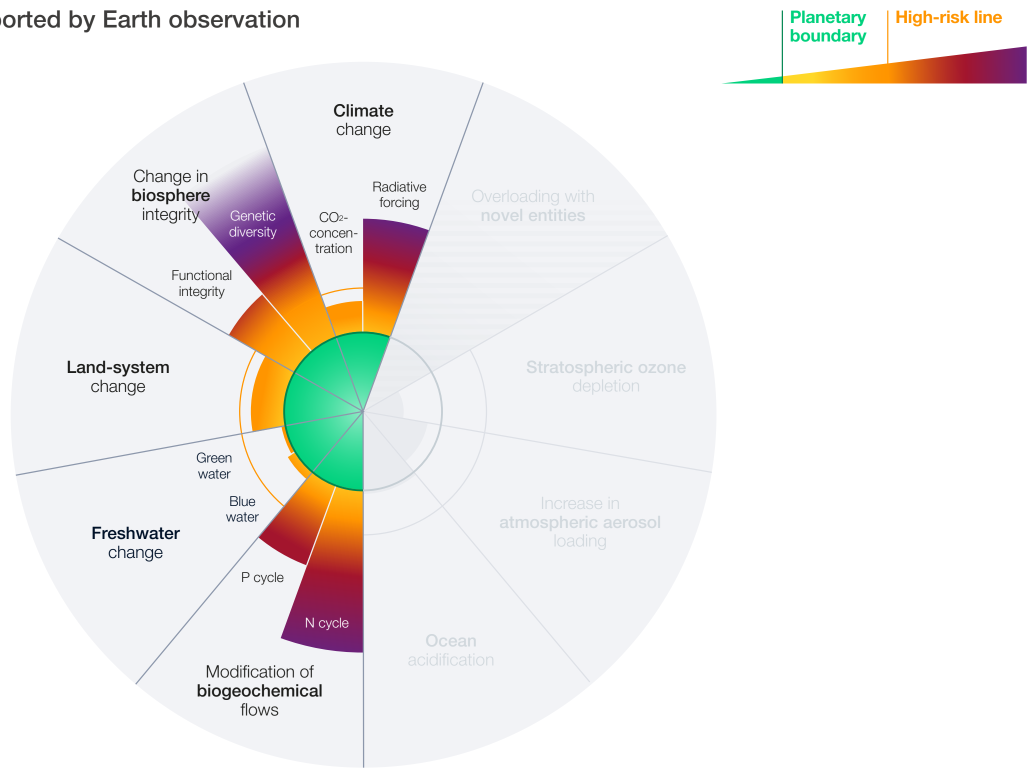
Finance lens

Currently, high costs and private ownership limit access to the highest-fidelity commercial EO systems and may influence data demand and access. While private and public data serve complementary roles, investment in multiple open-access platforms and applied tools – for climate monitoring, disaster preparedness or land-use planning – can expand the societal value of EO. If dominated by commercial interests, critical capabilities may remain out of reach for communities that need them most.

Equity lens

Supporting local infrastructure and technical capacity can enable farmers, city planners and civil society groups to act on EO insights. Without targeted investment, these tools may reinforce existing disparities in environmental decision-making and risk management.

Planetary boundaries supported by Earth observation



- → **Climate change**: Tracks greenhouse gas emissions, surface temperature and precipitation trends and extreme weather impacts in near real time.
- → **Land-system change**: Monitors deforestation, urban expansion, agricultural activity and land degradation at high resolution.
- → **Biosphere integrity**: Supports biodiversity monitoring through habitat mapping, species detection and ecosystem health assessments.
- → **Freshwater use**: Provides timely data on surface water levels, drought severity and watershed stress.
- → **Biogeochemical flows**: Informs nitrogen and phosphorus models using observations of land use, fertilizer application and runoff dynamics.

08 Modular geothermal energy

Scaling round-the-clock renewable heat and electricity.

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Societally, modular geothermal could strengthen energy resilience in underserved communities by enabling locally managed power.

In the clean energy landscape, geothermal energy offers a rare combination: constant output, minimal land use and the potential to scale globally. Despite its promise, geothermal supplies less than 1% of global electricity.[66] Advances in modular, factory-built geothermal systems and improvements in drilling technologies are expanding where and how geothermal can be deployed. By displacing fossil fuels and reducing land disturbance, water use and pollution, modular geothermal systems support key planetary boundaries related to climate change, land-system change, freshwater use and atmospheric aerosol loading.

Conventional geothermal depends on naturally occurring hydrothermal reservoirs and requires lengthy custom builds. Modular geothermal energy solutions refer to scalable, often prefabricated systems that harness the Earth's heat for power generation or heating. Unlike traditional large geothermal plants tied to specific high-temperature reservoirs, modular systems do not require specific geological conditions and can be deployed in a variety of formats – from small power units on individual wells to containerized heat pump installations for buildings. They can deliver weather-independent heating, cooling and baseload electricity to residential homes, apartment blocks and offices, as well as manufacturing sites, and can be installed in diverse locations, often with small footprints, reducing construction time and complexity.[67] A new generation of closed-loop systems involves sealed, underground pipe networks that circulate fluid to extract heat from surrounding rock, without tapping aquifers or releasing emissions into the environment.[68,69] Breakthroughs in drilling technologies – drawing on methods developed in the oil and gas sector – are enabling the deployment of closed-loop systems. Key innovations include directional drilling to reach targeted depths, improved wellbore sealing to withstand high temperatures and thermal modelling to optimize performance.

Combined, these advances are opening new markets for geothermal energy. In 2023, Fervo Energy demonstrated one of the first commercial-scale applications of enhanced closed-loop geothermal using horizontal drilling and fibre-optic sensing techniques adapted from the oil and gas industry. The pilot project in Nevada, US, produced 3.5 megawatts (MW) of round-the-clock electricity, validating the viability of closed-loop geothermal in previously inaccessible geologies.[70] Building on this success, Google partnered with Fervo to supply clean power to its Nevada data centre – marking a milestone in applying modular geothermal systems to digital infrastructure.[71] Modular geothermal isn't limited to power generation and also includes ground-source heat pump systems for buildings and small-scale units that can be added or moved as needed. The technology is being piloted for district heating in Europe, backed by a €7.4 billion investment across Germany, France and the Netherlands to build low-carbon heating infrastructure.[72] Ground-source heat pumps from companies like Vattenfall and Dandelion Energy tap into the moderate geothermal warmth just metres below ground and are an efficient replacement for oil or gas boilers in homes.[73,74] As modular geothermal systems scale, they advance climate goals while benefitting industries, economies and communities. Environmentally, they reduce greenhouse gas emissions by displacing fossil fuels, and use far less land, water and materials than many other renewables, helping ease pressure on planetary boundaries related to land-system change, freshwater use and atmospheric aerosol loading. In industry, co-locating modular units with data centres, manufacturing plants or agricultural facilities can provide consistent energy, enable energy cogeneration and reduce reliance on volatile fuel markets. Transitioning to modular geothermal could support job creation in drilling, engineering, construction and maintenance – particularly in regions where existing fossil expertise and infrastructure can be redirected towards clean energy. Currently, however, upfront costs are high and permitting pathways remain unclear in many jurisdictions. Societally, modular geothermal could strengthen energy resilience in underserved communities by enabling locally managed power. This technology offers a rare opportunity to expand clean energy access without requiring an entirely new workforce, pipelines or infrastructure footprints – making it especially valuable in regions seeking just and practical energy transitions.

Make or break

The success of modular geothermal may depend on clear policy frameworks, targeted investment and inclusive planning in regions new to geothermal development.

Policy lens

Clear permitting frameworks, risk-sharing mechanisms and public procurement standards can accelerate deployment. Without coordinated support, projects may face delays, inconsistent approvals or exclusion from clean energy targets.

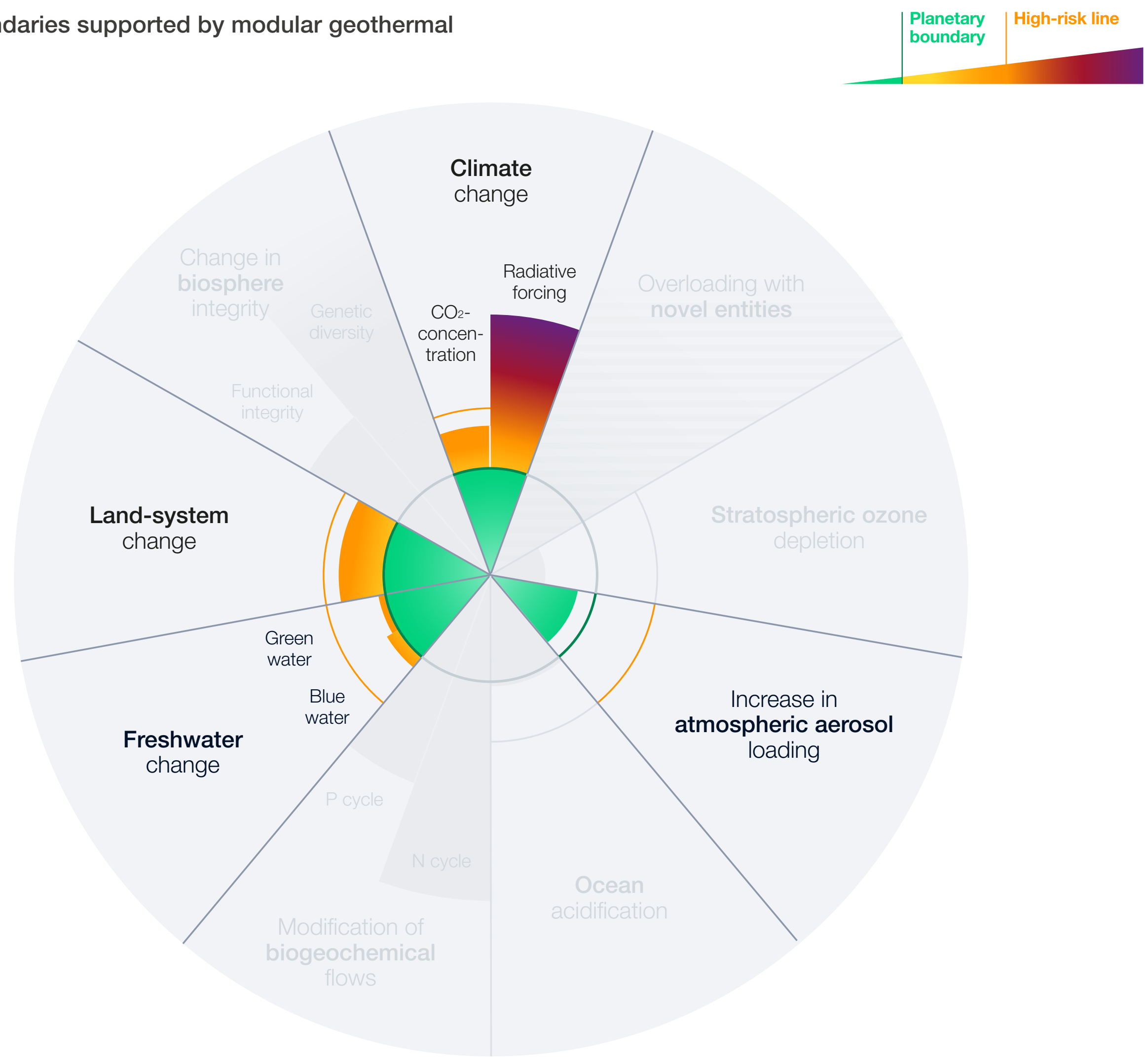
Finance lens

Early-stage investment, blended finance models and incentives for modular manufacturing can help overcome high upfront costs. If financing continues to favour wind, solar and hydrogen, geothermal may remain underutilized despite its complementary role.

Equity lens

Repurposing oil and gas infrastructure and workforce capacity offers a chance to diversify clean energy jobs and expand access to energy. Without attention to affordability, land rights and local capacity, benefits may remain concentrated in well-resourced regions.

Planetary boundaries supported by modular geothermal

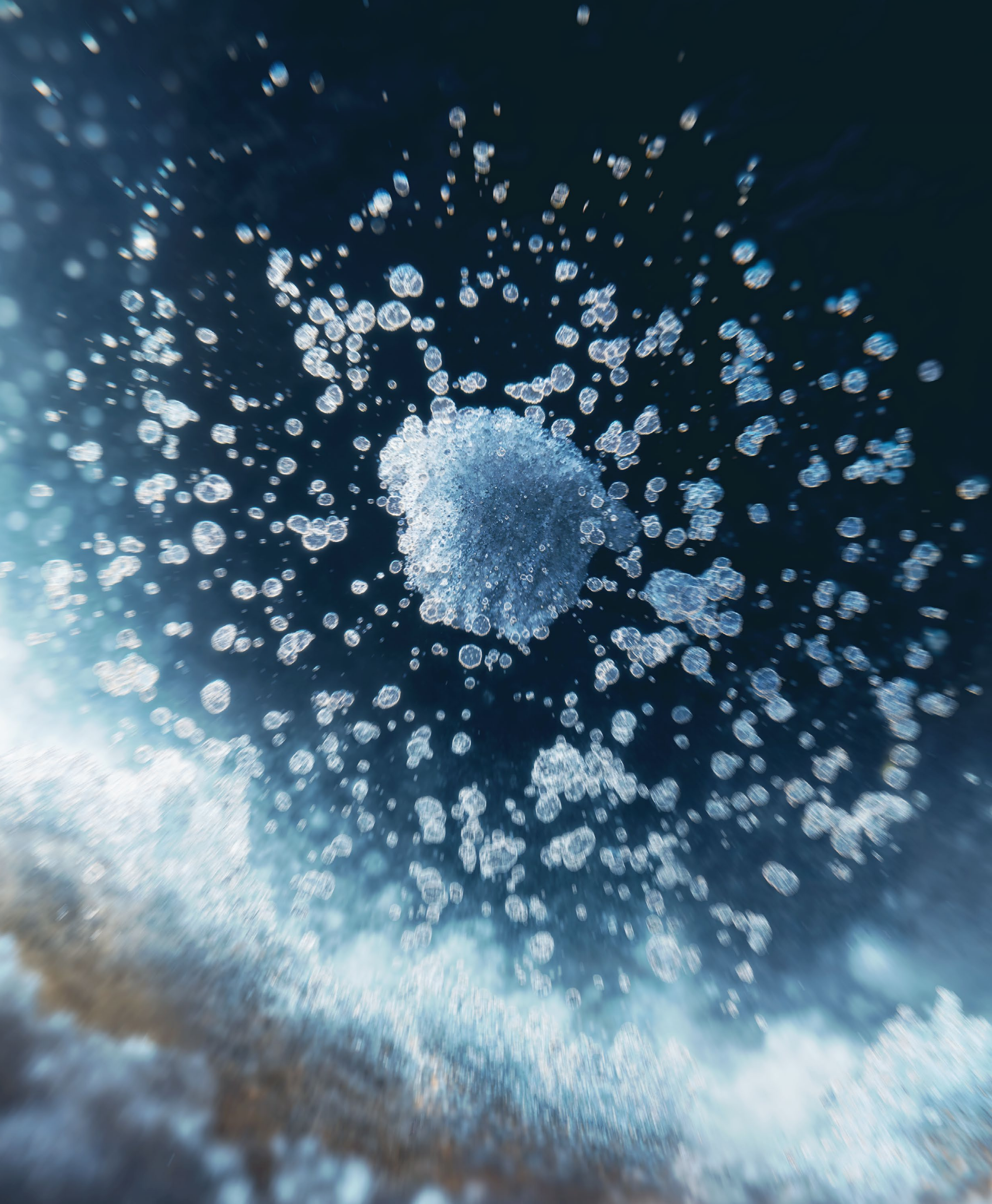


- **Climate change**: Provides stable, low-emission energy for heating, cooling and electricity, displacing fossil fuels across sectors.
- **Land-system change**: Requires minimal surface area and enables energy production without large-scale land transformation or habitat disruption.
- **Freshwater use**: Operates with limited water requirements, especially in closed-loop configurations that avoid groundwater extraction or contamination.
- **Atmospheric aerosol loading**: Eliminates combustion-related air pollution and associated health and climate effects common to fossil fuel and biomass energy systems.

09

Regenerative desalination

Recovering resources while delivering clean water.



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Several arid countries across the Middle East rely on desalination to meet 50-100% of their municipal water demand, including Kuwait, Oman and Saudi Arabia,[75] as water scarcity continues to intensify globally. Regenerative desalination is a sustainable approach to water purification that reuses and recycles water and resources within the process, thereby minimizing waste, energy demand and environmental impacts compared to conventional desalination methods. When powered by renewable energy, regenerative desalination systems can further reduce water treatment-related emissions. Together, these advances could make desalination more sustainable, easing pressure on planetary boundaries related to climate change, freshwater use, novel entities and biosphere integrity.

Most conventional desalination systems use energy-intensive reverse osmosis (RO), which forces seawater through high-pressure membranes to separate freshwater from salts and produces brine that is discarded through costly and resource-intensive disposal methods.[76] In contrast, an emerging regenerative method called electrodialysis with bipolar membranes (EDBM) splits water molecules to produce hydrogen and hydroxide ions, which then combine with salt ions to form usable acids and bases like hydrochloric acid and sodium hydroxide.[77] Desalination plants can recover and reuse these chemicals, reducing reliance on external inputs, lowering costs and decreasing the volume and chemical load of brine wastes. When paired with sustainable sources like solar, wind or low-grade waste heat, EDBM can support lower-emission, lower-impact desalination in resource-constrained or remote settings.[78]

Pilot projects are already demonstrating the feasibility of recovering valuable materials from high-salinity brine. For instance, a semi-industrial site in Southern Europe processed seawater brine into hydrochloric acid and sodium hydroxide using EDBM, achieving product purities above 90%.[79] On Lampedusa Island, an integrated system combining nanofiltration, evaporation ponds and EDBM recovered high-purity magnesium and calcium hydroxides while minimizing liquid discharge.[80] Start-ups like Desolenator are using solar energy or industrial waste heat to power circular desalination without emitting any greenhouse gases during operations and fully eliminating toxic brine disposal,[81] or using wave energy like Oneka to desalinate seawater in a sustainable and emission-free way without any emissions or chemicals. This can be combined with lower salinity, highly diluted brine or be used as artificial reefs for marine life.[82] Other pilots are exploring brine reuse in aquaculture, algae cultivation and constructed wetlands – using the minerals in brine to support plant and animal growth or restore natural habitats.

> “ Pilot projects are already demonstrating the feasibility of recovering valuable materials from high-salinity brine.

As regenerative desalination technologies advance, they could ease pressure on several key planetary boundaries, reshape industrial water use, generate usable outputs and expand water access. By drawing power from renewables rather than fossil fuels, regenerative systems support the climate change boundary. Recovering chemicals from brine reduces harmful discharges, helping address biosphere integrity and the spread of novel entities. With a projected 40% gap between freshwater supply and demand by 2030,[83] sustainable seawater treatment could help ease pressure on freshwater resources, alongside urgent alternative solutions, which are also needed to ensure reliable supply. However, costs remain high, and renewable energy used for desalination could compete with other needs – especially in energy-constrained regions.[84] Further, despite promising pilot results, widespread deployment may take a decade or more due to high energy demands, uncertain markets for recovered materials and limited policy support.[85,86] Economically, adoption could create new roles in membrane engineering, chemical recovery, decentralized water treatment and environmental monitoring. Modelling studies of hybrid RO-BMED (bipolar membrane electrodialysis) systems suggest potential cost reductions of up to 25% compared to standalone desalination, assuming high-value acid and base recovery.[87] However, these systems remain at early-stage or modelled scale, and most experts agree that broader deployment depends on membrane advances, co-product markets and policy support – factors that could take a decade or more to align. With proper technical configurations and local investment, regenerative approaches could reduce the environmental trade-offs of desalination while expanding access to freshwater.

Make or break

The success of regenerative desalination may depend on supportive regulation, integrated financing strategies and equitable access to affordable, sustainable water treatment.

Policy lens

Regulatory support for chemical recovery, brine reuse and integration with renewables could accelerate adoption in environmentally constrained regions. Recent investments illustrate how renewable energy integration remains optional[88] and without clear standards or permitting frameworks, systems may face delays or be excluded from large-scale planning.

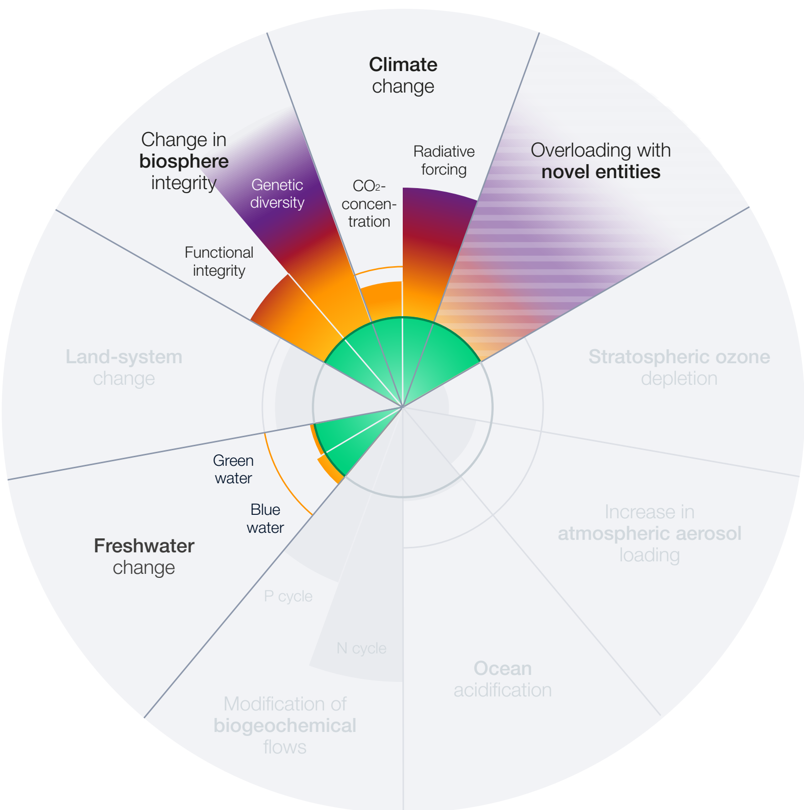
Finance lens

Combining public and private capital can help reduce early-stage deployment risks. If funding continues to favour conventional desalination, regenerative systems may struggle to scale.
The economic value of recovered chemicals also depends on access to complementary infrastructure or nearby users. Without integration into local value chains, co-products may have limited financial return, weakening the business case for regenerative systems.

Equity lens

Locally tailored systems and inclusive governance models could help regenerative desalination improve water access without exacerbating energy competition or affordability barriers. Without attention to community needs and operating costs, deployments may widen existing disparities in clean water access.

Planetary boundaries supported by regenerative desalination



- → **Climate change**: Replaces fossil-fuel-based systems with renewable-powered alternatives, lowering emissions associated with water treatment.
- → **Freshwater use**: Reduces demand on overdrawn freshwater sources in drought-prone and arid regions by expanding access to sustainable seawater treatment.
- → **Novel entities**: Minimizes the release of synthetic compounds and hazardous waste into marine environments by recovering chemicals and limiting brine discharge.
- → **Biosphere integrity**: Protects coastal ecosystems and marine species by limiting chemical and thermal pollution from desalination outflows.

10 Soil health technology convergence

Restoring soils with sensors, microbes and AI.

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Soil health technologies may lower farmers' input costs and improve crop yields, while generating new roles in environmental analytics, digital agronomy and microbial product development.

Healthy soils are critical to food production, water storage and climate regulation. Yet, more than one-third of Earth's soils are already degraded,[89] with major consequences for ecosystems and economies alike. A convergence of emerging technologies – including proximate and remote sensing, microbiome engineering and AI-enabled diagnostics – is making soil health maintenance visible, measurable and actionable. If widely adopted, these technologies may ease pressure on planetary boundaries related to nutrient cycles, climate change, land-system change and biosphere integrity.[90,91]

Proximate sensing technologies enable assessment of chemical and physical soil conditions directly in the field, with unprecedented speed and resolution. Handheld or in-situ devices using near-infrared spectroscopy, electrochemical sensors or multi-sensor arrays can now measure key indicators of soil health like pH, moisture, organic matter and nutrient availability within seconds.[92] By eliminating the need for lab-based testing, these technologies permit frequent, localized soil monitoring. Proximate sensor data can be used in site-specific decision-support tools that integrate chemical, physical and biological soil data to inform sustainable, site-specific soil and nutrient-management practices.[93] These practices support long-term improvements in soil resilience and crop productivity, while reducing nutrient runoff and enhancing carbon storage.

Soil microbial communities – collectively known as the soil microbiome – are one key component of soil health that could be assessed using proximate sensing tools, permitting a holistic soil health assessment by integrating biological, chemical and physical soil indices. Soil microbes regulate nutrient cycling, carbon storage and plant interactions, making them a logical target for intervention. Microbiome engineering seeks to enhance soil function by introducing targeted mixes of beneficial species or stimulating native populations using prebiotics or soil amendments.

Recent developments in AI, such as machine learning, can support the integration of soil data from multiple sources – including proximate sensing tools, microbial profiles, satellite imagery and historical land use – into the aforementioned decision-support tools that can diagnose soil health conditions and allow targeted land management practices.[94] Open-source platforms and shared soil health indices are beginning to standardize interpretation across locations and data types, creating a more coherent foundation for sustainable land management. The Open Soil Index, for example, is used by governments, farmers and banks to support sustainable soil management, unlocking the associated societal and environmental benefits.[95]

As soil health technologies advance, impacts are becoming visible across environmental, economic and social dimensions. By optimizing fertilizer use, soil health technologies reduce runoff, supporting the biogeochemical cycles planetary boundary. Microbial amendments and carbon-focused practices increase soil carbon retention, contributing to climate change mitigation. Site-specific interventions can help maintain ground cover and prevent degradation, reducing pressure on land-system change. Industrially, the convergence of proximate sensing, microbial interventions and AI could create new markets for microbial soil treatments, sensor-linked diagnostics and precision agriculture advisory tools. Soil health technologies may lower farmers' input costs and improve crop yields, while generating new roles in environmental analytics, digital agronomy and microbial product development. However, benefits may remain concentrated in well-resourced regions if infrastructure, training and data protections are not addressed – highlighting the importance of inclusive design as the sector scales. When adopted systemically, soil health technologies could shift agriculture from an extractive model to one that restores soil function, reduces external inputs and supports both food and ecosystem resilience.[96]

Make or break

The success of soil health technologies may depend on clear standards, targeted investment and equitable access to tools, data and training.

Policy lens

Clear standards for soil diagnostics – such as agreed thresholds for organic matter or nutrient availability – along with transparent validation of AI decision tools can support trust and interoperability. Addressing fragmented data systems and aligning market incentives – such as risk-sharing partnerships – are also key to increasing adoption. Without these, inconsistent data or opaque algorithms could undermine credibility, confuse users and stall regulatory approval.

Finance lens

Targeted investment in handheld sensors, soil improvers and public-private data platforms could expand access beyond industrial farms. Still, if financing favours proprietary systems or centralized infrastructure, smallholders and farmers in low-income regions may be excluded from both tools and benefits.

Equity lens

Affordable tools, capacity strengthening, mobile-friendly interfaces and locally relevant soil benchmarks can help ensure farmers in digitally underserved areas are included. Without attention to connectivity gaps, language barriers and community-level data ownership, adoption may reinforce rather than reduce agricultural inequality. Protecting data ownership also ensures those who provide data can participate in decision-making and share in the economic benefits.

Planetary boundaries supported by soil health technologies

- **Climate change**: Lowers greenhouse gas emissions by improving carbon retention and reducing nitrous oxide release through optimized fertilizer use.
- **Land-system change**: Prevents soil degradation and promotes sustainable land use through enhanced soil monitoring, erosion measures and targeted improvements of soil health.
- **Biogeochemical cycles**: Reduces nitrogen and phosphorus runoff into ecosystems through site-specific nutrient application and biologically guided soil inputs.
- **Biosphere integrity**: Supports biodiversity above and below ground by improving soil health and strengthening ecosystem resilience.

Conclusion

In the current global context of mounting risk and uncertainty, technology stands out as a powerful lever for change. While no single solution can address the scale of the challenge, innovative technologies are redefining what's possible for people and planet alike.

If adopted and scaled in a thoughtful and inclusive manner, the technologies outlined in this report have the potential to change the world – safeguarding planetary boundaries and supporting a more sustainable relationship between people and nature.

It is crucial, however, to approach technological interventions with both ambition and responsibility – recognizing their potential, while remaining mindful of their limitations and unintended consequences. Ultimately, achieving a sustainable and resilient future will require harnessing the full spectrum of technological advances, alongside policy, investment and systemic shifts. Through coordinated action and shared purpose can we hope to secure a thriving planet for current and future generations.

Appendix

Planetary boundaries primer

The planetary boundaries framework identifies nine critical Earth system processes that regulate the stability and resilience of our planet. Scientists have defined safe operating limits for each of these processes to ensure a stable environment for humanity.

Biosphere integrity (boundary crossed)
Measures the health and diversity of ecosystems and species. Loss of biodiversity undermines the resilience of Earth's systems and the benefits they provide.

Climate change (boundary crossed)
Refers to the concentration of greenhouse gases in the atmosphere, primarily carbon dioxide (CO_2). Crossing this boundary increases the risk of severe and irreversible climate impacts.

Freshwater change (boundary crossed)
Concerns the consumption and management of freshwater resources. Overuse can lead to water scarcity and ecosystem degradation.

Land-system change (boundary crossed)
Involves the conversion of forests, grasslands and other natural habitats into agricultural or urban areas. Excessive land-use change disrupts ecosystems and carbon storage.

Modification of biogeochemical flows (boundary crossed)
Tracks the flow of nutrients, especially nitrogen and phosphorus, from fertilizers into the environment. Excessive flows cause water pollution and dead zones in oceans and lakes.

Novel entities (boundary crossed)
Covers the release of new substances, such as synthetic chemicals, plastics and elements for which humans have altered their abundances including heavy metals. These can have unknown or harmful effects on living organisms and ecosystems and contribute to climate change, atmospheric aerosol loading and stratospheric ozone depletion.

Ocean acidification (boundary crossed)
Results from increased CO_2 dissolving in oceans, lowering pH levels. This threatens marine life, especially organisms with calcium carbonate shells or skeletons.

Atmospheric aerosol loading
Refers to the presence of tiny particles in the atmosphere from pollution, dust or natural sources. High concentrations affect climate and human health.

Stratospheric ozone depletion
Involves the thinning of the ozone layer, which protects life on Earth from harmful ultraviolet radiation. Ozone depletion increases health risks and damages ecosystems.

Staying within these boundaries is considered essential for maintaining a stable and resilient planet.

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Endnotes

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