Green Technology Book Solutions for restoring climate-impacted ecosystems



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Contents

Foreword 6

Foreword by partners 8

Acknowledgments 10

Acronyms 12

Key messages 14

Executive summary 18

Methodology 23

1 Introduction 26
1.1 The growing imperative for ecosystem restoration 26
1.2 Restoration has been underfunded by the public sector 28
1.3 Scaling ocean restoration requires better monitoring and spatial planning 30
1.4 The increasing role of private sector funding in restoration 30
1.5 Where does technology fit into the restoration picture? 31
1.6 Patent trends in ecosystem restoration technologies 32

2 Land-based systems 36
2.1 Heat, drought and disturbance 37
2.2 Biodiversity loss and soil decline 62
2.3 Scaling land-based restoration 81

3 Ocean ecosystems 99
3.1 Ocean warming 100
3.2 Ocean acidification 127
3.3 Atlantic meridional overturning circulation (AMOC) and ocean current disruption 146

4 Freshwater 160
4.1 Altering hydrological regime 161
4.2 Heat stress and water quality 179

5 The cryosphere 204
5.1 Sea ice and glacial melting 205
5.2 Permafrost 224

Bibliography 244

Foreword



Climate change is fundamentally reshaping the Earth's ecosystems. Land, oceans, freshwater systems and the cryosphere are experiencing ecosystem decline and degradation driven by rising temperatures, altered hydrological cycles, changing disturbance regimes and increasing human pressure. This matters because these ecosystems are crucial for climate regulation, biodiversity conservation, water security, food systems and human well-being.

Climate change, biodiversity loss and ecosystem degradation are converging to make ecosystem restoration one of this decade's top global priorities in respect to conserving biodiversity, strengthening climate resilience, securing water and food systems, sustaining livelihoods and recovering ecosystem services.

This fifth edition of WIPO's *Green Technology Book* explores how practical innovation is answering technology needs in the field of ecosystem restoration across the four ecosystems under discussion. Examples range from listening in on forests to storing water as ice. In Costa Rica, researchers analyzed more than 16,000 hours of forest recordings to assess biodiversity recovery. Autonomous underwater vehicles are enabling large-scale coral transplantation to revive degraded coral reefs. In Chile's Andes, artificial ice reservoirs are being used to store water in readiness for release during warmer months, helping communities cope with glacier retreat and drought.

A central message runs through this edition: restoration must address how ecosystems function. Natural regeneration, agroforestry and the reconnecting of rivers with their floodplains are examples of how the natural functioning of ecosystems can be restored and resilience strengthened. Satellites and sensors provide the vital information needed to guide this work, while predictive models allow practitioners to explore options for intervention. The choice of approach depends on the place, its ecology and the people who will carry the work forward.

WIPO works to help innovations reach those who need them in several ways. Patent information helps in identifying relevant technologies, patent analytics in identifying trends, and technical assistance in helping interested groups identify opportunities for licensing and collaboration while WIPO connects technology providers with those seeking solutions through WIPO GREEN and its Database of needs and green technologies.

Across all of the four ecosystems discussed in this year's edition of the Green Technology Book, restoration is becoming increasingly digital, predictive and data driven. Nonetheless, the technologies featured extend beyond simply monitoring to include advances in ecological engineering, restoration materials, biotechnology, hydrological management, nature-based solutions, precision restoration, biotechnology and fish breeding, robotics and ecosystem modelling.

But technology has its limits. A prime example of this is the cryosphere where, although it can improve monitoring, protect infrastructure and help communities in adapting to changing water availability, technology alone cannot reverse the scale of ice loss seen under

conditions of continual warming. Therefore, reducing greenhouse gas emissions continues to remain indispensable.

Financing remains a major challenge. Investment needs for ecosystem restoration are estimated to reach USD 296 billion a year by 2030. Mobilizing resources at this scale requires credible evidence of outcomes. Advances in monitoring and verification can make that evidence easier and less costly to obtain, helping funders assess projects and direct investment.

I thank our partners at the Climate Technology Centre and Network (CTCN) and the Egyptian Academy of Scientific Research and Technology (ASRT), who, together with the experts and contributors, have made this edition possible.

I invite readers to explore the solutions presented in these pages and consider how they might address their own challenges. Furthermore, I hope this book will inform practical decisions and encourage the partnerships necessary to restore ecosystems and sustain the lives of the people who depend upon them.

Marco M. Alemán
WIPO Assistant Director General
IP and Innovation Ecosystems Sector

Foreword by partners



Climate Technology Centre and Network (CTCN)

Climate change is placing unprecedented pressure on the ecosystems that sustain our societies and economies. Forests, rivers, wetlands, oceans and the cryosphere are all being transformed by rising temperatures, changing water cycles and increasingly severe climate impacts. Restoring these ecosystems is essential not only for protecting biodiversity, but also for strengthening climate resilience, safeguarding food and water systems, and supporting the communities whose livelihoods depend upon them.

The Climate Technology Centre and Network (CTCN) is honored to continue its close partnership with WIPO on the *Green Technology Book*, which this year focuses on solutions for restoring ecosystems affected by climate change. As climate impacts place growing pressure on ecosystems and the communities that depend upon them, identifying and deploying effective technologies will become increasingly important. WIPO's Green Technology Book helps ensure that countries are able to access the right technologies, knowledge and expertise needed to turn restoration goals into practical, locally appropriate action.

This edition demonstrates how rapidly the technological landscape for ecosystem restoration is evolving. Earth observation, artificial intelligence, drones, sensors and digital models are enabling ecosystems to be monitored and understood with increasing precision. Predictive tools help in identifying emerging risks and guide where interventions are most likely to have the greatest impact. At the same time, advances in ecological engineering, biotechnology and nature-based solutions are expanding the range of approaches available to restore ecosystem function and strengthen resilience.

Importantly, some of the most promising solutions bringing the two worlds of ecosystem restoration together Advanced technologies can complement natural regeneration, community-based restoration and established ecological practices rather than replace them. Such a convergence reflects an important lesson from the CTCN's work: namely, technology is most effective when it responds to local needs and circumstances and is accompanied by the knowledge, institutional capacity and partnerships needed for its successful deployment.

Technology alone cannot reverse ecosystem degradation, nor can it substitute for ambitious climate action. However, when innovation is combined with local and Indigenous knowledge, inclusive planning, appropriate financing and international cooperation, it can help countries and communities better understand change, anticipate risks and restore the ecological functions upon which they depend.

The solutions presented in this book demonstrate both the urgency of the challenge and the breadth of innovation available to address it. I hope they inspire new partnerships, accelerate knowledge sharing and help ensure that climate technologies reach the people and ecosystems where they can make the greatest difference.

Ariesta Ningrum,Director of the Climate Technology Centre and Network (CTCN)



Academy of Scientific Research & Technology (ASRT)

Climate change is no longer just altering our environment; it is fundamentally reshaping the ecosystems upon which societies, economies and communities have come to depend. Whether it be on land, in the oceans and freshwater systems or within the cryosphere, rising temperatures and changing climate patterns are accelerating the ecosystem degradation that is threatening biodiversity, water security and livelihoods. [RC1.1] Restoring and strengthening the resilience of these systems has therefore become an essential part of our collective response to climate change.

Ecosystem restoration, the focus of this fifth edition of the *Green Technology Book*, sits at the heart of that mission. The Academy of Scientific Research and Technology (ASRT) has supported national efforts to rehabilitate the Red Sea's coral reefs, restore mangrove habitats along Egypt's coastlines, and conserve the plant genetic resources so critical to future food and ecological security. These initiatives reflect a conviction that we at ASRT share with WIPO GREEN and our partners at the Climate Technology Centre and Network (CTNC): namely, that restoring what climate change has degraded requires not only ecological knowledge, but the technology, data and institutional coordination needed to act upon it at scale.

This edition arrives at a moment when land, ocean, freshwater and cryosphere ecosystems are under mounting strain, and when restoration has become one of the decade's defining global priorities. The technologies profiled here – ranging from AI-enabled ecosystem monitoring to digital twins for forests, oceans and glaciers [RC2.1]– illustrate how far the field has advanced, and how much the challenge now is how to connect innovators with the practitioners, financiers and policymakers able to put these solutions to work. ASRT sees its role as helping build exactly those connections, in Egypt and across the wider Arab and African regions.

ASRT is proud to continue its partnership with WIPO in bringing this flagship publication to a global audience. We hope this edition will not only inform, but mobilize governments, researchers and innovators to invest in the technologies our ecosystems urgently need – and that in so doing it will help build global awareness of Egypt's own role in that effort.

Prof. Mamdouh Moawad, President, Academy of Scientific Research and Technology (ASRT)

Acknowledgments

We are pleased to present the fifth edition of the WIPO *Green Technology Book*, showcasing technologies that can help restore climate-impacted ecosystems. This edition has been made possible through the collective efforts and contributions of numerous individuals and organizations. We extend our heartfelt gratitude to all those who have supported this project.

The book, an initiative under WIPO GREEN, was prepared through the general auspices of Daren Tang, WIPO Director General, Marco M. Alemán, Assistant Director General, IP and Innovation Ecosystems Sector, and Nompumelelo Obokoh, Head of the Climate Change and Food Security Unit. It was conceived and led by Peter Oksen, Green Technology and Research Manager, who also acted as editor. The book was researched and written primarily by Heather Jacobs, Climate Technology Expert, as well as by Natasha Mahezabin, Climate Technology Expert, and Peter Oksen. Maria Lorenzo Heredero supported the identification and management of technologies in the WIPO GREEN Database. WIPO GREEN staff members Eugenia Vazquez Pol, Christy Nomura and Tatiana Hartop provided important communications and operational support, while the rest of the WIPO GREEN team has been instrumental in ensuring that the book reaches the ones who can benefit most from it, as well as a wider audience.

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Acronyms

AGF	artificial ground freezing
AI	artificial intelligence
ALT	active layer thickness
AMOC	Atlantic Meridional Overturning Circulation
AUV	autonomous underwater vehicle
BAER	burned area emergency rehabilitation
BDA	beaver dam analogue
BGT	borehole ground temperature
CAMS	Copernicus Atmosphere Monitoring Service
CDR	carbon dioxide removal
CFR	community fish refuge
CO_2	carbon dioxide
CRDS	(closed-path) cavity ring-down spectroscopy
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTCN	Climate Technology Centre and Network
CTD	conductivity, temperature, depth
DAF	dissolved air flotation
DHW	degree heating week
DRIFT	downstream response to imposed flow transformation
DTO	digital twin of the ocean
eCDR	electrochemical carbon dioxide removal
eDNA	environmental DNA
ELJ	engineered logjam
ERT	electrical resistivity tomography
ESA	European Space Agency
ESG	environmental, social and governance
EU	European Union
EWS	early warning system
FAO	United Nations Food and Agriculture Organization
FMNR	farmer-managed natural regeneration
GHG	greenhouse gas
GIS	geographic information system
GLIMS	Global Land Ice Measurements from Space
GLOF	glacial lake outburst flood
GNSS	global navigation satellite system
GPS	global positioning system
ICRI	International Coral Reef Initiative
InSAR	interferometric synthetic aperture radar
IoT	internet of things
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
JPL	Jet Propulsion Laboratory
LiDAR	light detection and ranging
L-VOD	L-band vegetation optical depth
MAR	managed aquifer recharge
mCDR	marine carbon dioxide removal

MENA	Middle East and North Africa
MHW	marine heatwave
MIT	Massachusetts Institute of Technology
MRV	monitoring, reporting and verification
MTBS	Monitoring Trends in Burn Severity
NASA	National Aeronautics and Space Administration
NBR	normalized burn ratio
NbS	nature-based solution
NFM	natural flood management
NOAA	National Oceanic and Atmospheric Administration
N2O	nitrous oxide
OA	ocean acidification
OAE	ocean alkalinity enhancement
OIEau	Office International de l'Eau
pCO_2	partial pressure of CO_2
PES	payment for ecosystem services
RaaS	robotics-as-a service
ROV	remotely operated vehicle
SaaS	software-as-a-service
SAR	synthetic aperture radar
SDG	Sustainable Development Goal
SST	sea surface temperature
TNDF	Taskforce on Nature-related Financial Disclosures
TRL	technology readiness level
UAV	uncrewed aerial vehicle
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
USV	uncrewed surface vessel
VCM	voluntary carbon market
WGMS	World Glacier Monitoring Service
WIPO	World Intellectual Property Organization
WIPPS	WMO Integrated Processing and Prediction System
WMO	World Meteorological Organization
WRI	World Resources Institute
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research

Key messages

Technology is enabling a transition from observation to continuous ecosystem intelligence, facilitating better measurement, monitoring and planning of interventions

Ecosystem restoration is shifting from periodic observation toward continuous environmental intelligence. Historically, field surveys, intermittent measurements and isolated datasets have been used to monitor ecosystem function. We now employ satellites, drones, IoT sensors, acoustic monitoring, eDNA, LiDAR and SAR, among other technologies and data sources, combined with AI and advanced analytics, to perform biodiversity monitoring, wildlife tracking, glacier monitoring, reef monitoring and watershed monitoring. Platforms combine such elements (LiDAR, drones, acoustic monitoring, camera traps, satellite imagery, IoT sensors, eDNA and AI) to provide continuous and integrated ecosystem assessment. Ocean monitoring is also moving from ship surveys and diver observations toward sensor networks, autonomous vehicles, satellites and other Earth-observation technologies, acoustic monitoring and eDNA. AI-enabled systems now monitor coral bleaching, marine heatwaves, biodiversity changes and ecosystem health in near real time. Information is increasingly becoming a limiting factor in restoration, rather than ecological knowledge. Therefore, the focus of innovation is shifting from restoration methods toward managing information. Advances are making ecosystems increasingly quantifiable, enabling forms of management previously impossible.

Digital twins and predictive models aid practitioners in making predictions and testing restoration scenarios before taking real-world action

Ecosystems are increasingly being managed through predictive digital models, such as digital twins, rather than backward-looking observation. We can now observe, predict and simulate using connectivity models for land restoration planning models, digital twins for glaciers and oceans and entire watersheds, and ocean circulation models. Land models, such as LANDIS-II, iLand, 3-PG and Trends.Earth, are increasingly being used to simulate forest growth, ecosystem change, climate impacts, fire, pests and restoration outcomes before interventions occur. Wildlife connectivity tools use ecological modeling to predict species movement and identify future corridors undergoing climate change. Digital Twins of the ocean integrate satellite observations, sensor networks, AI and ocean circulation models into the near-real-time simulation of marine systems, while glacier digital twins combine remote sensing, sensor networks, AI and numerical models to simulate glacier dynamics, runoff, hazards and future melt scenarios. The fastest growing innovation category is therefore not restoration itself, but the decision-support systems guiding restoration. Many technologies do not directly restore ecosystems, but rather helping managers decide where and when to intervene, which species to target or use, where risks are emerging, and how money should be allocated.

Nature is becoming measurable enough to finance

New monitoring technologies are transforming ecosystem outcomes into measurable assets able to attract investment. Historically, restoration has been funded by the public sector in the

form of grants. We can now leverage carbon and biodiversity credits, blue carbon investments and ecosystem accounting, and digital monitoring, reporting and verification (MRV) for tracking and verifying purposes. Digital MRV combines satellites, drones, field sensors, AI and ecological models in the conversion of ecosystem outcomes into measurable indicators such as carbon, biomass, biodiversity and ecosystem condition. AI-enabled monitoring systems, such as DINOv3 and TerraFund, are lowering monitoring costs and helping restoration projects attract grants, loans, equity and climate finance. eDNA, acoustic monitoring, digital twins and biodiversity intelligence platforms are making marine ecosystem conditions measurable at scales previously impossible. In addition, MRV infrastructure is becoming an innovation sector in its own right. Emerging technologies verify restoration outcomes and help gain the trust of potential investors.

Restoration science is increasingly moving to below the surface, refocusing innovation on the integration of above- and below-surface systems

Innovation is increasingly focused on hidden ecosystem processes beneath the water surface, including soil microbiomes, fungal networks, root systems, soil carbon, subsurface thaw in permafrost, hydrothermal dynamics, benthic systems and marine carbon, environmental conditions in rivers and lakes, and sediment processes. SPUN's global mapping of fungal networks has highlighted the fact that biodiversity hotspots below ground often do not coincide with those above ground. Ocean monitoring increasingly includes benthic systems, reef structures, biodiversity, oxygen dynamics, carbon cycling and eDNA-derived biological information. Cryosphere monitoring now extends beyond ice surfaces to include permafrost thaw, hydrological systems, sediment transport, glacier-fed lakes and the subsurface processes driving instability.

A shift is underway, from restoring ecosystem components to restoring ecosystem function

Restoration is increasingly focused on ecological processes rather than individual species. Traditionally, restoration was more concerned with planting trees, saving species and cleaning rivers. The emerging paradigm is one that restores holistic ecosystem function using processes such as agroforestry, farmer-managed natural regeneration (FMNR) and soil biology. In respect of the cryosphere, attempts are being made to manage hazards, rather than simply save and measure ice. In the oceans, technologies target larger scale reef restoration. Dense monoculture planting is increasingly viewed as inadequate compared with approaches emphasizing natural regeneration, biodiversity and treating the greater ecosystem. Reef restoration is moving beyond placing coral fragments toward rebuilding ecological function through habitat complexity, recruitment processes and biodiversity support. And technology is enabling a shift from trying to save glaciers themselves toward preserving the ecosystem services they provide such as freshwater storage, hazard regulation and hydrological stability.

Hybridization of high- and low-tech solutions creating scalable solutions

The most scalable solutions often combine ecological practices with more advanced digital technologies, rather than replacing nature with technology. We can combine FMNR with satellites, agroforestry with AI-driven apps, and check dams by using GIS. In the oceans, robotics is supporting coral gardening. Remote sensing, including satellite-based Earth observation, can monitor lakes for algae bloom, directing further detailed monitoring and also helping to identify river flow dynamics and water level changes for directing restoration activities. In the cryosphere, sensors guide snow compaction and AI assists with thermosyphons.

Adaptation is equally as important as restoration

In some areas, such as the cryosphere, innovation is shifting from preventing change toward managing change that is unavoidable. Glacier preservation is often impossible, for example, therefore the focus may shift to water security and infrastructure adaptation. This is also true on land for drought resilience and wildfire adaptation. In the oceans, where extensive damage to coral reefs caused by excessive heat has already occurred, technology supports climate-resilient reefs and coastal protection. And for freshwater, several adaptation methods are being employed in the management of drought and changing water conditions, including water storage, managed aquifer recharge, environmental flow management and wetland restoration. Infrastructure, such as dams and facilities that use river water for cooling, can adapt water release so as to avoid adding heat to already warmed waters at critical periods or to cool downstream fish migration routes by releasing cold water from the depths of reservoirs. Breeding new fish species more tolerant to a changing environment and the associated stress factors is also being undertaken, spearheaded by aquafarming.

Democratization of monitoring enables the public to contribute toward addressing ecosystem decline

Environmental intelligence is moving from specialized institutions and organizations toward distributed citizen participation. Citizens are now being provided with the opportunity via applications and platforms to report biodiversity-related and Earth observations. In the cryosphere, such is the case with technologies like MountainNow, as well as simple electronic monitoring devices and open source radar. Even in the oceans, opportunities exist to use technology for citizen reef monitoring and community science.

Ecology and engineering are converging

The distinction between ecological restoration and engineering intervention is becoming blurred. Restoration increasingly combines ecological processes with engineered systems. This can be seen on land through the use of biochar, rehydration structures and restoration drones. Thermosyphons, artificial freezing, glacier coverings and snow engineering are examples for the permafrost. Reef structures exemplify this trend in the ocean. Likewise, biological and digital infrastructure are becoming increasingly intertwined. On land, biodiversity monitoring networks, AI wildlife systems and carbon MRV are blending both worlds.

In freshwater systems, climate resilience can be built through working with nature, not against it

Rivers and lakes are dynamic systems, and trying to control their flow can put additional pressure on freshwater ecosystems. As climate change increases the risks of flooding, drought and water scarcity, dams, channels and other infrastructure are increasingly being used to manage the challenges. However, these same structures can alter natural water flows, disconnect habitats and affect those species that depend upon them. There is growing scope to combine conventional infrastructure with approaches that work with natural processes. Technologies such as floodplain reconnection, river re-meandering, environmental flow management and nature-based solutions can help manage climate risks, while maintaining ecological function. At the same time, fish passages, fish-friendly turbines and monitoring systems can reduce the impact of existing infrastructure on aquatic life. Together, these approaches point to a shift from simply controlling water to managing it in ways that support both human needs and healthy freshwater ecosystems.

Multi-scale integration of diverse technologies for monitoring and detection

It is encouraging to observe the multitude and great diversity of solutions being continuously produced within the innovation ecosystem. In particular, solutions are often composed of technologies that work at different scales, and use various technology approaches and form factors. An example of a series of technologies used in a succession of monitoring activities is the detection of algae blooms in water bodies and the potentially poisonous cyanobacteria they contain. Satellite-based observation is able to detect algae bloom and indicate the presence of cyanobacteria at a large scale. This can be followed up by drone observation of particular areas in greater detail, which can in turn direct *in situ* monitoring using handheld or stationary fluorometers. The actual risk of poison release is then determined, based on DNA analyses of the algae within a laboratory. In this way, a string of diverse technologies are deployed at different scales to identify and direct mitigation measures against a serious environmental threat.

Executive summary

Climate change is fundamentally reshaping the Earth's ecosystems. Land, oceans, freshwater systems and the cryosphere are experiencing ecosystem decline and degradation driven by rising temperatures, altered hydrological cycles, changing disturbance regimes and increasing human pressure. These ecosystems are crucial for climate regulation, biodiversity conservation, water security, food systems and human well-being.

Climate change, biodiversity loss and ecosystem degradation are converging to create one of the key challenges of this decade. In 2024, global temperatures reached record highs, while seven of the nine planetary boundaries have now been exceeded. Restoring degraded ecosystems has therefore become a top global priority to conserve biodiversity, strengthen climate resilience, secure water and food systems, sustain livelihoods and recover ecosystem services.

On land, climate change is intensifying drought, wildfire, pests and disturbances. In recent years, the limitations of traditional tree-planting methods become a subject of debate. Within the oceans, warming, acidification and the changing patterns of the Atlantic Meridional Overturning Circulation (AMOC) are exerting pressure on marine ecosystems. Within freshwater ecosystems, altered river flow regimes driven by shifting precipitation patterns together with drought and flooding are disrupting ecological connectivity, wetlands and aquatic biodiversity, while heat stress and the effects of climate change on water quality threaten the habitats and living conditions of many species and those that feed upon them. Within the cryosphere, accelerating glacier retreat, permafrost thaw, declining snow cover and shrinking sea ice are together reshaping the frozen environment and altering freshwater availability, contributing to sea-level rise and increasing natural hazards.

Restoration is becoming a global policy priority, but financing remains a challenge

Despite a growing political momentum, ecosystem restoration remains severely underfunded. Global restoration financing is estimated currently to be between approximately USD 64–133 billion annually, whereas annual investment needs are projected to reach USD 296 billion by 2030. Governments continue to provide about three-quarters of restoration financing, but public funding alone is insufficient to meet global restoration goals. Increasing attention is therefore being paid to mobilizing private capital through carbon and biodiversity markets, blended finance, impact investing, green and blue bonds, and payment for ecosystem services. Despite this, investment in restoration remains challenging. This is because projects often have a long time-horizon and uncertain returns, added to which there is a shortage of profitable projects in which to invest.

Over the past decade ecosystem restoration has become a central pillar of international climate and biodiversity policy. Global initiatives such as the UN Decade on Ecosystem Restoration, the Kunming–Montreal Global Biodiversity Framework, the Bonn Challenge, the EU Nature Restoration Law, and the Trillion Trees Initiative have established ambitious restoration targets, while aiming to mobilize governments, businesses and civil society in addressing ecosystem decline.

Technology is increasingly becoming a key enabler of restoration finance. Advances in remote sensing, Earth observation, artificial intelligence (AI), drones, sensors and digital monitoring are making restoration easier to measure and verify, and strengthening the monitoring, reporting and verification (MRV) systems upon which carbon markets, biodiversity finance and other private investment mechanisms rely.

However, technology is no substitute for strong governance. While digital monitoring and innovative financing can reduce costs and improve transparency, successful restoration still depends upon effective institutions, public investment, local community engagement and ecological and social safeguards.

Technology is transforming ecosystem restoration

Across all four ecosystems discussed in this year's edition of the *Green Technology Book*, restoration is becoming increasingly digital, predictive and data driven. Earth observation satellites, drones, autonomous vehicles, sensor networks, LiDAR, radar, the internet of things (IoT) and even blockchain technologies are now able to continuously monitor ecosystem change at an exceptional spatial and temporal resolution. AI, machine learning and digital twins are allowing the earlier detection of ecosystem degradation. They enable the forecasting of marine heatwaves, droughts and flooding, and help practitioners identify where interventions are likely to have the maximum ecological impact. Automation and robotics are also lowering restoration costs, while at the same time making interventions more scalable across extensive and remote landscapes.

The technologies featured in this edition extend beyond monitoring, however. They include advances in ecological engineering, restoration materials, biotechnology, hydrological management, nature-based solutions, precision restoration, biotechnology and fish breeding, robotics and ecosystem modelling. Many innovations combine engineering with natural processes, such as coral restoration systems, adaptive forest restoration and localized cryosphere adaptation. This allows for a holistic approach to be taken to the restoration of ecosystem function, as opposed to simply addressing the issues at individual sites.

Land – seeing the forest for the trees

Land ecosystems are experiencing an unprecedented degree of pressure as a result of climate change and unsustainable land use. Forests and soils currently absorb around 30 percent of anthropogenic emissions; but warming temperatures, drought, more frequent wildfires, biodiversity loss and continued land degradation are reducing their resilience. Approximately a quarter of the world's land is already degraded, while competing demands for food production, carbon storage, energy and development are placing growing pressure on landscapes. Restoration is therefore becoming more focused on creating landscapes that can adapt to a warmer, drier and more disturbance-prone future.

On land, restoration is evolving beyond large-scale tree planting toward more holistic ecosystem management. There is a growing recognition of the importance of restoring ecological processes, soil health, hydrological function and biodiversity alongside forest cover if restoration is to be successful. Approaches such as assisted natural regeneration, agroforestry, biochar, landscape rehydration, fuel management and community-based restoration illustrate how local, nature-based solutions can provide greater resilience than uniform tree planting campaigns. Restoration should be tailored to particular ecological and social contexts and avoid a one-size-fits-all approach.

As with other ecosystems, land restoration is becoming increasingly data driven. Satellites, drones, hyperspectral imaging, LiDAR, soil sensors and AI foundation models are transforming how ecosystems are monitored. These tools allow practitioners to detect drought stress, wildfire risk, biodiversity change and forest recovery at unprecedented spatial and temporal scales. Predictive models, digital mapping platforms and geospatial intelligence are enabling the identification of priority intervention areas and the simulation of responses. They also are improving the MRV systems that support restoration finance. These technologies complement

rather than replace field expertise by enabling continuous monitoring and more adaptive management. Combining nature-based approaches, local knowledge and advanced monitoring technologies provides the potential to restore ecosystem function and scale restoration efforts across complex and dynamic landscapes.

Oceans – restoring resilience

Oceans are the planet's largest climate regulator, absorbing more than 90 percent of the excess heat trapped by greenhouse gases (GHGs) and approximately a quarter of CO_2 emissions. This buffering capacity has reduced warming, but as a consequence it is altering ocean conditions through rising temperatures, acidification, deoxygenation and changes in ocean circulation. These stressors are driving marine heatwaves and coral bleaching, disrupting species distribution and degrading coral reefs, kelp forests and seagrass meadows.

Three major technological trends are emerging to help combat climate impacts on the oceans. First, monitoring is becoming increasingly autonomous and continuous through the use of satellites, sensor networks, autonomous underwater vehicles, environmental DNA, acoustic monitoring and animal-borne sensors to observe ocean conditions and marine biodiversity. Second, by forecasting marine heatwaves, coral bleaching and ecosystem change weeks or months in advance, AI and digital twins are enabling a shift away from reactive conservation toward predictive ecosystem management. Third, restoration itself is becoming scalable through the application of robotics, ecological engineering and biotechnology. Innovations such as automated coral propagation, micro fragmentation, larval seeding, AI-designed reef structures, kelp restoration systems and mechanized seagrass planting are moving restoration beyond small projects toward large-scale implementation.

Early-stage technologies include localized reef cooling, digital ocean twins, AI-powered biodiversity mapping, and experimental approaches to reoxygenation and assisted evolution. They demonstrate that future ocean conservation will depend not only on protecting existing ecosystems, but also on continuously monitoring, predicting and restoring resilience to those ecosystems impacted by climate change.

Freshwater – restoring the rhythm of water

Freshwater ecosystems are among the most biodiverse on Earth, supporting around 10 percent of all animal species and approximately 40 percent of known fish species. Yet they are under growing pressure from human activity and climate change. Rivers, lakes and wetlands face habitat loss, fragmentation and pollution. Climate change is adding to the pressures. Changing rainfall, earlier snowmelt, higher rates of evaporation and more frequent floods and droughts are changing how much water is available and when it flows. This can disrupt fish migration and spawning, degrade habitats, reduce connectivity and adversely affect water quality. Changing water levels also put wetland biodiversity and carbon storage at risk. Peatlands are particularly important in this respect, as they store large amounts of carbon, but can become a source of GHG emissions when they dry out.

Restoration is increasingly focused on restoring the natural hydrological processes that connect rivers, floodplains, wetlands and lakes. River re-meandering, floodplain reconnection and environmental flow management are all important measures. Water management technologies, such as stream gauges, remote sensing, real-time sensors and predictive models, can help us respond to changing flow regimes. Fish passage systems and fish-friendly turbines can reduce the impact of dams and hydropower on aquatic biodiversity. Peatlands can be restored through the simple blocking of drainage canals in combination with monitoring technologies. The most effective solutions often combine advanced technologies with nature-based solutions to better manage a change in hydrology, while preserving freshwater ecosystems.

Increased runoff and rising temperatures are severely affecting rivers and lakes. Nutrient pollution from agriculture triggers eutrophication and toxic algae blooms, which deplete oxygen, emit GHGs and devastate aquatic life. Advanced technologies, including satellite imaging, water quality sensors, fluorometers and DNA analysis, are vital for detecting these

acute threats. Mitigation strategies range from precision agriculture to chemical treatments, ultrasound, deep water oxygenation and simple mechanical devices able to remove invasive plants from the environment. Furthermore, warming waters cause what is known as an oxygen squeeze, accelerating the metabolisms of aquatic life, while at the same time reducing the dissolved oxygen available, disrupting reproductive cycles and creating migration barriers. This thermal stress also promotes the rapid spread of invasive species and virulent pathogens. Ultimately, combining innovative monitoring and targeted mitigation technologies is essential for protecting vulnerable freshwater ecosystems around the globe.

The cryosphere – protecting what remains

The cryosphere is one of the Earth's most climate-sensitive systems, comprising glaciers, ice sheets, sea ice, permafrost, seasonal snow and frozen ground. It regulates the global climate, stores freshwater, influences sea level and supports those ecosystems and communities that depend on seasonal meltwater. Yet it is undergoing rapid and accelerating change. Glaciers are retreating worldwide, Arctic sea ice continues to shrink and permafrost is thawing, polar and high mountainous regions warming faster than the global average. These changes also disrupt river systems, increasing the risk of glacial lake outburst floods (GLOFs), landslides and infrastructure failure, while threatening freshwater supplies for billions of people. They also create feedback loops that further accelerate climate change through reduced albedo (surface reflectivity) and the release of GHGs from thawing permafrost.

Unlike many other ecosystems, however, the cryosphere cannot realistically be restored through technological intervention under continued global warming. Rather than reversing glacier retreat or preventing widespread permafrost degradation, technology is increasingly focused on understanding change, reducing risks and helping societies adapt. Monitoring is becoming ever more precise, with the integration of satellites, drones, LiDAR, synthetic aperture radar (SAR), GNSS, sensor networks and AI enabling the continuous observation of glacier movement, permafrost thaw and sea ice conditions. Digital twins, machine learning and global observation systems are improving the forecasting of glacier melt, GLOFs, avalanches and other hazards. Localized engineering interventions, such as reflective geotextiles, artificial snowmaking, thermosyphons, artificial ice reservoirs and glacier early warning systems, can delay ice loss, stabilize infrastructure and help preserve water resources, but they remain expensive and site-specific.

Therefore, when it comes to the cryosphere, technology is imperative for bolstering resilience, but it cannot be considered a substitute for climate mitigation. Future innovation will depend on combining advanced monitoring, predictive modeling, international observation networks and locally appropriate adaptation strategies with global efforts to reduce emissions.

Innovation trends in ecosystem restoration

Patent activity demonstrates a growing technological development in fields enabling ecosystem restoration. They include AI, remote sensing, robotics, autonomous systems, digital monitoring, advanced materials and biotechnology, that support ecosystem restoration. Rather than occurring within a single "restoration technology" sector, innovation is increasingly taking place across multiple technology domains whose applications converge in ecosystem monitoring, management and restoration. At the same time, restoration-specific innovations are emerging in certain areas, such as coral reef restoration, showing how technological development is becoming tailored to specific ecosystem challenges. Innovation is helping to scale restoration, while improving the MRV systems that underpin restoration finance and investment.

Looking ahead

The technologies presented in this book demonstrate that ecosystem restoration is entering a new era. Digital technologies, AI, robotics and advanced monitoring are making restoration more measurable, scalable and adaptive than ever before. Global innovation ecosystems are producing technology-based solutions at every scale and level of complexity. Yet technology

alone cannot restore degraded ecosystems. The next stage of the green technology transition is not simply the development of more technologies, but their appropriate application and deployment at scale. This requires stronger connections between innovation, evidence, intellectual property, finance, implementation and measurement, as well as the local and Indigenous knowledge, community engagement and partnerships needed to adapt solutions to local conditions.

From connections to deployment

Technology does not automatically equal impact. The availability of a technology does not by itself establish that it will produce the desired environmental or social outcome. Digital and physical technologies can improve the availability of information, increase the precision of interventions, reduce monitoring costs and support faster learning, but they do not replace the institutional and social conditions required for successful climate adaptation and ecosystem management. Effectiveness can depend on ecological conditions, implementation capacity, infrastructure, cost, skills, governance, local knowledge, maintenance and the way the technology is integrated into wider restoration or adaptation approaches. The value of technology therefore lies not only in innovation itself, but in its appropriate application, integration, evidence and ability to deliver measurable outcomes.

The *Green Technology Book* provides a knowledge and technology intelligence foundation for understanding these opportunities. Its connection with the WIPO GREEN database provides a pathway for continued exploration of technologies and needs, and for identifying potential partnerships and opportunities for collaboration and deployment beyond the publication.z

Methodology

The *Green Technology Book* 2026 presents an overview of the global state of innovation in technologies addressing ecosystem decline. By showcasing concrete and practical technological solutions, it highlights how innovation can help monitor ecosystem change, reduce climate impacts, restore degraded ecosystems and strengthen ecosystem resilience. The publication is intended for policymakers, conservation practitioners, researchers, businesses, investors, local communities and others seeking practical solutions to the strengthening ecosystem resilience and biodiversity conservation.

This year's *Green Technology Book* does not attempt to cover every pressure point affecting global ecosystems. Instead, it focuses on the major forms of ecosystem decline directly driven or significantly exacerbated by climate change, and for which innovative technologies offering a remedy exist or are emerging. While many of these same technologies also provide benefits for biodiversity conservation, pollution reduction and sustainable resource management more broadly, they have been primarily selected because they respond directly to the ecological changes associated with climate change. The publication is organized around four broad ecosystem domains – land, oceans, freshwater, and the cryosphere. Rather than arranging technologies by sector alone, this edition groups them according to the major climate-induced ecological changes affecting the four different types of ecosystem. Each chapter begins by describing the underlying climate drivers and associated ecological processes affecting the ecosystem in question before presenting the technologies designed to help monitor, manage, restore or increase resilience to the impacts outlined.

The *Green Technology Book* recognizes that innovation extends beyond advanced digital technologies. Accordingly, this edition highlights a diverse range of solutions ranging from simple field-based tools and ecological restoration techniques to sophisticated remote sensing platforms, artificial intelligence, robotics, biotechnology and decision support systems. Many of the most effective innovations combine engineering, ecological knowledge and nature-based approaches tailored to local conditions.

The *Green Technology Book* is more than a catalogue meant for inspiration – it is a living project to which everyone can contribute. It links to the free public WIPO GREEN Database of needs and green technologies where users can create a profile and share climate solutions and needs.

From climate and ecosystem challenges to technology action

The *Green Technology Book* brings together evidence, innovation intelligence and technology examples to help readers move from understanding climate and ecosystem challenges to exploring technological responses. It highlights technologies across different stages of maturity, considers the evidence and conditions that influence their effectiveness, and provides insights into their potential applications, opportunities and limitations.The Book also provides a starting point for further exploration. Readers can use the information presented to understand emerging areas of innovation, identify potential technology approaches, consider evidence and deployment conditions, and explore opportunities for collaboration, technology transfer and application.

How we wrote the book

Technology identification followed a multi-stage process. First, scientific and gray literature was reviewed to identify the principal climate impacts affecting ecosystems and the ecological processes through which they occur. Relevant technologies were then identified through reference to internet search engines, literature searches, company websites, innovation platforms, research institutions, and international technology databases. Translation engines enabled us to search articles in several languages to ensure a broad geographical spread.

Owners of the technologies identified were contacted, and all technologies uploaded to the WIPO GREEN Database of needs and green technologies, either by the technology owner themselves or by us at WIPO.

How we found the technologies

Throughout the publication, we operate with three concepts: innovation, solution, and technology. Although sometimes used almost interchangeably, they do have different meanings. We use the term innovation to cover all intellectual creativity that could result in a solution. Solution is broadly taken to mean the deployment of an innovation output to solve a specific challenge. The third concept, technology, is a broad term, but we apply it more narrowly to mean any physical entity or technique, with or without additional equipment, which is deployed to resolve a specific challenge. We cover technologies that range from the very simple to the highly complex. Often the scope of ecosystem technologies is expanded to include enabling mechanisms such as ownership and the institutional arrangements that pertain to that technology (e.g., insurance mechanisms and community platforms). However, while recognizing the importance of such mechanisms, the primary focus is on tangible technologies or actual techniques.

It is important to emphasize that the technologies presented here have not been tested or in any way vetted by WIPO, and that we rely on publicly available material. Inclusion within the *Green Technology Book* is therefore not a recommendation of a particular technology. Technologies presented should instead be seen simply as examples of a technological area, and there may be many other similar offerings that to our knowledge are in no way inferior. Photos illustrating the various technologies are reproduced with permission from the technology owners. When such permission could not be obtained, relevant stock-photos or AI-generated images have been used instead. Photos of technologies may therefore not always represent the actual technology described. Technology owners can freely upload their technology to the WIPO GREEN Database and in doing so become part of the project.

The appropriateness of a technology is often highly context-specific and relates to factors other than geographical location. Therefore, no recommendations on where, when or how the technologies might be suitable have been provided. Such an assessment should always be made with the involvement of local experts and stakeholders.

The following criteria were used when selecting technologies for the *Green Technology Book*:

- relevance for climate-induced ecosystem decline;
- relevance to the Earth system being considered: 1) land, 2) oceans, 3) freshwater; and 4) cryosphere.
- pertinence to:
  - a product or service available for purchase or licensing;
  - a product or service available for free/open source;
  - a guidebook on the application of a method or technique;
  - a research project or similar (for horizon technologies).

The following additional factors were also taken into consideration:

- anticipated impact from implementation;
- availability of sufficient quality information or third-party endorsements;
- market availability (for proven and frontier technologies);
- cost in relation to impact;
- geographical balance;
- business balance (large- and small-scale businesses, humanitarian organizations, start-ups, research teams, non-governmental organizations and so on);
- no harm principle.

Technologies have been divided into three broad groups to indicate their maturity and availability. **Proven** technologies are those that have been on the market for some time and therefore rely on a tried and tested concept. **Frontier** technologies are those that are available, but still relatively new, and as such possibly less validated within a real-world setting. **Horizon** technologies are those new concepts currently at the research or development stage and expected to become available within a few years' time.

Technologies have been classified to provide an easy guide to relevance for a reader. We have aimed for a broad representation of technologies at various levels of complexity and stages of readiness. Technologies are classified as having either a low, medium or high level of complexity. This is an indication only and does not adhere to a strict definition of complexity; rather, it reflects the level of human, material and monetary resources required to implement the solution in question. Meanwhile, technology maturity is broadly assessed according to the quasi-standard Technology Readiness Level (TRL) definition. According to this measure, horizon technologies (TRL 2–6) have the lowest readiness level, but are nonetheless close to full development, whereas proven and frontier technologies (TLR 7–9) have been validated and are ready to be scaled-up, if this has not already been done.

We hope you will be inspired by the creativity, ingenuity and diversity of the technologies presented here. We welcome any feedback and suggestions, which can be sent to us through the WIPO GREEN website.

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Users should undertake appropriate technical, environmental, financial, legal and other due diligence before making decisions concerning the application, acquisition, licensing, financing or deployment of any technology described in this publication.

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1 Introduction

1.1 The growing imperative for ecosystem restoration

Climate change continues to intensify, with 2024 the hottest year on record (WMO, 2025). At the same time, nature loss continues unabated, driven by patterns of production and consumption, population dynamics, technological development and governance systems, which in turn generate land use change, overexploitation of natural resources, climate change, pollution and invasive alien species (IPBES, 2019). Despite a growing scientific consensus on the urgency of these challenges, the current political climate is not always conducive to taking decisive action.

This broader environmental crisis is reflected in the fact that the Earth is increasingly operating beyond safe ecological limits: seven of the nine planetary boundaries have been exceeded, indicating risks to the planet's stability and resilience are growing (Kitzmann *et al.*, 2025). This is already incurring substantial economic and social costs. The combined cost of damage arising from land degradation, desertification and drought now amounts to at least USD 878 billion a year (UNCCD, 2025). Ecosystem decline is often discussed as though it is simply an issue of biodiversity, but for many people it is also an impediment to food security, their livelihood, water security, health and economic resilience. An estimated USD 50 trillion in annual economic activity globally is moderately or highly dependent on natural ecosystems and the services they provide (McElwee *et al.*, 2024).

> Restoring degraded ecosystems has emerged as a global priority, recognized as essential for helping to address climate change, recover biodiversity, strengthen ecosystem resilience and support human well-being

The implications for human well-being are substantial. Impacts are already affecting food systems, freshwater supplies, livelihoods and human health across all major Earth systems. Approximately 1 billion people live within 100 km of the coral reef on which they depend for food, livelihood, tourism and storm protection; yet a third of reef-building coral species are already at a high risk of extinction (McElwee *et al.*, 2024). Migratory freshwater fish providing critical food and livelihoods for millions worldwide have declined by over 80 percent since 1970 (Weston, 2024b). Two-thirds of irrigated agriculture worldwide could be affected by glacier retreat and declining snowpack (Harvey, 2025). And inadequate pollination is estimated to be a contributing factor in roughly 500,000 premature deaths annually through the resulting reduced availability of nutritious food (Dickie, 2026).

Against this backdrop, restoring degraded ecosystems has emerged as a global priority, recognized as essential for helping to address climate change, recover biodiversity, strengthen ecosystem resilience and support human well-being. Ecosystem restoration is also essential in either maintaining or reinstating critical ecosystem services and contributes to climate change mitigation through carbon sequestration (Ermgassen and Löfqvist, 2024).

Restoration has been rising up the global agenda. This has been due in large part to the establishment of the UN Decade on Ecosystem Restoration. This global initiative – spearheaded by the United Nations Environment Programme (UNEP) and the Food and Agriculture Organization of the United Nations (FAO) – is aimed at preventing or otherwise halting and reversing ecosystem degradation worldwide (UNEP, 2026b). It works by mobilizing political commitment, supporting restoration initiatives on the ground and providing a platform for knowledge-sharing, partnerships and financing to help scale restoration efforts. Box 1.1 summarizes the fundamental principles of ecosystem restoration, according to the UNEP.

Box 1.1 Fundamental principles of ecosystem restoration

Ecosystem restoration is often misunderstood and oversimplified. The following principles help clarify what restoration entails, what it seeks to achieve, and how it contributes to environmental, social and economic outcomes. It is important to distinguish the most important elements of restoration, and to dispel any associated myths – given the myriad information in circulation about this critical topic.

Restoration is about recovery and not just conservation: it involves assisting the recovery of degraded, damaged or destroyed ecosystems, while conserving those ecosystems that remain intact.

Restoration is about ecosystem function: it aims to recover ecosystem function and services, not simply to restore species or vegetation.

Restoration can be active or passive: it may involve active interventions, such as planting or species reintroduction, or passive approaches that remove pressures and allow recovery processes to occur naturally.

Restoration is not necessarily undertaken to recreate historical conditions, but rather to support functional ecosystems in meeting ecological and societal needs under changing environmental conditions.

Restoration is increasingly recognized as an environmental, social and economic investment, rather than simply an expense. Between now and 2030, the restoration of 350 million hectares of degraded land and aquatic systems is predicted to generate USD 9 trillion in ecosystem services, while also removing from 13 to 26 gigatonnes of green house gas from the atmosphere. The economic benefit these interventions is slated to be ninefold the investment cost, whereas the cost of inaction is estimated to be three times more than restoration.

Source: Adapted from UNEP, 2026c.

Recognizing the urgent need to halt and reverse ecosystem degradation, governments, international organizations, businesses and civil society have launched a range of initiatives to promote and scale ecosystem restoration. Key examples are summarized in Table 1.1. While the Bonn Challenge, trillion Trees Initiative, Kunming–Montreal Global Biodiversity Framework and EU Nature Restoration Law establish restoration targets, commitments and policy obligations, the UN Decade on Ecosystem Restoration functions globally as an overarching platform to mobilize stakeholders, share knowledge, build partnerships and accelerate restoration implementation. Collectively, these initiatives illustrate the growing political momentum behind ecosystem restoration.

Table 1.1 High-level policy initiatives for large-scale ecosystem restoration

Initiative	Key restoration goals
Bonn Challenge	Global initiative to restore 350 million hectares of degraded and deforested landscapes by 2030, with regional targets including AFR100 (100 million ha), Europe, the Caucasus and Central Asia Initiative (ECCA30) (30 million ha), and Initiative 20x20 (50 million ha).
Trillion Trees Initiative	Mobilizes private sector action to plant, grow, and conserve one trillion trees by 2030.
Kunming–Montreal Global Biodiversity Framework	Calls for restoration of at least 30% of degraded terrestrial, freshwater, coastal, and marine ecosystems by 2030, alongside increased public and private biodiversity finance.
EU Nature Restoration Law	Establishes legally binding targets to restore degraded ecosystems, improve habitat connectivity and biodiversity, and restore 25,000 km of free-flowing rivers by 2030.
UN Decade on Ecosystem Restoration	Global initiative (2021–2030) to prevent or halt and reverse ecosystem degradation through coordinated action by governments, businesses, and civil society.

Source: Adapted from Ermgassen and Löfqvist, 2024.

Although policy commitments have expanded rapidly, achieving restoration goals at scale remains challenging. Restoration is often constrained by monitoring, implementation, financing and long-term management. But advances in technology are increasingly helping to address these challenges through improvements in restoration planning, implementation, measurement and reporting.

This latest edition of the *Green Technology Book* addresses ecosystem restoration across four major Earth systems – land, oceans, freshwater, and the cryosphere. Each presents unique challenges and opportunities, yet technology is playing an important role in advancing restoration agendas across all of them. Achieving restoration at scale across these major systems will depend not only on technology and policy, but also on adequate financing.

1.2 Restoration has been underfunded by the public sector

International restoration commitments are increasing the pressure to scale restoration finance. While restoration has traditionally relied on public funding, growing attention is being paid to private sector mechanisms, such as carbon and biodiversity markets, blended finance and impact investment, although effective governance remains essential in ensuring positive outcomes.

> Achieving restoration at scale across these major systems will depend not only on technology and policy, but also on adequate financing

According to the UNEP, global restoration finance amounted to approximately USD 64 billion in 2022. Estimates vary, but global funding for nature restoration is currently thought to be approximately USD 133 billion a year, according to the Ecosystem Restoration Integrated Program (ERIP, 2026). In any case, annual investment needs are projected to rise to USD 296 billion annually by 2030 to meet global restoration goals, representing a quadrupling within this decade (Olsen and Hang, 2024). Many publications acknowledge that nature-based solutions (NbSs) more broadly (including restoration, conservation, sustainable land

management, etc.) receive only a fraction of the required funding, with global NbS finance estimated at roughly between USD 200–220 billion annually and investment needs estimated at USD 571 billion annually by 2030. Simultaneously, nearly USD 7 trillion a year goes toward funding activities that directly harm nature (UNEP, 2026a; IISD SDG Knowledge Hub, 2026). This shows the effort required not simply to raise new financing, but also to redirect existing finance (UNEP, 2026a; IISD SDG Knowledge Hub, 2026).

Ecosystem restoration has historically been largely funded by the public sector. Governments provide roughly 75 percent of restoration finance globally, with the majority coming from national budgets, and the remainder flowing from development banks and international assistance programs (Olsen and Hang, 2024). Many restoration projects have therefore struggled, as they often depend on grants, rather than revenue-generating business models. A baseline assessment undertaken at the outset of the UN Decade on Ecosystem Restoration illustrates the scale and characteristics of restoration funding in Europe prior to the recent acceleration in restoration commitments (Box 1.2).

Box 1.2 A snapshot of restoration funding leading up to the UN Decade

In preparation for the launch of the UN Decade on Ecosystem Restoration, a baseline assessment of restoration finance in Europe found that more than €1.2 billion had been committed to over 400 projects between 2010 and 2020, restoring more than 11 million hectares of degraded ecosystem (UNEP-WCMC *et al.*, 2020). Funding came from more than 200 organizations, including the European Commission, national governments, foundations and the private sector. More than 85 percent of projects focused on terrestrial ecosystems, receiving over €1 billion in funding, while marine restoration received over €138 million, primarily for coastal ecosystems. Biodiversity conservation was the primary objective of most projects, accounting for nearly 80 percent of known funding, with the remainder focused largely on climate mitigation and adaptation.

For the private sector, ecosystem restoration is increasingly viewed as a way to meet sustainability and corporate net-zero commitments, manage nature-related risks, improve operational performance, capitalize upon existing business opportunities and even create new ones. A growing awareness of nature-related dependencies and impacts is driving interest from companies and investors alike. A range of financial instruments such as equity, debt, green bonds, carbon and biodiversity credits, and insurance products are being used to direct private capital into restoration activities (World Bank, 2024).

However, despite this progress, ecosystem restoration remains a challenging investment area. Even though commercial restoration models are emerging in areas such as sustainable agriculture, forestry and carbon markets, investment remains constrained by a limited pipeline of bankable projects. Restoration projects often involve higher costs, require greater technical complexity and have longer time horizons than do conservation activities (World Bank, 2024). Due to the slow accrual of ecological and financial benefits as ecosystems recover, such projects may not meet the expected return on investment. Additionally, restoration requires specialized knowledge, robust monitoring protocols and ongoing technical support (World Bank, 2024), all factors that increase implementation costs and risks.

One key challenge is the mismatch between the capital available and a project's needs. Much of the available financing targets mature investments, whereas restoration projects often require early-stage, risk-tolerant funding to support development and scaling. Addressing this gap requires a range of capital providers: for example, grant makers, impact investors, commercial lenders and private equity. In respect of key action areas for scaling private finance for restoration, the World Bank recommends supporting early-stage restoration ventures by investing in emerging business models and technologies, while using blended finance that combines public and private funding in order to reduce investment risks and attract private capital. Blended finance, along with aggregators and specialized fund managers, can help attract private investment by improving risk–return profiles and reducing transaction costs (World Bank, 2024).

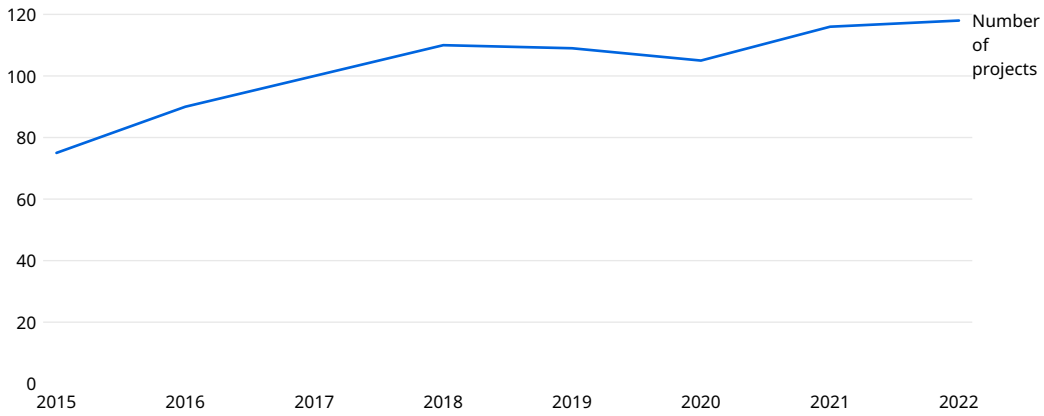
1.3 Scaling ocean restoration requires better monitoring and spatial planning

Funding for ocean restoration remains fragmented. According to the International Coral Reef Initiative (ICRI), as of 2021, approximately USD 258 million had been invested in coral reef restoration across 56 countries over the previous decade, with funding largely dependent on short-term grants and concentrated in developed countries (Hein and Staub, 2021).

A UNEP–World Conservation Monitoring Centre (WCMC) assessment of ocean restoration finance between 2015 and 2022 found most funding to have been directed toward coastal ecosystems, with mangroves receiving the largest share because of their links to blue carbon, climate adaptation and coastal resilience (UNEP-WCMC, 2022). The assessment also identified major gaps in spatial planning, monitoring and MRV (measurement, reporting and verification) systems. Robust mapping tools, restoration priority assessments and standardized monitoring frameworks remain limited across many marine ecosystems. Figure 1.1 shows how ocean restoration funding has changed over time.

These findings suggest that the next frontier in marine restoration may not be better restoration techniques alone, but improved systems for identifying where restoration ought to occur and measuring the outcome. This creates significant opportunities for technologies such as remote sensing, Earth observation, GIS platforms, AI-driven spatial planning and digital MRV systems.

Figure 1.1 Number of ocean restoration projects per year, 2015–2022



Source: UNEP-WCMC, 2022.

1.4 The increasing role of private sector funding in restoration

The current policy conversation is about how to mobilize more private capital. The carbon markets where investors purchase the carbon credits generated by restored ecosystems is the most mature private finance mechanism for funding restoration activities. Biodiversity credits is an emerging market area where companies are able to finance measurable biodiversity improvements is, as discussed in Chapter 2 in the section of scaling land-based restoration. It is still at the early development stage, and therefore small compared with the carbon market, but is attracting attention. However, questions remain about standards and integrity. Proponents favor developing this area further at a local level, rather than offering global offsets. Critics argue that biodiversity credits risk diverting attention away from more effective solutions such as addressing the underlying drivers of biodiversity loss and increasing public finance for conservation (Weston, 2024a).

An initiative of note is the Nature Transition X-Curve. Developed by the authors of the 2026 UNEP *State of Finance for Nature* report as an adaptation of the broader X-Curve framework used in sustainability transitions research (developed by DRIFT, the Dutch Research Institute for Transitions), it illustrates the need for a dual transition: phasing out environmentally harmful finance and subsidies, while simultaneously scaling up investment in NbSs. Achieving

such a shift requires policy reform, public investment, regulatory incentives, nature-related risk disclosure and a greater mobilization of private capital through blended finance, de-risking mechanisms and high-integrity nature markets (UNEP, 2026a).

The Taskforce on Nature-related Financial Disclosures (TNFD) is a global framework enabling businesses and financial institutions to identify, assess, manage and disclose nature-related dependencies, impacts, risks and opportunities. Designed as an analogue to the Task Force on Climate-related Financial Disclosures (TCFD), its aim is to improve transparency, support better risk management and help redirect capital toward nature-positive outcomes (TNFD, 2026). It is one of the major mechanisms being used to translate biodiversity goals into corporate and financial sector decision-making and disclosure practices. There are currently 730 adopters of the TNFD, representing assets under management of USD 22.4 trillion (UNEP, 2026a)

Alongside disclosure frameworks such as TNFD, there is a variety of financial instruments and investment mechanisms being used to channel private capital into restoration activities (UNEP, 2026a; World Bank, 2024). Prominent among them are:

- *Payment for ecosystem services (PES)*: Ecosystem services are the material and immaterial benefits obtained by humans either directly or indirectly from ecosystems (UNEP, 2026b). Beneficiaries pay land managers for ecosystem services such as flood mitigation, watershed protection, soil conservation and pollination.
- *Green, blue and sustainability bonds*: governments, banks or companies issue bonds with proceeds going toward financing restoration activities.
- *Impact investing*: investors accept longer investment timelines, while prioritizing environmental outcomes alongside financial returns.
- *Debt-for-nature swaps*: countries restructure debt and redirect savings toward restoration and conservation activities.
- *Blended finance*: public or philanthropic capital absorbs early-stage risk in order to attract commercial investors, pension funds, insurers and private equity.

1.5 Where does technology fit into the restoration picture?

A major reason restoration struggles to attract private finance is the difficulty in measuring the ecological outcomes. Investors, insurers and regulators increasingly require evidence that restoration is not just occurring, but generating measurable environmental benefits. This has created a growing demand for technologies that improve MRV.

Technology may be useful in overcoming a number of obstacles, but is critical when it comes to one major barrier to investment: namely, potential investors skeptical as to whether restoration is truly producing measurable outcomes that can be robustly verified at a low cost. Without MRV technology, most nature markets cannot function at scale. Private finance mechanisms have tended to underinvest in monitoring and impact evaluation mechanisms, preferring to back cost-effective NbSs, such as plantation monocultures, instead of naturally regenerated ecosystems (Ermgassen and Löfqvist, 2024).

> The bottom line is that investors are more willing to finance restoration projects when outcomes can be measured and verified

Technology increasingly addresses an array of such issues with the scale-up of satellite observation, Earth observation data, remote sensing, LiDAR and drones. The bottom line is that investors are more willing to finance restoration projects when outcomes can be measured and verified. As discussed in the following chapters, these technologies streamline MRV and reduce monitoring costs across diverse ecosystems. Some of the potential trade-offs

between investment incentives and social and ecological outcomes can be addressed through technological, institutional and financial innovation (Ermgassen and Löfqvist, 2024). Critics underscore the fact that technological solutions cannot possibly mitigate every risk, therefore fundamental investment in governance and civil society oversight is required in order to ensure ecological and social safeguards (Ermgassen and Löfqvist, 2024).

1.6 Patent trends in ecosystem restoration technologies

Climate change is accelerating ecosystem decline through species range shifts, habitat degradation, ocean warming and acidification, glacier retreat, drought and other wide-ranging stressors. These impacts are prompting a need for new technologies to support monitoring, restoration, adaptation and resilience.

Because ecosystem restoration is an application area, rather than a discrete technological field, patent trends are difficult to directly assess. Patent activity associated with ecosystem restoration is dispersed across a range of enabling technologies, rather than concentrated within a distinct "restoration technology" sector. Innovation trends are therefore typically assessed through patent activity in areas such as remote sensing, AI, environmental monitoring, robotics, biotechnology, drones, environmental sensors and digital platforms, which increasingly support restoration planning, implementation and monitoring. Patent information can provide valuable insights into emerging technological trends, identify leading innovators, indicate where investment is taking place, and help governments and organizations identify the technologies available for licensing, collaboration or deployment. Table 1.2 presents a breakdown of ecosystem restoration technologies.

Table 1.2 Restoration technologies and associated patent activity

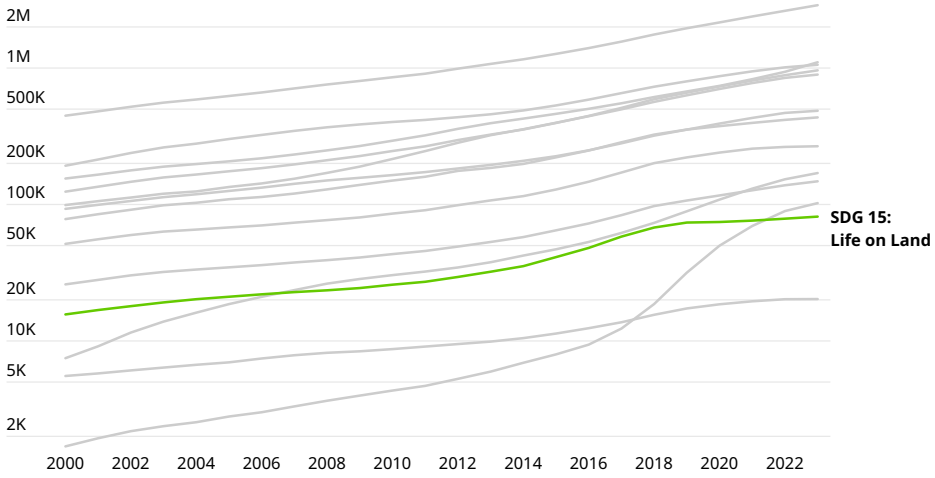
Technology area	Relevance to restoration	Typical patent activity
Remote sensing and Earth observation	Monitoring ecosystem condition and recovery	Sensors, image processing, satellite analytics
AI and machine learning	Species identification, restoration planning, predictive modelling	Algorithms, decision-support systems, automated classification
Drones and autonomous systems	Seeding, mapping, monitoring, spraying	UAV hardware, navigation systems, deployment mechanisms
Environmental sensors and IoT	Soil moisture, water quality, biodiversity monitoring	Sensor design, networks, communications systems
Digital platforms and decision-support tools	Restoration planning, MRV, project management	Software patents where permitted, data integration systems
Biotechnology and nature-based engineering	Native species propagation, soil restoration, bio-remediation	Biological processes, genetic technologies, microbial applications

Note: IoT, internet of things; MRV, measurement, reporting and verification; UAV, unmanned aerial vehicle.
Source: Authors.

Patent activity provides an indication of areas in which technological development and inventive activity are taking place. Patent landscapes can help identify emerging technology domains, active innovators and potential areas for collaboration, licensing and technology transfer. Patent activity should not, however, be interpreted as evidence of commercial availability, environmental effectiveness, affordability or suitability for a particular context

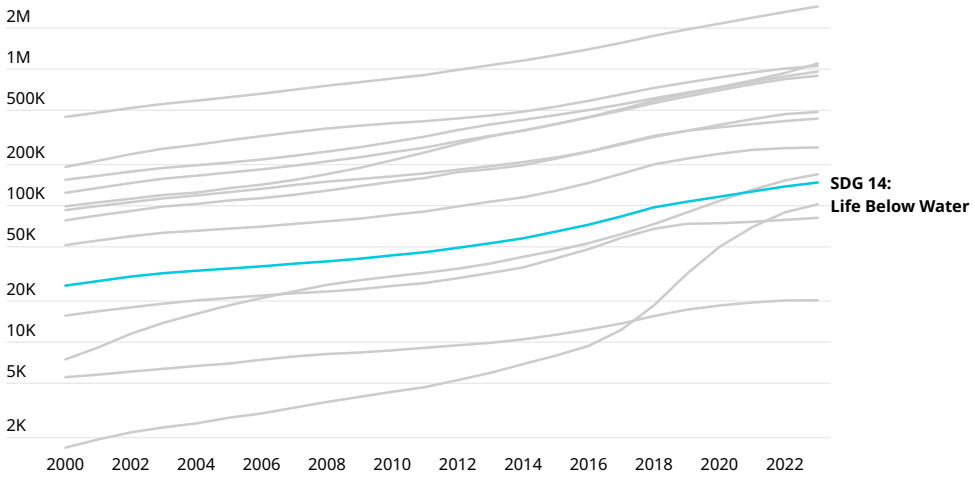
Patent activity related to environmental technologies has increased substantially over the past two decades. According to WIPO, environmental technologies account for the largest share of Sustainable Development Goal (SDG)-related patent families, highlighting the scale of innovation occurring across environmental sectors (WIPO, 2024). Trends in patents related to SDGs 15 (Life on Land) and 14 (Life Below Water) provide a useful proxy for innovation in technologies relevant to land and ocean restoration. Figure 1.2 depicts the number of patents related to SDG 15, while Figure 1.3 shows those related to SDG 14.

Figure 1.2 Number of patents related to SDG 15, Life on Land, 2000–2023



Note: Gray lines indicate other SDGs.
Source: WIPO, 2024.

Figure 1.3 Number of patents related to SDG 14, Life below Water, 2000–2023

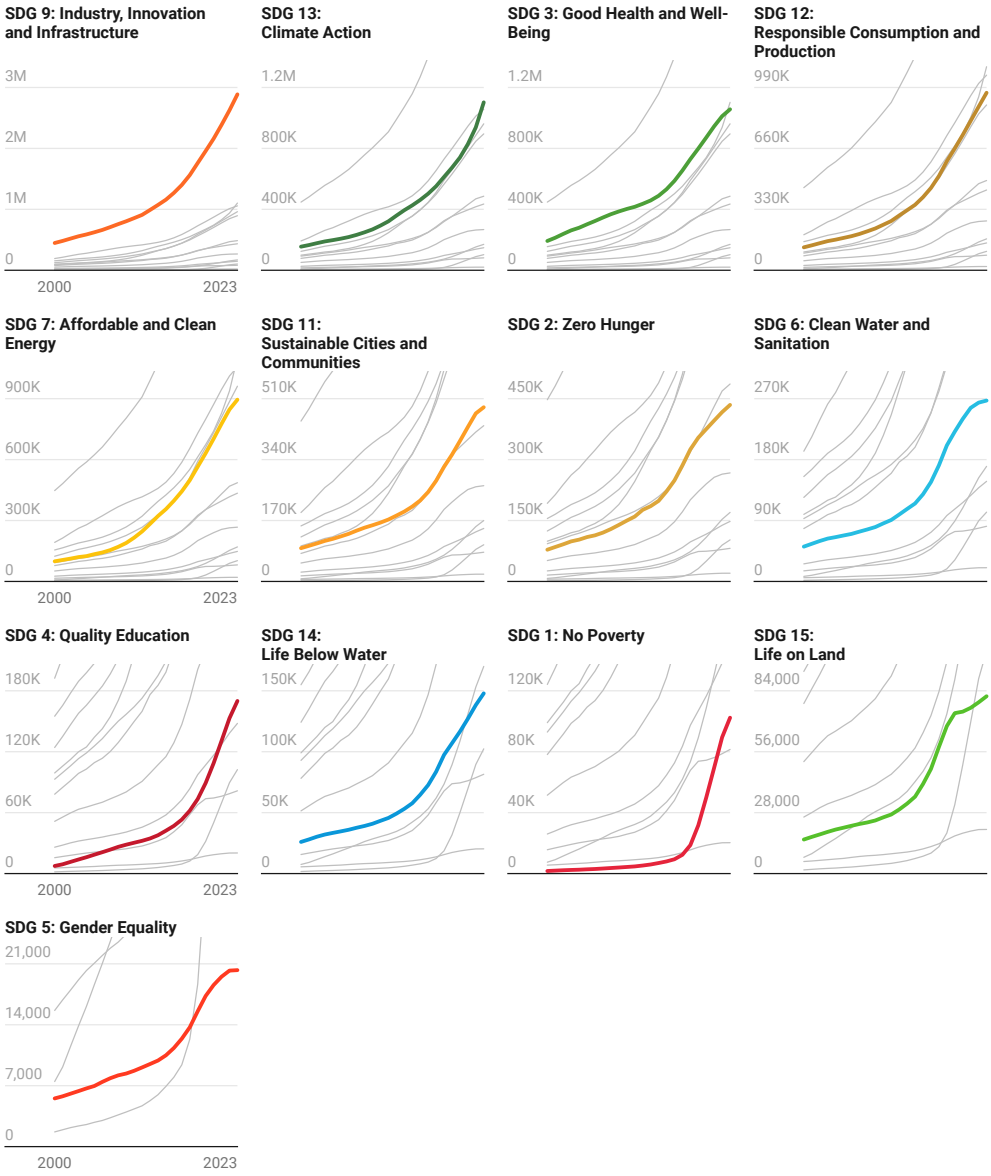


Note: Gray lines indicate other SDGs.
Source: WIPO, 2024.

As Figure 1.4 makes evident, SDGs 14 and 15 have fewer patents than some other SDGs, but this is most likely because they are emerging areas for innovation.

Two narratives can be seen to emerge regarding innovation patterns in ecosystem restoration. The first is that of technology enabling restoration, which includes the use of AI, drones, sensors and monitoring platforms. The second is that of restoration-specific technologies being designed to directly restore a particular ecosystem. Coral reef restoration provides one of the clearest examples of the latter and illustrates both the opportunities and challenges associated with patent-driven innovation in restoration.

Figure 1.4 Number of global SDG-related active patent families (largest to smallest), 2000–2023



Note: Gray lines indicate other SGDs.
Source: WIPO, 2024.

Patent activity associated with ecosystem restoration is dispersed across a range of enabling technologies, rather than concentrated within a distinct "restoration technology" sector

Patent activity in coral restoration has increased rapidly, but recent research suggests that patents, academic research and restoration practice often evolve separately, highlighting challenges in translating innovation from research into patents and ultimately into practical restoration. A key finding is that coral restoration patent activity is largely disconnected from both academic restoration research and practitioner communities.

This disconnect is reflected in both the geography and focus of patent activity. China dominates coral restoration patent filings, accounting for 61 percent of patents, followed by the United States (14 percent) and Japan (6 percent). Many countries with extensive coral reef systems show no patent activity at all; among the 15 largest coral reef regions globally, only four had filed coral restoration patents. Restoration projects, by contrast, were much more geographically dispersed (Roch *et al.*, 2023). A similar mismatch exists between patented technologies and those most commonly used in practice. Patents are concentrated in artificial reef technologies, accounting for 54 percent of filings, followed by *ex situ* aquaculture systems and *in situ* nurseries. However, practitioners more commonly employ approaches such as coral gardening, coral transplantation and *in situ* nurseries (Roch *et al.*, 2023).

While coral restoration illustrates the innovation within restoration-specific technologies, much of the broader innovation landscape is being driven by enabling technologies that can be applied across multiple ecosystems. On land, drones and AI are helping shift restoration away from labor intensive planting toward technology-enabled approaches able to operate at the landscape scale. Several companies are developing automated restoration systems. For example, Dendra reports that its drones can seed areas equivalent to around 100 football fields per day, while Distant Imagery planted 5.5 million mangroves in the United Arab Emirates in 2024. Such technologies are able to extend restoration into remote or inaccessible degraded areas where traditional approaches may be either prohibitively expensive or slow.

Increasingly, drones are being integrated with AI, remote sensing and geospatial analytics to support the entire restoration cycle, from site selection and planting through to monitoring and reporting (Robinson *et al.*, 2022). These technologies can improve restoration planning, strengthen MRV systems and help support emerging nature and carbon markets.

More broadly, ecosystem restoration is emerging as a multidisciplinary innovation field at the intersection of climate technology, robotics, AI, geospatial analytics and environmental monitoring. At the same time, important questions remain regarding ecological effectiveness, seedling survival, cost-effectiveness, regulatory frameworks and long-term impacts. Moreover, although innovation is advancing rapidly, evidence for large-scale ecological effectiveness remains limited (Holl, 2020; Boström-Einarsson, 2020).

A synthesis of findings from the literature, alongside the solutions presented in this edition of the *Green Technology Book*, suggests that the different restoration systems follow a distinct pattern of technological innovation. Table 1.3 provides an overview of the emerging trends.

Table 1.3 Sampling of dominant innovation trends across restoration areas

Restoration area	Dominant innovation trend
Coral reefs	Restoration-specific technologies
Forests	Enabling technologies (AI, drones, MRV)
Mangroves	Combination of restoration and enabling technologies
Soils	Biological and chemical innovations
Freshwater systems	Monitoring and treatment technologies

Note: MRV, measurement, reporting and verification.
Source: Authors.

Ecosystem restoration is rapidly evolving from a largely project-based activity into a multidisciplinary field drawing on advances in technology, finance, policy, engineering and science. Although many innovations remain at an early stage and important questions regarding effectiveness and scalability remain, experimentation and investment are increasing. The chapters that follow examine these developments across a range of ecosystems, highlighting the opportunities, challenges and lessons learnt for scaling restoration in the years ahead.

2 Land-based systems



Global land ecosystems encompass the mountains, plains, forests, savannahs and deserts that provide a home for much of the world's biodiversity and supply humankind with oxygen, food and water. Land plays a central role in human, economic and climate systems, acting as both a source of and sink for greenhouse gases (GHGs), while at the same time regulating energy, water and atmospheric exchanges. Soils and forests are particularly important carbon sinks, and during the past decade land-based ecosystems have absorbed roughly 30 percent of anthropogenic carbon emissions (UNCCD, 2022).

The Earth is not a pristine system. Human use directly influences about 70 percent of the global, ice-free land surface (Arneth *et al.*, 2019;Planet A. Ventures, 2023). Land is a finite resource experiencing intense pressure from both climate change and human activity. At the same time, deforestation and land degradation contribute significantly to GHG emissions, making land both part of the climate system and highly vulnerable to its changes.

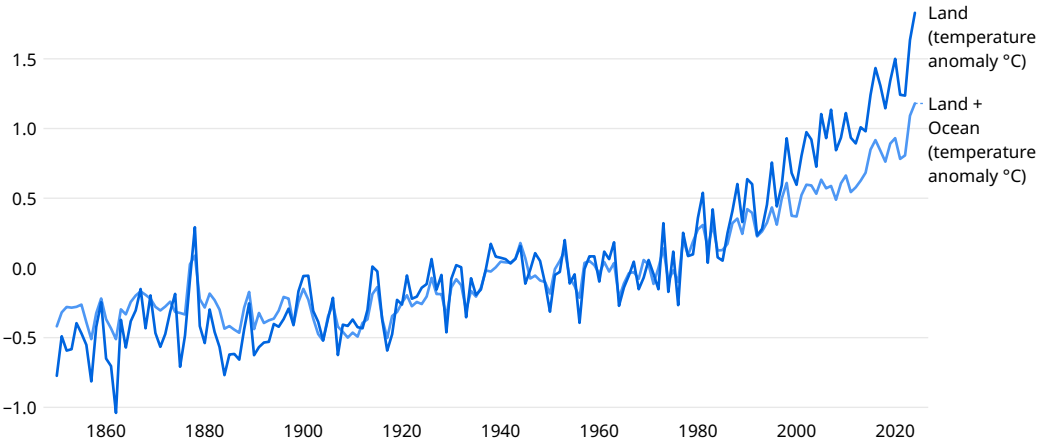
Climate change is causing many land systems to become warmer and drier, intensifying existing degradation processes, particularly in vulnerable dryland and coastal regions. Since 1961, the area of dryland experiencing drought has expanded by around 1 percent a year. Combined with pressures from urbanization, deforestation and agricultural expansion, this is accelerating ecosystem degradation and undermining resilience. Approximately a quarter of global land is already degraded, while soil erosion rates are estimated to be from 10 to more than 100 times faster than soil is able to form naturally (Shukla *et al.*, 2019;IPCC, 2019).

Land systems are also becoming increasingly constrained through the competing demands of food, carbon storage, energy and development (Shukla *et al.*, 2019). This is increasing the demand for restoration approaches capable not only of repairing degraded ecosystems, but also improving climate resilience, monitoring ecosystem change and supporting long-term land management. The good news is that innovation ecosystems around the world have created a wealth of technologies that can help in this regard. Although much of the restoration literature and many technological applications focus on forests, the technologies discussed in this chapter are increasingly applicable across a wider range of land-based ecosystems, including drylands, grasslands and peatlands.

2.1 Heat, drought and disturbance

Climate change is reshaping land systems through raising temperatures, shifting rainfall patterns and increasing the frequency of disturbances such as drought and wildfire. Figure 2.1 shows the observed temperature change relative to 1951–1980, illustrating that land surface temperatures have risen substantially faster than the global average over time. While both trends have increased steadily since the mid-20th century, warming over land reached nearly 2°C by 2018, compared to just over 1°C for the global land–ocean average (Shukla *et al.*, 2019).

Figure 2.1 Observed temperature anomalies over land and the global surface, 1850–2024



Note: Annual land and global land–ocean temperature anomalies relative to the 1951–1980 average, based on the Berkeley Earth temperature average. The figure illustrates that land surfaces have warmed substantially faster than the global average because oceans absorb and redistribute much of the excess heat.

Source: (Rohde and Hausfather, 2020)

Across land systems, climate change is intensifying the interaction between heat stress, drought, wildfire, wind, insects and pathogens, thereby reinforcing disturbance feedbacks and increasing the likelihood of ecosystem shifts (Dudney *et al.*, 2025). Such disturbances interact across space and time to shape ecosystems. Yet the combined effect remains poorly understood, particularly under changing climatic conditions (Dudney *et al.*, 2025). Research undertaken in the Mediterranean has shown that the interaction and timing of fire and drought can trigger tipping points, driving abrupt and hard-to-predict ecosystem shifts (Batllori *et al.*, 2019). In parallel, ecosystems already limited by water availability are experiencing more extreme heat, with rising temperatures contributing to more frequent severe heat events that reduce plant productivity and impact net primary production (Jagadish *et al.*, 2021).

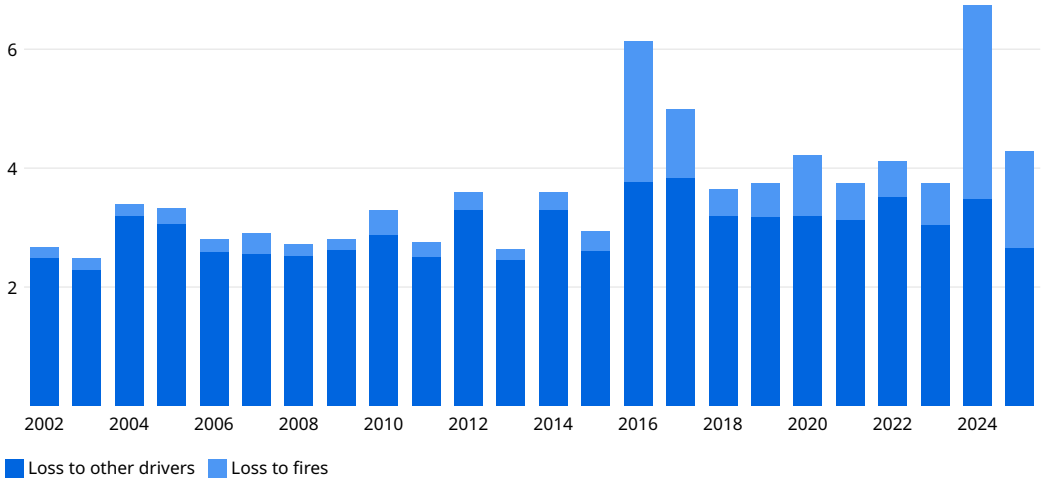
Drought does more than just reduce soil hydration. Studies indicate that the primary response is lower net primary production and forest stand water use, with mature trees becoming more vulnerable to insects and disease during severe or prolonged drought (Hanson and Weltzin, 2000). Wildfires can further intensify impacts. Increasing drought under climate change is expected to alter the frequency and distribution of large, high-intensity fires, while the drought-driven drying of vegetation and fuel loads has been linked to more extreme wildfire events (Ruffault *et al.*, 2018).

Although tropical forest loss remains driven primarily by land-use pressures, climate change is increasingly influencing its dynamics. The Earth loses 18 football pitches of primary tropical rainforest every minute (WRI Global Forest Review, 2026). According to the World Resources Institute (WRI), in 2025, 4.3 million hectares of tropical primary rainforest were lost (WRI, 2026c). This is 46 percent higher than a decade ago and far above the levels needed to meet the 2030 goal of halting deforestation. The good news is that in 2025 tropical rain forest loss decreased 36 percent from a record high in 2024.

> Because climate change is altering disturbance regimes, historical restoration models sometimes fail to function reliably in certain contexts

More significantly, 2025 marked a turning point, with fires accounting for 42 percent of the 25.5 million hectares of global forest loss (WRI, 2026c). Climate change is increasing fire risk by creating hotter, drier conditions, while the fires themselves release large amounts of carbon, thus reinforcing a damaging feedback loop. Although many tropical fires are human caused, the most severe impacts are seen in boreal and temperate regions. Figure 2.2 depicts tropical primary forest cover loss and its drivers between 2002 and 2025. Tropical primary forest loss decreased by 36 percent from 2024 to 2025 following a record-breaking year for extreme fire events.

Figure 2.2 Tropical primary forest loss (Mha), 2002–2025



Note: Tropical rainforest loss slowed in 2025 but fire is a growing threat to forests worldwide. World Resources review (WRI), Global Forest Review.

Source: (WRI Global Forest Review, 2026)

From planting trees to designing adaptive forest restoration systems

Intensifying disturbances are exposing the limitations of conventional restoration approaches and increasing the demand for more adaptive restoration systems. Forest restoration has gained strong momentum, especially under the UN Decade on Ecosystem Restoration. This United Nations (UN) initiative, operating from 2021 to 2030, is a global effort to prevent, halt and reverse ecosystem degradation. It aims to restore ecosystems to combat climate change, enhance biodiversity and secure livelihoods. It also emphasizes the need to expand capacity building and strengthen knowledge exchange among indigenous, traditional, local and scientific communities to better define and share ecosystem restoration best practice (UNEP, 2026b).

Because climate change is altering disturbance regimes, historical restoration models sometimes fail to function reliably in certain contexts. Moreover, forest resilience varies according to its structure, age and management, which influences drought resistance and recovery capacity. Reforestation practices that mimic forestry plantings (dense, evenly spaced planting) are increasingly poorly suited to future conditions, especially with more drought and fire, as they are liable to increase vulnerability by creating forests that are too dense and uniform, and therefore prone to mortality under stress (North *et al.*, 2019).

> Overall, restoration needs to work with natural processes to cultivate diverse climate-resilient forests

Researchers have identified several traps that previous forest restoration efforts have fallen into, namely: overly dense planting that creates greater competition for water; uniform spacing that enables wider fire spread and greater severity; an over reliance on planting instead of natural regeneration; and inadequate follow-up management through methods like thinning (North *et al.*, 2019). They recommend instead employing more a flexible approach that combines clustered and dispersed trees with spacing adapted to local conditions. Spatially patterned restoration approaches concentrate planting or seeding in patches or strips rather than across an entire site, using these treated areas to encourage natural recovery in the surrounding landscape (Shaw *et al.*, 2020). Overall, restoration needs to work with natural processes to cultivate diverse climate-resilient forests (North *et al.*, 2019). However, large-scale tree planting and restoration initiatives are not always successful. Poorly designed planting efforts can reduce biodiversity, increase fire and drought vulnerability or fail altogether when local ecological and social conditions, including community needs and involvement, are not adequately considered (Fleischman *et al.*, 2020). Box 2.1 outlines the common pitfalls associated with large-scale tree planting campaigns.

Box 2.1 When more trees are not better

Most tree-planting fails when it prioritizes scale over suitability and numbers over outcome. The following are the main pitfalls that organizations fall into when launching a tree planting campaign.

Picking either the wrong species or wrong location, or bad seed quality.

Treating planting as the goal rather than the restoration outcome. A focus on the number of trees rather than ecosystem recovery may negate enhanced biodiversity, soil health and climate benefits.

Neglecting to match local community needs with the project. This leads to low participation and inadequate long-term maintenance. Strive to design the approach together with the community (Di Sacco *et al.*, 2021).

Unintended effects. Planting on agricultural land may push farming elsewhere, leading to more deforestation. Large-scale monocultures can strain water resources.

Thinking too short-term. Being too short-term means funding and attention stop after planting has been done. If there is no longer term care, governance or incentives, trees may not survive.

Using a top-down approach. When external organizations design projects without local ownership, local knowledge may not be incorporated, ultimately creating less accountability.

Poor area targeting. If efforts are spread too thinly or channeled into the wrong places, there will be no restoration benefit.

Treating naturally open ecosystems as though they are "degraded forests". Large-scale afforestation in naturally open ecosystems, such as savannas, grasslands, shrublands, alpine systems or drylands, can reduce biodiversity, alter fire regimes, disrupt hydrology and threaten species adapted to open habitats, for example, some bird species. Recent research (von Jeetze *et al.*, 2026) highlights that restoration efforts based solely on increasing tree cover and carbon sequestration (e.g., carbon dioxide removal (CDR)) may unintentionally damage those ecosystems that have evolved with low tree density or periodic fire. Effective restoration therefore requires distinguishing between degraded forests and ecosystems that are naturally open, and aligning interventions with local ecological dynamics rather than universal tree-cover targets.

It is important to remember that trees are a means, but not the end goal. Letting ecosystems recover through natural regeneration (with support) can be better than mass planting. Local engagement and leadership are critical: projects work better when communities participate in the design, reap real benefits and exercise decision-making power. Importantly, restoration must reckon with trade-offs, as different ecosystem areas and objectives do not always align. Therefore, one-size-fits-all planting is not an appropriate strategy. Finally, finance and incentives are important in sustaining benefits.

Source: (WRI Africa, 2025)

Choosing the appropriate restoration methods for diverse environments and social contexts remains difficult. One key challenge is balancing ecological impact with economic constraints. Despite ambitious global forest landscape restoration targets, there is an annual funding gap of more than USD300 billion in what is required to achieve them (Ding *et al.*, 2017). Restoration efforts need to succeed environmentally, but they must also be financially viable and benefit local communities if long-term success is to be assured.

Highly degraded land often requires active interventions like tree planting that are more expensive than natural regeneration. Moreover, natural regeneration itself does not currently have a broad financial model, as it is difficult to finance with carbon markets. One recent study conducted a large-scale review of thousands of studies on forest restoration to identify innovative approaches that meet both ecological and economic demands (Werden *et al.*, 2024). Table 2.1 lists the seven potentially scalable restoration techniques identified, which often outperform conventional methods such as monoculture plantation in restoring vegetation and carbon. Several have specific examples where they have been less expensive and more scalable when aiming to restore native vegetation cover. No single method works everywhere, as effectiveness depends on the local context. Innovative approaches are emerging, but very few studies provide detailed cost-benefit analysis, exacerbating the difficulty of assessing scalability. Additionally, most restoration studies have tested approaches at scales of less than one hectare, further limiting our knowledge of feasible approaches at scale (Shoo and Catterall, 2013). Restoration knowledge has advanced considerably, but larger scale application requires fitting methods to local ecological, climatic and social conditions, as well as adapting them to future disturbance regimes. Box 2.2 discusses the experiences of two of the world's largest restoration initiatives – Africa's Great Green Wall and China's Three-North Shelterbelt Program – illustrating both the challenges of large-scale tree planting and the shift toward a more integrated landscape restoration approach.

Table 2.1 Summary of cost-effective and potentially scalable forest restoration methods

Restoration method	Control/business-as-usual approach	Core benefit
Mixed native species planting	Monoculture plantations	Enhancing species diversity and ecological functions in initial restoration plantings by using a wider range of native species
Economic (profitable) species integration	Plantations using only native species	Including fast-growing economic species (either exotic or native) in initial plantings to harvest them in the short term; adds income incentives for locals
Spatially patterned planting	Plantation-style forestry	Planting in clusters/patches to cut costs and mimic nature
Direct seeding / vegetative propagation	Planting tree seedlings	Using direct seeding or vegetative propagation (i.e., stakes) instead of tree seedlings - cheaper alternatives to planting seedlings
Soil microbiome additions	No live soil or live spores added No biowaste added	Incorporating live soil or live spores to tree seeds or saplings when planting
Biowaste inputs	No biowaste added	Using agricultural waste, compost or sewage to improve soil fertility
Biochar application	No biochar added	Integrating biochar to enhance poor soils and support long-term productivity

Source: adapted from (Werden *et al.*, 2024)

Box 2.2 Beyond tree planting: what large-scale restoration initiatives have taught us

Launched by the African Union in 2007, the original plan for the Great Green Wall was to plant a continuous 15 km wide, 8,000 km long band of trees stretching across 11 countries from Senegal to Djibouti to halt the southward expansion of the Sahara Desert (National Geographic Society, 2025). Over time, however, practitioners came to recognize that a continuous belt of planted trees was poorly suited to many Sahelian landscapes, where water scarcity, maintenance challenges and variable ecological conditions limit tree survival. The United Nations Convention to Combat Desertification (UNCCD) subsequently shifted the strategy to an integrated landscape approach relying on farmer-managed natural regeneration (FMNR), indigenous rainwater harvesting methods such as “half-moons” (semi-circular earth bunds that catch rainwater to recharge the soil) and agroforestry (National Geographic Society, 2025). FMNR has demonstrated that restoration can also be achieved at large scale. In Niger, more than 3 million hectares have been revegetated through FMNR since the 1980s while maintaining agricultural production (Lohbeck *et al.*, 2020).

Similar lessons have emerged from China’s Three-North Shelterbelt Program, often referred to as China's “Great Green Wall.” Launched in 1978 and running until 2050, the Three-North Shelterbelt Program spans 40 percent of China, creating a vast patchwork of forests designed to shield towns, farms and transport links from the advancing Gobi and Taklamakan deserts. It has several faced challenges, including drought-related tree mortality and vulnerable monoculture plantations. In response, China has shifted toward a more targeted restoration approach that combines drought-tolerant vegetation with long-term financing, renewable energy infrastructure and advanced monitoring technologies, raising regional forest coverage from 5 percent to nearly 14 percent by 2026 (Zheng *et al.*, 2026). Innovations include shelterbelts irrigated with saline groundwater and the integration of solar energy infrastructure into restoration efforts.

Africa's Great Green Wall and China's Three-North Shelterbelt Program illustrate a broader shift in restoration practice away from planting trees toward restoring landscapes.. Experience suggests that successful restoration depends on matching interventions to local ecological conditions, as well as community participation, sustained financing and the monitoring of outcomes over time.

Low-tech restoration and solar-powered resilience: a high-impact combination

Across Africa, climate change and land degradation are increasingly reinforcing one another. Unsustainable land use, deforestation and soil erosion have degraded millions of hectares of land, while rising temperatures, shifting rainfall patterns and more frequent droughts and floods are intensifying water stress and reducing agricultural productivity. Today, an estimated 65 percent of Africa's land mass is affected by degradation and drought, impacting more than 400 million people and generating economic losses of over USD 70 billion annually (UNDP Climate, 2025).

African countries are increasingly combining ecosystem restoration with climate adaptation using both low-tech and emerging land management tools. Ethiopia is employing large-scale soil and water conservation techniques such as terraces, trenches, gabions, rainwater harvesting basins, tree planting, composting, the planting of drought resistant crops, and community-led rehabilitation. Senegal is focused on agroforestry and assisted natural regeneration, employing drought-resistant native species, sustainable grazing management, and ecological perimeters to restore degraded drylands and strengthen food security. Rwanda is combining ecosystem restoration with infrastructure upgrades (see Innovation examples). In these three countries, restoration is tied to community governance, climate-smart agriculture and women-led local management systems rather than relying solely on high-tech interventions (UNDP Climate, 2025).

Across African dryland agricultural and agroforestry regions, solar irrigation pumps are becoming increasingly crucial. This is because they improve water access, while reducing dependence on expensive diesel pumps and unreliable rainfall. In drought-prone areas, these pumps help stabilize crop production and support tree establishment in agroforestry and restoration projects. When combined with efficient irrigation methods, such as a drip system, solar irrigation can improve water-use efficiency, reduce pressure on degraded land and enable year-round cultivation and livelihood diversification for smallholder farmers. Within a restoration context, these systems are increasingly viewed not simply as agricultural technologies, but also as tools for landscape resilience in water-stressed regions.

See the *Green Technology Book* Energy edition and EXPO Special edition for more information on solar-powered irrigation systems.

Fire: shaped by ecology, shaping ecology

Fuel reduction and fire treatments, such as thinning, and prescribed fire and fuel breaks, are core fire management strategies. The effectiveness of most landscape-scale fuel treatment scenarios is dependent on method, timing and the treatment location (Ott *et al.*, 2023) . Geographic information system (GIS)-based fire propagation models, vulnerability maps and risk prioritization tools are used to decide where to treat first and how to coordinate fire prevention with restoration. They are also often viewed as essential in helping managers prioritize the spending of a limited budget in those places where intervention is needed most (Gooden and Pritzlaff, 2021; Ott *et al.*, 2023). The *Green Technology Book* Climate disaster edition covers technologies for preventing and suppressing wildfires and strategies for using fire as an ecological tool.

Repeated wildfires significantly increase global soil erosion. The effect of such fires can be the removal of the organic matter and vegetation required to stabilize the soil, making landscapes more vulnerable to erosion, sediment transport and landslides, especially during periods of heavy rainfall following a fire event. Post-fire erosion now accounts for about 19 percent of total

global soil erosion, adding an estimated 5.1 billion tonnes of soil loss each year compared to before the fires had occurred (Vieira *et al.*, 2026). Post-fire ecological effects on land may include severe soil erosion, loss of vegetation cover, reduced soil fertility, altered hydrology, biodiversity decline, increased runoff and flooding, soil water repellency, and long-term changes to the ecosystem structure (Negri *et al.*, 2026). Severe fires may also damage soil microbial communities, reduce nutrient retention, alter water infiltration and increase vulnerability to invasive species (French *et al.*, 2025; Freeman *et al.*, 2007).

However, fire effects depend on ecosystem type and fire intensity; some ecosystems are naturally fire-adapted, and low- to moderate-intensity fires can even support regeneration and nutrient cycling, as well as habitat diversity. Recognizing that fire can be both a disturbance and a natural ecological process, fire management under a more severe fire regime and harsher climate generally relies on two complementary approaches: mitigation strategies that reduce fire impacts and adaptation strategies that improve the capacity of an ecosystem to cope with a changing fire regime. Adaptation strategies focus on vegetation management to reduce fire hazards and increase ecosystem resilience. Restoration techniques include resprouting woody species and increasing the diversity of species in post-fire afforestation/reforestation projects (Ruffault *et al.*, 2018). Post-fire restoration can also involve decisions about whether fire itself can serve as a site preparation treatment. In eastern Madagascar, an experiment comparing burned sites with manually cleared sites found that although seedlings initially survived better and required less weed maintenance on burned plots, trees on manually cleared plots showed greater long-term growth, illustrating trade-offs between different site-preparation approaches (Logan *et al.*, 2025). Box 2.3 discusses normalized burn ratio (NBR) and burned area emergency rehabilitation (BAER), tools used in post-fire restoration.

Box 2.3 Fire rehabilitation and restoration using NBR and BAER

The normalized burn ratio (NBR) is a remote sensing index used to assess fire impacts and vegetation recovery using satellite imagery, and remains a standard method for mapping burn severity, especially using Landsat data. It underpins many national-scale monitoring systems, because it provides a consistent record dating back to the 1980s and is well calibrated against field observations. Satellite-derived NBR products are widely used to support burned area emergency response (BAER) efforts. BAER focuses on employing rapid, post-fire assessments to identify immediate risks such as erosion, flooding and threats to either infrastructure or ecosystems. Satellite-derived products such as NBR provide initial burn severity estimates that help prioritize field assessments and inform soil burn severity maps and response plans.

The Monitoring Trends in Burn Severity (MTBS) project is a US government program run jointly by the US Geological Survey and the US Forest service. It provides consistent, long-term national datasets dating back to 1984 that can be used to analyze fire trends and support large-scale land management. BAER relies on quickly generated maps refined with field data to guide emergency stabilization actions, whereas MTBS uses higher-quality, later-season imagery for more accurate long-term analysis. Although they may map the same fires, different timing and purposes make BAER and the MTBS complementary. BAER supports immediate response, while MTBS enables monitoring, planning and integration into broader ecological and modeling frameworks (MTBS, 2026). As an example, BAER teams were deployed following major California wildfires in 2025 to assess soil burn severity and evaluate risks such as flooding and debris flows, supporting immediate post-fire response and recovery planning.

Measuring ecosystem health at scale

Ecosystem drought resistance is strongly shaped by forest cover, forest quality and management. Remote sensing and *in situ* monitoring track drought resistance, canopy stress and recovery, especially where dense forest or a large area makes field monitoring impossible. A recent study concluded that improved monitoring, especially with L-VOD (L-band vegetation optical depth – a satellite-derived measure of L-band microwave signal absorption by vegetation indicating biomass and canopy water content), may improve estimates of ecosystem resistance and help distinguish between primary and secondary forests and management effects (Xiao

et al., 2023). L-VOD accurately detects such differences, especially in dense forests, in contrast to traditional indices, which struggle in dense forests due to saturation. The same study determined that forests cope with drought better than cropland, with resistance increasing as forest cover grows denser according to satellite indicators. L-VOD has also confirmed that primary(old growth) forests are more drought-resistant than secondary forests, and that older trees are more drought-resistant than younger ones (Xiao *et al.*, 2023).

Indeed, satellites have revolutionized the use of global forest data for monitoring and assessment. However, the majority of data are available at 10 or 30 meter resolution, which is too coarse to discern details of dispersed forest systems, including drylands, alpine and agroforestry forests (Brandt *et al.*, 2026). Now, artificial intelligence (AI) foundation models (general-purpose AI models trained on massive amounts of data) are transforming land and ecosystem monitoring by enabling the rapid, large-scale analysis of satellite and aerial imagery. Their key advantage is scalability. Once trained on massive datasets, they can be adapted to multiple geospatial tasks such as tracking deforestation, measuring tree height, monitoring restoration progress, and detecting subtle land changes more quickly and precisely than traditional methods. They also allow users to generate high-resolution insights without the need to build models from scratch, and can also integrate diverse data sources, including satellite, drone and field data. These models still depend on high quality ground data for calibration and validation, and local communities can play an important role in collecting such data (Danielsen *et al.*, 2021).

Large-scale ecosystem assessment also depends on accessible soil and land analysis tools supporting restoration planning in regions where there is limited analytical infrastructure. Box 2.4 discusses CIFOR-ICRAF's soil–plant spectral technology, which is contributing to restoration planning across Africa.

Box 2.4 Scaling soil intelligence for African restoration

Developed in 2000, the soil–plant spectral technology developed by the CIFOR-ICRAF Soil and Land Health Laboratory in Nairobi (see Proven technologies) has helped lower the cost, time and technical barriers associated with soil analysis and restoration planning across Africa. By replacing slow and expensive laboratory "wet chemistry" methods with rapid spectral diagnostics, it has enabled large-scale standardized soil monitoring in support of restoration, climate adaptation, agricultural planning and carbon measurement. Its integration with satellite data and digital mapping platforms has helped create detailed soil information systems for Africa, improving the ability of governments and practitioners to identify degraded land, target interventions and monitor soil recovery over time. Equally important, the technology has helped build regional scientific infrastructure and local analytical capacity through a network of laboratories and open-access tools. This has reduced dependence on external laboratories and supported more locally grounded environmental management systems.

The WRI's Global Restoration Initiative and Land & Carbon lab have partnered with Meta in developing an AI foundational model called DINOv3 designed to produce the first global map of the tree canopy. This data set was released in 2024 and updated in 2026. Researchers have built ultra-high-resolution global tree canopy maps using the DINOv3 (see Innovation examples) trained on 18 million satellite images via self-supervised learning. By adapting depth-estimation techniques, the model is able to predict tree height from satellite images calibrated with LiDAR data from multiple countries. The dataset uses mainly imagery from 2018 to 2020 and maps trees over 1 meter in height, making it possible to detect single trees at global scale. The 2026 updated model has improved accuracy, reduced bias in tall forests, and is able to capture finer details such as canopy edges and gaps. Because both the data and model are open access, users are able to refine canopy height estimates by training on country-specific or other additional data (Brandt *et al.*, 2026).

AI foundation models are transforming land and ecosystem monitoring by enabling rapid large-scale analysis of satellite and aerial imagery

However, AI foundation model effectiveness relies heavily on data quality. Models may struggle with low-resolution imagery and require strong local ground-truthing. Moreover, like any other AI model, they may amplify biases present when training data. While powerful, they are also not fully autonomous solutions, since human expertise remains essential for validating outputs and interpreting results accurately (Ogden and Mills, 2025).

Fixing the foundations – water and soil

As drought and land degradation worsen, restoration strategies are increasingly being focused on retaining water within landscapes and rebuilding soil moisture systems. Rock detention structures – small, low-tech barriers placed in streams to slow runoff and trap sediment – have been used in heavily degraded drylands, alongside check dams and other structures often adapted from indigenous land management practices. Low-cost, nature-based technologies can restore degraded dryland watersheds through erosion reduction and flood prevention, as well as increase soil moisture and improve sediment retention, often with multiple co-benefits beyond just water management (Gooden and Pritzlaff, 2021).

Landscape rehydration refers to nature-based strategies for restoring the natural water cycle by slowing, spreading and sinking rainwater into the soil rather than letting it run off. Technologies aim to restore local water cycles at the property and catchment scale. Core interventions include permeable structures designed to slow and retain water within a landscape, helping to restore hydrological function and create conditions for vegetation recovery. Leaky weirs and log sills are porous structures composed of rocks, logs or hay bales laid on stream beds or in gullies to lift the water table, recharge floodplains and trap sediment (Andrews, 2026; Minkle, 2021). Contour banks and swales intercept and slow water flow overland and increase infiltration into the soil (University of Sydney, 2026; Wieffering, 2025). Check dams and sieve filters are low-cost barriers made from branches or loose stones that stabilize eroding gullies in arid regions, while also promoting aquifer recharge. Landscape planning approaches that redistribute water across a given terrain provide a broader spatial design framework for improving hydrological function. Keyline design is one such technique that uses topography and strategically aligned cultivation patterns to spread water laterally across a landscape, from wetter valley areas toward drier ridges, in order to slow water movement, increase infiltration and reduce erosion (Tallarico, 2024).

In addition to nature-based rehydration approaches, there are emerging data-driven technologies to manage water and soil resources more precisely. Within the Middle East and North Africa (MENA) region, which faces significant climate challenges, over 86 percent of land is degraded, with only 4 percent under restoration (Katleb, 2025). Here, precision agriculture is emerging as an essential tool for land restoration, beyond its traditional use for improving agricultural efficiency. The precision agriculture market within the MENA region is projected to reach 2.2 billion by 2029, growing at over 11 percent annually (Katleb, 2025). Precision agriculture uses remote sensing, internet of things (IoT) and Al in methods, such as variable rate irrigation and ultra-low energy drip technologies, which can reduce water use by up to 30 percent, while improving soil health through targeted nutrient application. Using global positioning system (GPS)-guided equipment, drones and nutrient mapping, amendments are applied precisely where needed. By applying water, nutrients and soil amendments where they are most needed, these approaches can also support the recovery of degraded soils and vegetation while reducing pressure on scarce water resources.

Landscapes depend largely on vegetation and soil biology to retain moisture. Planting native reeds, sedges and trees along streambanks helps stabilize soil and filter water. Modern rehydration relies on modeling to prioritize interventions. Remote sensing using drones and

satellites tracks changes in vegetation and soil moisture over time. The CReST (Catchment Rehydration Strategic Tool) is a GIS-based modeling platform for identifying the most critical areas within a catchment requiring rehydration, based on landscape dysfunction and potential benefit (Mulloon Institute, 2026). Released in 2024, it helps land managers determine where interventions, such as leaky weirs, revegetation and erosion control structures, are likely to deliver the greatest ecological and hydrological benefit across a given catchment. This tool is helping to shift restoration planning away from isolated site interventions toward landscape-scale management.

Tried and true: low-cost, locally adaptable nature-based methods

Proven, low-cost restoration approaches grounded in ecology and local knowledge have been employed for decades across diverse regions. To tackle heat stress and drought, methods such as FMNR and agroforestry have been widely used to restore degraded land, improve soil fertility, provide shade and increase water retention.

FMNR involves regenerating trees from existing root systems without the need for replanting and is widely practiced across African drylands (World Vision Australia, 2024). It requires minimal equipment beyond basic pruning tools. Agroforestry is a land management approach in which trees and other woody plants are intentionally combined with crops and/or livestock, either simultaneously or sequentially. It enhances productivity, strengthens food security, improves soil and drought resilience, increases carbon sequestration, and can moreover diversify income for smallholder farmers (ICRAF, n.d.).

Integrating trees into farmland has both ecological and economic benefits. Agroforestry systems produce timber, tree-based and non-timber forest products, while also moderating local microclimates, reducing wind and heat stress, increasing infiltration and stabilizing soil moisture. Trees contribute to carbon sequestration not only through aboveground biomass, but also through their deep root systems and the enhancing of soil organic carbon. Agroforestry can reduce dependence on synthetic fertilizers and pesticides by improving nutrient cycling, supporting natural pest regulation and enhancing pollinator habitat.

Agroforestry systems may combine trees with crops (agrosilvicultural), livestock (silvopastoral) or both (agrosilvopastoral), and have been promoted for decades through organizations such as the World Agroforestry Centre across Africa, the Middle East, and South Asia (FAO, n.d.).

From monitoring to prediction: intelligent restoration systems

Forest restoration technologies are increasingly being connected to systems that monitor forests, predict complications and guide restoration. In terms of sensing, constellations of satellites and drones generate continuous high-resolution views of vegetation and disturbance. Newer methods like solar-induced fluorescence from National Aeronautics and Space Administration (NASA) missions reveal real-time photosynthetic stress before visible damage appears. These technologies are being used in concert with *in situ* sensor networks measuring soil moisture and temperature, thereby helping connect what is happening in the forest canopy to soil conditions.

> Forest restoration technologies are increasingly being connected to systems that monitor forests, predict complications and guide restoration

AI-driven geospatial platforms are rapidly advancing from serving as mapping tools to being systems able to predict early drought stress, pest outbreaks and fire risk by combining satellite imagery, terrain and weather data. Restoration intervention technologies are also evolving from smarter planting systems that naturally capture and retain water in dry soil to autonomous

drones that can monitor remote and difficult-to-access landscapes. Rather than relying on a single breakthrough, the technological future will depend on further integrating continuous sensing, AI interpretation, and site-specific interventions to make ecosystems more resilient under heat and drought stress.

These same technologies are also advancing the modeling of disturbance and ecosystem recovery. New remote sensing and geospatial approaches are enabling more precise measurement. Satellite-derived indices (e.g., vegetation and burn severity metrics) use multispectral imagery to assess canopy loss, plant health and post-disturbance recovery over time. Radar and LiDAR data add a structural dimension by capturing biomass loss, canopy height changes and forest complexity. These remote sensing layers are combined with geospatial models of soil erosion and land degradation, which estimate topsoil loss, runoff and landscape instability after an event such as a fire. They help identify not just where the disturbance has occurred, but where recovery is failing or where intervention is most needed.

Tools such as the 3-PG model, Trends.Earth (see Proven technology solutions) and LANDIS-II are being increasingly used to support forest and land restoration planning and monitoring. 3-PG and LANDIS-II simulate forest growth and the impacts of climate, fire and management decisions over time, allowing practitioners to test restoration scenarios before implementation. Trends.Earth, developed by several collaborators under the United Nations Convention to Combat Desertification (UNCCD), uses satellite and geospatial data to monitor land degradation and restoration progress. It operates through a QGIS plugin and cloud-based processing system, allowing users to analyze large datasets without the need for advanced technical infrastructure. It also supports the monitoring of Sustainable Development Goal (SDG) 15.3 relating to land degradation neutrality.

Rather than relying on a single breakthrough, the technological future will depend on further integrating continuous sensing, AI interpretation and site-specific interventions

The current shift is toward per-tree or micro-site intelligence, which allows land managers to make decisions that are more targeted instead of relying on broad averages. Researchers evaluating 12 years of the iLand model (see Proven technology solutions) concluded that individual tree modeling at landscape scale has proven to be a powerful approach for understanding forest dynamics under changing conditions. Researchers found that iLand can robustly simulate how forests respond to interacting drivers such as climate change, fire, wind, pests and management interventions. By tracking individual trees while scaling up to entire landscapes, the model enables a more realistic representation of ecosystem processes and services (Rammer *et al.*, 2024). Researchers also note the imperative to improve modeling of belowground processes and species interactions, and to expand beyond forest ecosystems.

Belowground soil degradation and erosion modeling has taken place since the 1990s using models such as the revised universal soil loss equation (RUSLE); the Water Erosion Prediction Project (WEPP, a process-based model simulating erosion and sediment transport); and more recently SoilGrids, a global high-resolution digital soil mapping system providing spatial soil property data for land analysis (see Proven technology solutions). These tools estimate erosion and various soil properties in support of land management and restoration planning. New underground models, such as SPUN's mapping of mycorrhizal fungal networks, are also beginning to emerge (see the next section on Biodiversity loss and soil decline formore information).

Innovation examples

AI foundation models bring in a new era of restoration finance in Africa

Meta, WRI, Bezos Earth Fund, Land & Carbon Lab



Source: Getty Images/yalax

DINOv3 is an advanced AI foundation model developed by Meta, with support from the World Resources Institute (WRI) and the Land & Carbon Lab, that is helping transform how restoration projects are measured, verified and financed. By analyzing satellite, drone and field imagery, the model can accurately count trees and measure their growth without the need for costly ground monitoring or manual labeling. This technology underpins initiatives like TerraFund, which invests in locally-led restoration projects across Africa. Many local organizations struggle to prove impact and attract funding. TerraFund addresses this by combining grants, loans and equity (typically USD 50k–USD 500k) with training, technical support and AI-powered monitoring. Its monitoring, reporting and verification (MRV) system integrates field data with satellite analysis to track tens of thousands of sites, verifying tree growth and outcomes every six months. When calibrated with data from initiatives such as TerraFund, DINOv3 can achieve roughly 80 percent of the accuracy of traditional forestry measurements, while substantially reducing monitoring costs. This is helping shift restoration finance beyond upfront philanthropy. By reducing the cost of verification and providing more transparent evidence of outcomes, AI-enabled MRV systems can help build investor confidence and channel greater public and private capital toward locally-led restoration projects (Ogden and Mills, 2025; Stam *et al.*, 2026; Bergen, 2025; Brandt *et al.*, 2026; TerraFund, 2026).

Multispectral drones detect species-specific drought stress before it is visible

Swiss Federal Institute for Forest, Snow and Landscape Research (WSL)



Source: Getty Images/Олег Копьёв

Researchers at WSL used drone-based remote sensing to detect and analyze drought stress in forests during the hot summer of 2023. The drones, equipped with multispectral cameras, captured visible imagery alongside wavelengths linked to protective pigments that trees produce under drought conditions. This allowed scientists to identify “invisible” signs of drought stress before damage could be seen in seven native tree species. By repeatedly scanning forest canopies, they tracked changes in leaf color and density, which provided insight into longer-term stress such as defoliation. The technology revealed species-specific responses. Oaks

recovered quickly from a previous hot day, while conifers showed delayed signs of drought stress – but then suddenly died. Researchers are now studying non-native trees to help identify which ones could replace native trees in areas especially susceptible to the impacts of climate change. Compared to traditional field methods, this approach enables more continuous large-area monitoring and precise assessment of how specific species respond to heat and drought (Valsangiacomo, 2026).

Triple wins: restoration, resilience and livelihoods in Rwanda

UNDP and Global Environment Facility (GEF) Least Developed Countries Fund



Source: Photo by Tobias Doering on Unsplash

Rwanda is emerging as a model for integrating ecosystem restoration, climate adaptation and rural development. In the country's *imidugudu* rural settlement areas, climate change has intensified land degradation through irregular rainfall, drought, floods and soil erosion. To address these challenges, the Government of Rwanda launched a project with the support of the United Nations Development Programme (UNDP) and GEF in the Gakenke and Kirehe districts that combines ecosystem restoration with infrastructure upgrades, climate-smart agriculture and sustainable livelihood development. The initiative includes terraces, forest rehabilitation, tree planting, riverbank protection, agroforestry and improved cookstoves to reduce pressure on biomass resources. One of its most innovative features has been the deployment of small-scale solar-powered irrigation systems across 80 hectares in drought-prone Kirehe. Combined with newly constructed terraces, these systems have improved water access, strengthened resilience to drought and significantly boosted agricultural productivity. Since the project began in 2022, more than 5,000 hectares of degraded land has been restored, benefiting over 286,000 people. Farmers have reported tripled harvests due to reduced soil erosion, improved water management and ecosystem restoration efforts, illustrating how integrated land restoration can simultaneously strengthen climate resilience, food security and rural livelihoods (UNDP Climate, 2025).

Drones restore remote landscapes in the Republic of Ireland and Scotland

Precision drone spray



Source: Getty Images/Herbert Pictures

High-capacity agricultural drones like the DJI Agras T25 and DJI Agras T50 are being applied as practical tools to support land restoration in remote environments. Rather than replacing

traditional methods, they expand upon them by enabling reseeding, targeted material application and monitoring on remote, wet or unstable terrain. The core value of the technology lies in precision and access. Drones can distribute seeds or soil treatments without disturbing fragile ground. They reach steep or fragmented sites quickly, and operate safely in conditions that limit human or vehicle access. They also provide repeatable aerial data, allowing teams to track vegetation recovery, establish baselines and generate verifiable evidence for reporting. In Scotland, drones are used within ecology-led programmes to reseed peatlands, stabilize soils and monitor restoration outcomes over time. Likewise in the Republic of Ireland, they are being used for native woodland support and post-disturbance response. This integration ensures that technology supports, rather than drives, restoration decisions (Precision Drone Spray, 2026).

The following collection of technologies is divided into three groups: Proven technologies have been on the market for some time and hence are well tested, Frontier technologies are available but relatively new, while Horizon technologies are close to being available but still under development.

Proven technology solutions

Forest and land use satellite monitoring

Planet Labs



Source: Photo by Abdullah Madawi on Unsplash

Planet Lab's forest monitoring technologies use high-frequency, high-resolution satellite imagery and AI-powered datasets to help users track forest conditions globally. By imaging the Earth daily using its large satellite fleet, Planet enables near-real-time detection of forest cover change, illegal deforestation, harvest boundaries, and disturbances like fires or pest outbreaks. This data supports forest health monitoring using spectral analysis (e.g., vegetation indices), helps assess natural disaster impacts, and supports REDD+ and carbon project measurement, reporting and verification (MRV) by quantifying canopy and biomass change over time. Planet's Forest Carbon products estimate aboveground forest carbon, canopy height and cover at a fine spatial resolution, providing scalable, consistent carbon stock and tree-scale change insights for carbon accounting, reforestation monitoring and land-use planning. Accessible through tools, application programming interfaces(APIs), mosaics and historical archives, these technologies make large-area, consistent forest observation actionable for managers, governments and conservation groups.

- Technological maturity: Proven
- Contracting type: Subscription-based SaaS platform
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Wireless *in situ* soil moisture and temperature sensor system

Soil Scout



Source: Soil Scout

Soil Scout is a soil monitoring technology company that develops fully buried wireless sensors for real-time measurement of soil conditions. Designed for agriculture, sports turf and ecosystem management, its sensors monitor parameters such as soil moisture, temperature, salinity and oxygen directly within the root zone, transmitting data wirelessly to cloud-based dashboards without the need for cabling or surface equipment. The system's patented underground radio technology allows long-term monitoring at depths of up to 2 meters, while minimizing any disturbance to soils and land use activities. By generating continuous "underground weather" data, Soil Scout supports more precise irrigation, soil restoration, drought management, and vegetation health monitoring. Its long battery life (up to 20 years in some models) and maintenance-free design make it particularly suited for large-scale or remote landscape management applications.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: Medium
- Place of origin: Finland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Drone for forestry

Eagle NXT



Source: Getty Images/Maksim Safaniuk

Eagle NXT provides forestry drone solutions that use unmanned aircraft equipped with advanced sensors (red, green, blue (RGB), multispectral, thermal, and LiDAR) to support forest management and monitoring. The company's systems capture detailed aerial data in order to map forest structure, tree health and canopy cover, estimate biomass and carbon stocks and detect stress, disease or pest damage early. By combining accurate geospatial imagery with analytics software, these drones help forestry professionals assess regeneration success, inventory timber resources, plan harvests and monitor changes over time with greater speed and safety than ground surveys. The technology also supports risk assessment by identifying fire hazards, mapping fuel loads and tracking post-disturbance recovery. Eagle NXT's workflow integrates automated flight planning, reliable data capture and easy-to-interpret outputs, enabling more informed decision-making for sustainable forest management, conservation and restoration.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

GeoAI platform

Picterra



Source: Picterra

Picterra is a GeoAI platform that turns satellite and aerial imagery into continuous, plot-level intelligence on land and vegetation. Restoration and conservation teams use it to map vegetation and land cover, track change over time, identify invasive species, assess habitats, measure above-ground carbon, and verify outcomes such as tree survival, canopy growth, and erosion. Machine learning models can be adapted to specific species, landscapes, and project types rather than generic global datasets. It combines drone, satellite, and environmental data, and analyzes large areas repeatedly over time. Because every result is georeferenced and traceable to its source, Picterra helps projects produce the independent, verifiable evidence funders, certification schemes, and regulators require.

- Technological maturity: Proven
- Contracting type: Subscription-based SaaS platform
- Technology level: High
- Place of origin: Switzerland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Smart plant cocoon planting device

Groasis



Source: Getty Images/FSTOPLIGHT

Groasis Waterboxx® is a patented ecological planting device – essentially a smart plant cocoon – designed to help trees, shrubs and vegetables survive and grow in dry, degraded or eroded land without irrigation. It collects rainwater and condensation in its reservoir and releases small amounts of water into the soil through capillary action, thus stabilizing temperature and moisture around young roots. This encourages deep root systems, reduces evaporation and significantly raises survival rates while lowering water use and cost compared with traditional irrigation. Groasis has deployed its Waterboxx® and biodegradable Growboxx® plant cocoons in dozens of countries over two decades to restore ecosystems, fight desertification and support agroforestry. Its technology has demonstrated ~90 percent survival rates using up to 90 percent less water than conventional methods.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: Medium
- Place of origin: The Kingdom of the Netherlands
- Availability: Worldwide
- Contact: WIPO GREEN Database

AI-powered tree intelligence platform

SeeTree



Source: SeeTree

SeeTree is an AI-powered agriculture optimization platform that digitizes farms, orchards, plantations, and agricultural assets at scale by integrating imagery and data from drones, satellites, field operations, and other sources. The platform delivers highly granular insights on crop inventory, health, biomass, productivity, and field performance. Through advanced AI, computer vision, and predictive analytics, SeeTree enables growers and agribusinesses to improve yield forecasting, optimize harvest planning, manage replanting programs, detect stress, pests, and diseases early, and drive more efficient field operations. Although originally focused on orchards and high-value crops, SeeTree's per-tree monitoring, GIS mapping and predictive insights are applicable to forest health monitoring, restoration planning and carbon stock estimation over vast landscapes.

- Technological maturity: Proven
- Contracting type: Subscription-based SaaS platform
- Technology level: High
- Place of origin: Israel
- Availability: Worldwide
- Contact: WIPO GREEN Database

Global digital soil mapping system using machine learning

International Soil Reference and Information Centre (ISRIC)



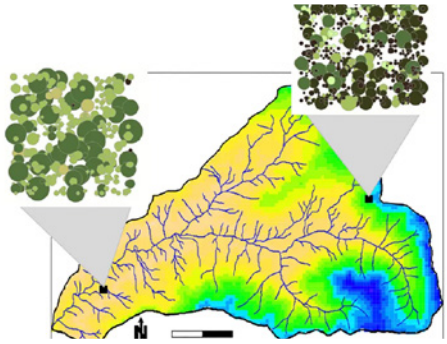
Source: International Soil Reference and Information Centre

SoilGrids is a global digital soil mapping system developed by ISRIC – World Soil Information that uses machine learning to model the spatial distribution of soil properties worldwide. It combines thousands of soil profile observations from the WoSIS database with hundreds of environmental covariates including climate, land cover and terrain data to generate high-resolution predictions. The platform provides maps of key soil characteristics (e.g., soil organic carbon, texture, pH, bulk density and nutrients) at 250-meter resolution across multiple depth layers, along with pixel-level uncertainty estimates. By delivering consistent, spatially explicit soil data at the global scale, SoilGrids supports land-use planning, restoration design and environmental modeling.

- Technological maturity: Proven
- Contracting type: Open access
- Technology level: High
- Place of origin: Kingdom of the Netherlands
- Availability: Worldwide
- Contact: WIPO GREEN Database

Forest landscape model for ecosystem dynamics (disturbance)

Technical University of Munich



Source: Technical University of Munich

iLand is a process-based, individual-tree forest landscape model designed to simulate ecosystem dynamics across large spatial and temporal scales at the individual tree level. It represents forests as complex adaptive systems, explicitly modeling the growth, competition, mortality and regeneration of individual trees and how these interactions scale up to landscape-level patterns.
Using a multi-scale framework, the model integrates fine-scale physiological processes, such as photosynthesis, carbon allocation, and resource competition, with broader drivers including climate, soil conditions and disturbance regimes like fire, wind and pests. By simulating both continuous processes (growth, carbon cycling) and discrete disturbances, iLand can project forest development over decades to centuries and across very large areas. Its spatially explicit design captures how structure, composition and resilience emerge from interactions between individual trees and the environment, making it a powerful tool for evaluating climate impacts, disturbance effects and restoration or management strategies at landscape scale.

- Technological maturity: Proven
- Contracting type: Open source
- Technology level: High
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Process-based forest growth modelling system

University of British Columbia



Source: Photo by Kristaps Ungurs on Unsplash

3-PG (Physiological Principles Predicting Growth) is a process-based forest growth modelling system used to simulate how forests grow under different climate, soil and management conditions. Developed in the late 1990s, the model estimates forest productivity, biomass, carbon storage, water use and tree growth by combining weather, soil moisture, radiation and physiological processes such as photosynthesis. It is widely used in forestry, restoration and climate research, because it requires relatively simple input data, while still producing detailed predictions. Variants such as 3-PGS and 3-PGmix integrate remote sensing and GIS data or model mixed-species forests, allowing users to assess climate change impacts, restoration scenarios and long-term forest management outcomes across landscapes.

- Technological maturity: Proven
- Contracting type: Open source
- Technology level: High
- Place of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Earth observation-based land degradation monitoring tool

Conservation International, Lund University, NASA, GE, University of Bern, University of Colorado, USDA, USAID, University of California – Santa Barbara, University of North Carolina – Wilmington, and Brown University



Source: Photo by Zoshua Colah on Unsplash

Trends.Earth is an open-source geospatial monitoring platform developed under the United Nations Convention to Combat Desertification (UNCCD) to help countries and land managers assess land degradation and restoration progress. This tool combines satellite imagery, remote sensing, climate and soil data to track indicators such as vegetation productivity, land cover change and soil organic carbon. It operates through a QGIS plugin and cloud-based processing system, allowing users to analyze large datasets without the need for advanced technical infrastructure. Trends.Earth supports monitoring of Sustainable Development Goal (SDG) 15.3 on land degradation neutrality and helps governments identify degraded areas, prioritize restoration efforts and evaluate the effectiveness of interventions over time. Because it relies on globally available Earth observation data, it enables relatively low-cost, standardized monitoring across different ecosystems and regions.

- Technological maturity: Proven
- Contracting type: Open source
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier technology solutions

GPS-independent navigation and geolocation software suite for autonomous drones

Vantor



Source: Photo by Quentin Menini on Unsplash

RAPTOR is a GPS-independent navigation and geolocation software suite for autonomous drones, enabling precise operations when GPS signals are unavailable. Using only a drone's onboard camera and Maxar's 3D terrain data, it enables navigation, positioning and ground coordinate extraction when GPS signals are unavailable. The suite includes tools for drone positioning, video geo-registration and real-time coordinate extraction from video feeds. It can operate day or night, including in remote or heavily forested environments where GPS coverage may be unreliable.
The technology can support ecosystem restoration and environmental monitoring by enabling drones to map terrain, monitor vegetation change, assess erosion and water flow, and capture georeferenced imagery in difficult environments. Its GPS-independent capabilities may be useful in mountainous terrain, dense forests, deep valleys, and other environments where terrain or vegetation can reduce GPS accuracy and reliability.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Multispectral camera for forest health mapping

Wingtra



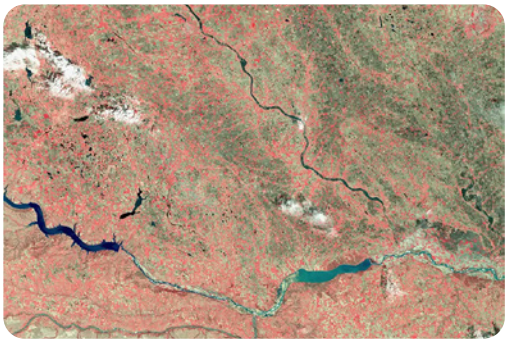
Source: Photo by Scott Blake on Unsplash

The MicaSense RedEdge-P is a high-resolution multispectral and panchromatic camera for drones that captures five narrow spectral bands (blue, green, red, red-edge, near-infrared) plus a high-detail panchromatic band in one flight. This allows the creation of RGB and vegetation index maps, such as NDVI and NDRE, which indicate chlorophyll levels and plant vigor. In forestry, these maps help assess tree health, detect stress or disease, monitor species variation and quantify canopy conditions over large areas. Its high spatial resolution and efficient data capture support detailed forest health monitoring and change detection when flown on a mapping drone like the WingtraOne.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: Switzerland
- Availability: Worldwide
- Contact: WIPO GREEN Database

AI-powered satellite forest monitoring platform

Salo Sciences



Source: Photo by USGS on Unsplash

The Salo Science Forest Observatory is a satellite-based forest monitoring system that uses high-resolution satellite data and AI algorithms to map forest structure and health at fine scales – including canopy height, canopy cover, vertical layers, dead trees, fuel density and vegetation moisture indicators. It turns raw satellite imagery into ecological metrics that show how forests are changing over time. For wildfire risk, it integrates fuel-load mapping (e.g., dry versus green vegetation), weather, topography and infrastructure to show where a forest is most vulnerable and help estimate hazard patterns and fire behavior. Because drought stress influences vegetation moisture and fuels, the same data layers can highlight areas under drought pressure and track how conditions evolve.

- Technological maturity: Frontier
- Contracting type: Subscription-based SaaS platform
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

AI-driven forest analytics platform

CollectiveCrunch



Source: Getty Images/Sergey Kuznetsov

CollectiveCrunch provides AI-driven forest analytics to help managers monitor ecosystem health, track pests like bark beetles, assess biodiversity, and update forest inventories using remote sensing and machine-learning models. Its bark beetle product analyzes satellite (and LiDAR/other) data to detect early signs of infestations invisible to the human eye and map damage severity so interventions can be planned sooner. It also supports near-real-time stress monitoring, helping mitigate pest impacts and protect forest resilience. The biodiversity index quantifies habitat value and deadwood presence, highlights high-value conservation areas, and gives management recommendations to improve ecological diversity. The forest inventory solution delivers annual tree stand metrics (species, volume, height, carbon stocks) on fine grids, replacing infrequent field surveys. All products rely on AI models trained on satellite and contextual data, integrating with GIS and management systems.

- Technological maturity: Frontier
- Contracting type: Subscription-based SaaS platform
- Technology level: High
- Place of origin: Finland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Multi-parameter soil sensor

Delta-T Devices



Source: Delta-T Devices

The WET150 is a research-grade, multi-parameter soil sensor designed for the continuous monitoring of root-zone conditions in restoration and land management systems. When buried, it simultaneously measures soil moisture, temperature and electrical conductivity (EC), providing insight into water availability, thermal conditions and nutrient status. Its ability to estimate pore water conductivity (ECp) makes it particularly valuable for understanding plant-accessible nutrients under changing environmental conditions. Built for long-term field deployment, the sensor is rugged, low-power and fully buriable, with stable performance across varying salinity and temperature ranges. Using a digital SDI-12 interface, it integrates easily into sensor networks, enabling multiple devices to connect to a single data logger for scalable monitoring. With onboard processing for data correction and averaging, the WET150 delivers high-quality, consistent measurements, supporting applications such as restoration monitoring, precision irrigation and environmental monitoring, reporting and verification (MRV) systems.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: Medium
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Bio-based soil remediation material

Green Technology Bank (Shanghai) Agricultural Technology Co., Ltd.



Source: Green Technology Bank (Shanghai) Agricultural Technology Co., Ltd.

Special Biomass Thickener (SBT) is a bio-based soil remediation material designed to restore degraded and saline soils, while improving long-term productivity. Composed of natural biomass-derived components including cellulose, lignin, chitin, algae and other organic materials, SBT enhances soil aggregation, aeration and water retention, regulates soil pH, reduces salinity, and promotes beneficial microbial activity. Supported by a full-chain design encompassing "material R&D - process optimization - equipment adaptation - method innovation," this technology integrates four customized core material systems to reconstruct desert soil structure, optimize water and fertilizer, activate soil life, and consolidate remediation effects. This approach enables the rapid formation of arable soil layers, achieving a comprehensive breakthrough from soil remediation to the construction of sustainable ecosystems. The technology has been successfully applied in saline-alkali soil remediation and desertification control at the edge of the Taklamakan Desert in Xinjiang, where SBT-based materials have been used to rehabilitate degraded desert and Gobi land into productive farmland. SBT was also deployed through a WIPO GREEN Acceleration Project, demonstrating its potential for broader international application.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: Medium
- Place of origin: China
- Availability: China, United Arab Emirates
- Contact: WIPO GREEN Database

Cloud seeding and weather modification technology platform

Rainmaker



Source: Getty Images/Popsuievych

Rainmaker is a cloud-seeding and weather-modification technology platform that modernizes the long-established process of cloud seeding by combining advanced radar, unmanned aircraft (drones) and weather-awareness systems to more precisely stimulate precipitation. Cloud seeding can trigger increases in rainfall or snow, which over time helps recharge aquifers, restore stressed ecosystems, alleviate drought and reduce wildfire risk by increasing landscape moisture. The company embeds scientific research and monitoring to validate results and guide operations responsibly. Its drone component and radar systems aim to make cloud seeding more efficient and responsive to real-time atmospheric conditions, while providing data to validate outcomes. The company operates primarily across the US West and works with water agencies and agricultural clients to address water scarcity and ecosystem stress.

- Technological maturity: Frontier
- Contracting type: For service contract
- Technology level: High
- Place of origin: United States
- Availability: United States
- Contact: WIPO GREEN Database

Environmental intelligence platform

Amini AI



Source: Photo by Tim Oun on Unsplash

Amini is an African AI and geospatial intelligence company that builds environmental data infrastructure for Africa and the Global South. The platform combines satellite imagery, AI, machine learning and ground-level environmental data to generate high-resolution insights on land use, drought, soil health, water availability, agriculture, deforestation and climate risks. Amini's technology is designed to address the severe scarcity of reliable environmental data across many African regions, where limited monitoring infrastructure has historically constrained climate adaptation, restoration planning, insurance, and investment decisions. Its platform integrates Earth observation data, local datasets and AI-driven analytics into accessible tools for governments, businesses, insurers and smallholder farmers. By building locally-calibrated environmental intelligence systems, Amini aims to strengthen climate resilience and support data-driven restoration and sustainability planning across the continent.

- Technological maturity: Frontier
- Contracting type: For subscription
- Technology level: High
- Place of origin: Kenya
- Availability: Africa and the Caribbean
- Contact: WIPO GREEN Database

Biochar from wildfire fuels/residue

Charm Industrial



Source: Charm Industrial

Charm Industrial uses fast pyrolysis to convert excess forest biomass into bio-oil that is injected underground for permanent carbon storage. By processing woody residues that would otherwise decompose or be burned, the system reduces wildfire fuel loads, while preventing carbon emissions and smoke pollution. Charm deploys mobile pyrolysis units in partnership with forest managers, communities and wildfire mitigation groups, enabling the on-site processing of surplus biomass in fire-prone areas. This approach helps reduce wildfire risk, improve air quality and create a productive use for low-value forest residues, while supporting long-term carbon removal. The company has expanded its efforts through collaborating with organizations that include the National Forest Foundation and forestry partners in the western United States.

- Technological maturity: Frontier
- Contracting type: For service contract
- Technology level: High
- Place of origin: United States
- Availability: Northern America
- Contact: WIPO GREEN Database

AI + tree-planting robot

Eason Intelligent Equipment (Beijing) Co., Ltd.



Source: Getty Images/ArtMarie

The AI + Tree-Planting Robot is an autonomous restoration system designed to improve the speed, precision and scalability of afforestation and desertification control. The platform integrates AI, autonomous driving, machine vision and 5G connectivity to automate tree planting when navigating challenging terrain. The system supports a full restoration workflow through an integrated planting–management–carbon sink (PMCS) approach, combining precision planting with digital forestry management and carbon sink monitoring. By reducing labor requirements and enabling more efficient deployment in remote or degraded landscapes, the technology aims to accelerate large-scale ecological restoration, while generating digital data that support long-term forest management and carbon accounting. It illustrates the growing convergence of robotics, AI and ecosystem restoration for climate resilience and sustainable land management.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: China
- Availability: China
- Contact: WIPO GREEN Database

Horizon technology solutions

Autonomous quadruped tree-planting robot

Trovador



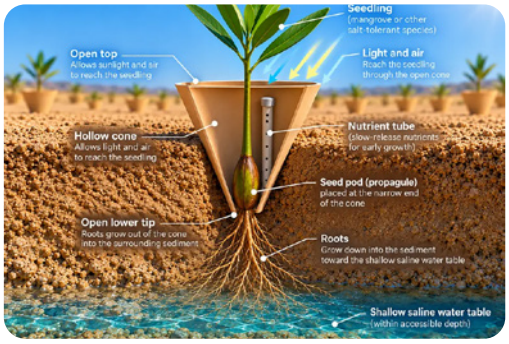
Source: Trovador

Trovador is an autonomous quadruped tree-planting robot designed to restore forests in steep, wildfire-affected and difficult-to-access terrain where conventional machinery is unable to operate. Using AI, onboard sensors and computer vision, the robot identifies suitable planting microsites, navigates slopes of up to 45°, and plants native seedlings with precise depth and root placement to improve survival rates. Each planted tree is GPS-tagged and logged, enabling digital monitoring and MRV (monitoring, reporting, verification)-ready reporting through a cloud-based platform. The system also incorporates mission-planning software that optimizes planting trajectories using terrain, hydrology and other environmental data. Trovador represents a new generation of autonomous restoration robotics that aims to increase the speed, precision and scalability of post-fire reforestation, while reducing labor requirements and minimizing soil disturbance.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: Portugal
- Availability: Under development
- Contact: WIPO GREEN Database

Passive planting system for heat- and drought-stressed land

Carbon Blue Solutions Limited LLC



Source: Carbon Blue Solutions Limited LLC — OasisCone™

The OasisCone™ is a patent-pending passive planting system designed to support mangroves, halophytes, and saline-tolerant vegetation in arid and saline environments without irrigation or freshwater inputs. The cone is installed with its base below the soil surface, allowing plant roots to access moisture in shallow subsurface saline sediments while shielding young plants from heat, wind and surface salt accumulation. Its semi-enclosed structure reduces evaporation and provides a buffered microenvironment during early plant development. A biodegradable nutrient tube can deliver nutrients directly to the root zone, reducing the need for repeated fertilization. By facilitating plant establishment under water-limited conditions, the technology aims to support vegetation recovery and ecosystem restoration in areas exposed to extreme heat, drought and salinity. The technology is currently in pre-pilot development, with the developer seeking partners for its first field deployment.

- Technological maturity: Horizon
- Contracting type: For collaboration/ partnership
- Technology level: High
- Place of origin: United States
- Availability: Under development
- Contact: WIPO GREEN Database

2.2 Biodiversity loss and soil decline

In its most recent global assessment, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) highlighted a severe decline in biodiversity: about three-quarters of the Earth's land surface has been significantly altered (IPBES, 2019). Climate change is a major driver of biodiversity loss, while ecosystem degradation weakens nature's ability to regulate GHG emissions and mitigate extreme weather events.

While biodiversity loss and soil degradation are often discussed as separate challenges, they are in fact tightly interconnected expressions of a deeper breakdown in ecosystem function. Above ground, biodiversity loss and declining habitat complexity reduce ecosystem resilience and productivity. Below ground, the decline in soil structure, organic carbon and microbial life undermines the foundation that sustains plant growth and ecosystem stability. Climate change further accelerates soil degradation through warming, drought, altered rainfall patterns and wildfires, contributing to erosion, organic matter loss and disrupted nutrient cycling (Mbabazize *et al.*, 2025).

Climate change is already shifting terrestrial species distribution and phenology, raising the risk of localized extinction, especially when it interacts with land use change (Warren *et al.*, 2021). Alongside climate change, land-use pressure contributes to habitat fragmentation and heightens extinction risk (He *et al.*, 2019). Addressing these challenges requires approaches that seek to restore ecosystem function as an integrated whole rather than treating biodiversity and soil as separate domains.

> As biodiversity and soil health decline, ecosystems become less able to recover from disturbance, more vulnerable to future climate shocks and increasingly prone to long-term degradation

In fact, the link between soil health and biodiversity is well established. Related interactions are being quantified through studies of soil microbial processes and carbon cycling. The loss of soil diversity has been found to reduce soil carbon respiration by 27 percent and plant tissue decomposition by 18 percent. Loss of microbial biodiversity has also been shown to reduce soil carbon respiration by 41 percent (de Graaff *et al.*, 2015). A recent 12-year study found that warming affects soil carbon in different ways depending on moisture: soil carbon is reduced under drought conditions (–12.2 percent), but increases under wet conditions (+6.7 percent). This effect is driven by changes in microbial activity and community composition, in particular the loss of mineral-associated carbon during drought. The inclusion of microbial processes in modeling leads to significantly improved predictions, evidence of their key role in soil carbon–climate feedback (Guo *et al.*, 2026). Mycorrhizal fungi are particularly important within microbial systems, because they form a symbiotic relationship with plants and play a central role in nutrient exchange. Two major groups are arbuscular *mycorrhizal fungi*, commonly associated with crops and grasslands, and *ectomycorrhizal fungi*, which are often linked to forest trees. Box 2.5 highlights how new mapping of mycorrhizal fungi is reshaping our understanding of soil biodiversity, climate resilience and conservation priorities.

Box 2.5 Mycorrhizal fungi – a new world mapped underground

Mycorrhizal fungi play a foundational, but often overlooked, role in linking biodiversity, soil health and climate, acting as underground networks that regulate nutrient flow and drive significant carbon storage (~13 billion tonnes of CO_2annually). New high-resolution mapping carried out by SPUN in its first representation of global mycorrhizal biodiversity shows global distribution is strongly shaped by environmental factors – especially climate – rather

than simply by plant diversity (SPUN, 2026) (see Frontier technology solutions). For example, warmer temperatures and higher evapotranspiration tend to increase arbuscular mycorrhizal fungal diversity, but decrease ectomycorrhizal diversity, meaning climate change will likely shift fungal communities in different directions across ecosystems. Biodiversity hotspots belowground often do not align with aboveground plant richness, highlighting a major blind spot in current conservation strategies. With over 90 percent of mycorrhizal diversity hotspots unprotected, these findings underscore the need to integrate soil biodiversity into restoration, conservation and climate frameworks, as disruptions to these networks can accelerate ecosystem degradation and weaken carbon storage capacity (SPUN, 2026).

For restoration projects, however, monitoring should focus on a practical set of affordable and standardized soil and biodiversity indicators that can be measured consistently at scale (Toro *et al.*, 2025).

As biodiversity and soil health decline, ecosystems become less able to recover from disturbance, more vulnerable to future climate shocks and increasingly prone to long-term degradation. Over time, these changes can lessen carbon storage capacity and, in some cases, transform ecosystems from carbon sinks into a net source of emissions.

Wildlife and habitat under climate stress

Wildlife corridors are impacted by climate change. As temperatures rise, low-lying corridors can become too hot for species to pass through. The destination at the end of a corridor may no longer be suitable for the species it was intended to protect. Fluctuations in rainfall and snowpack can reduce water availability at critical stopover points, such as riparian zones, which provide water, food and shelter during movement. And animals often begin migration based on environmental cues that may become misaligned with resource availability.

Climate change is also altering migration timing, breeding cycles and species distribution. For instance, many birds and mammals are adjusting their breeding season to match warmer conditions, while some insects are expanding into new regions as climates shift (Husson University, 2025). These changes can disrupt timing, with pollinators arriving after peak flowering has ended, for example. In the Arctic, caribou are shifting migration timing and experiencing greater stress due to insect swarms and erratic climatic conditions. Reindeer numbers have declined sharply from 5.5 million to 1.9 million over recent decades, and could have declined by as much as 60 percent worldwide by 2100, if emissions continue unchecked (Husson University, 2025).

Habitat loss is driven in part by climate change, but also by human activity exerting pressure on ecosystems. When ecosystems become fragmented, species lose habitat and resources, disrupting food webs and ecological balance. Conservation efforts to protect and restore habitats include protected areas and wildlife corridors (Sayo, 2026). As climate change and habitat fragmentation alter species movement, conservation efforts increasingly rely on technologies able to monitor wildlife movement, identify ecological barriers and support connectivity planning. Technologies for monitoring wildlife corridors help scientists and planners understand, predict and support how species move through a changing landscape. By combining spatial data, ecological modeling and decision-support systems, they enable the identification of wildlife corridors and ecological barriers.

GPS telemetry, satellite tracking systems such as the ICARUS Initiative, camera traps and remote sensing platforms allow researchers to track changes in migration patterns and habitat usage, as well as species range shifts under climate stress. These data are integrated into GIS-based connectivity and predictive movement models, such as Linkage Mapper and Circuitscape, which help identify corridors, ecological bottlenecks and priority areas across fragmented landscapes. Linkage Mapper identifies potential habitat corridors and least-cost pathways between important ecosystem areas by analyzing how difficult different landscapes are for species to traverse. Circuitscape complements this by applying circuit theory in order to model multiple potential movement routes and helping identify ecological “pinch points” and barriers.

> As climate change and habitat fragmentation alter species movement, conservation efforts increasingly rely on technologies able to monitor wildlife movement, identify ecological barriers and support connectivity planning

At a finer scale, AI-enabled camera trap systems, such as Wildlife Watcher and Spoor (see Frontier technology solutions), are increasingly being employed alongside satellite data, acoustic monitoring and environmental DNA analysis. Wildlife Watcher uses embedded AI models to process species recognition directly on remote camera systems in real time.

Rebuilding ecosystems with agroforestry and biochar

Agroforestry, as mentioned in the section above on Heat, drought and disturbance, helps restore and bolster ecosystem function and soil health through the joint cultivation of trees and crops. It enhances soil and crop productivity and supports diverse livelihoods. Agroforestry is particularly effective, because its integration of trees with crops restores soil structure and nutrients through leaf litter and root systems. It also creates more diverse habitats, supporting higher levels of biodiversity than conventional monoculture systems (FAO, n.d.; ICRAF, n.d.).

Complementary soil restoration approaches can further enhance these benefits, particularly in degraded landscapes. Biochar is a carbon-rich material created by heating organic matter in low-oxygen conditions and possesses properties that enhance soil structure, improve nutrient retention and support microbial activity (Vijay Kumar, 2019). In addition to its use on agricultural land, biochar can also support land restoration and help combat soil decline. Biochar can mitigate compaction, improve soil aeration and water retention, raise pH and support microbial activity, while also serving as a long-term carbon sink. Rebuilding soil organic matter is particularly important for long-term ecosystem health, including native vegetation and pollinator habitat restoration. Effectiveness depends on soil type, climate and biochar properties, but studies show it can significantly improve nutrient levels and increase plant growth on disturbed lands (USFS, 2024).

In dryland areas, biochar's porous structure creates protected microhabitats ("refugia") for soil microbes. It increases microbial biomass by 30–60 percent and reshapes microbial communities toward phosphorus-solubilizing and nutrient-cycling organisms, while also reducing GHG emissions, including ~18 percent lower N_2O emissions in some semi-arid systems (Waheed *et al.*, 2026). However, increases in microbial biomass do not always translate immediately into greater enzyme activity nor nutrient cycling, and these functional responses can lag behind biomass gains. Biochar can also alter microbial communities in a manner that varies according to soil type: in alkaline soils, for example, it may stimulate ammonia-oxidizing archaea and increase nitrification and nitrate leaching (Waheed *et al.*, 2026).

> Biochar is widely considered one of the most mature and scalable carbon dioxide removal technologies currently available

Biochar varies widely depending on feedstock and production method: agricultural-waste biochar mainly improves soil organic matter and water retention; forestry-residue biochar enhances soil structure and infiltration through high porosity; and manure-based biochar adds

nutrients to poor soil. It can also help remediate contaminated soil by adsorbing heavy metals and pollutants. Yet challenges remain, including inconsistent biochar properties, limited long-term research, farmer knowledge gaps and high upfront production and application costs, especially for small-scale producers (Vijay Kumar, 2019).

Biochar is widely considered one of the most mature and scalable carbon dioxide removal (CDR) technologies currently available. It has a high technology readiness level (TRL 8–9), meaning it is already deployed at a commercial scale (Chiaramonti *et al.*, 2024). This is because pyrolysis converts biomass carbon into highly stable carbon forms able to provide durable carbon storage for centuries. Its permanence can now be measured and verified using analytical methods and third-party MRV systems, making it suitable for carbon credit markets and national climate accounting (see the next section on Scaling land-based restoration for more information on biochar carbon removal credit mechanisms; also the *Green Technology Book* Mitigation edition).

From species counts to ecosystem intelligence

A shift is underway from sparse, manual surveys toward continuous, multi-layered intelligence that captures above and belowground dynamics. Molecular tools like eDNA – commercialized at scale by groups such as NatureMetrics – are making biodiversity measurable in a standardized form by detecting entire communities (including microbes) within soil and water without the need for direct observation. This is being combined with AI-driven platforms that mix bioacoustics, camera traps, satellite data and field inputs into biodiversity indices.

High-resolution 3D "digital twins" of ecosystems are emerging able to capture habitat complexity and not just list species. Predictive geospatial models are identifying ecosystems at risk before degradation occurs rather than documenting loss after the fact.

> In short, biodiversity technologies are evolving from counting species to continuously assessing ecosystem function

Attention is shifting below ground to restoring soil biology (e.g., fungal networks), stabilizing erosion and rebuilding native seed supply chains. In short, biodiversity technologies are evolving from counting species to continuously assessing ecosystem function. This shift toward ecosystem-scale intelligence is being enabled by a rapidly expanding monitoring infrastructure combining satellite, drone and field-based sensing technologies. Remote sensing tools use vegetation indices to detect those ecological changes relevant to biodiversity. Widely used indices such as the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI) and the Soil-Adjusted Vegetation Index (SAVI) measure vegetation health and cover (Melnyk and Brunn, 2025; Ekaputri *et al.*, 2024; Yan *et al.*, 2025). eDNA analysis (discussed more in detail in Chapter 3, Oceans) augments this by allowing the non-invasive detection of species presence and distribution (Sayo, 2026).

These technologies are being combined with machine learning, AI and cloud computing. Drones, hyperspectral imaging, radar, laser scanning and CubeSat constellations now enable the real-time tracking of habitat quality, species distribution and habitat connectivity, providing an early warning system for biodiversity loss (Zhidebayeva *et al.*, 2025). However, as AI becomes more integrated into biodiversity monitoring and decision-making, concerns remain around bias, surveillance, loss of local expertise and unequal control over ecological data. Box 2.6 explores these challenges in greater detail.

Box 2.6 AI and biodiversity: innovation with caution

As mentioned in the next section on scaling land-based restoration, caution is needed despite the urgent need to find solutions that reverse the biodiversity crisis. AI could serve to improve biodiversity conservation by handling complex and massive datasets, identifying patterns, scaling analysis and improving predictions and decision-making. Traditional methods of processing such diverse environmental data are often slow and limited. However, biodiversity systems are highly complex and interconnected with human systems, and the application of AI also introduces ethical, social and environmental risks that require careful oversight.

AI may, for example, be used to replace human expertise, thereby eroding field skills and ecological knowledge in the long term. Moreover, models trained on biased data sets may result in misaligned decisions. Tracking technologies could also be misused by poachers or other malign actors, while unequal control over biodiversity data may serve to reinforce existing global power imbalances, particularly when ecological data from the Global South is collected and used primarily by institutions in the Global North. AI may also divert funding away from fieldwork and locally-grounded conservation efforts. Its effectiveness therefore ultimately depends on human oversight, ethical design and a sensitivity to local context, including continued on-the-ground ecological work (Reynolds *et al.*, 2025).

New hyperspectral systems are central to this shift toward ecosystem-scale biodiversity monitoring. This is because they are able to detect subtle differences in vegetation composition, stress and habitat condition across a large area. For example, EnMAP (Environmental Mapping and Analysis Program) is a German Earth observation satellite designed to monitor ecosystems through advanced hyperspectral imaging. Launched in 2022, it captures data across over 200 narrow spectral bands from the visible to the shortwave infrared range compared to the typically between five and seven much broader multispectral bands used by most Earth observation satellites. Having a spatial resolution of about 30 meters and a swath width of ~30 km, EnMAP is able to map large areas, while detecting subtle structural differences within an ecosystem. Its high spectral sensitivity enables scientists to identify species traits and track changes (EnMAP, 2026).

Synthetic Aperture Radar (SAR) and LiDAR are effective tools for assessing forest structure, biomass and habitat variability. LiDAR delivers detailed 3D data allowing the accurate measurement of canopy height, biomass and volume, all key indicators of habitat quality. Combining LiDAR with optical remote sensing improves the long-term monitoring of forest structure. Tanase *et al.*been able to combine LiDAR and Landsat data to show significant forest recovery within the Iberian Peninsula, including an 11 percent increase in canopy cover and biomass growth from ~32 to 50 t/ha, underscoring the value of linking spectral and structural data (Tanase *et al.*, 2024).

Unmanned aerial vehicles (UAVs) and CubeSat satellite constellations are providing high spatial and temporal resolution data. UAVs capture fine-scale information using multispectral sensors, while CubeSats provide near-daily global coverage at a moderate resolution. Combining the precision of UAVs with the continuous coverage of satellites enables powerful monitoring capabilities. For example, PlanetScope is a commercial constellation of small CubeSat satellites (“Doves”) operated by Planet Labs that provides near-daily, high-resolution (≈3–5 meters) multispectral imagery of the Earth’s land surface (Planet, 2026). Through its integration into the Copernicus program as a “contributing mission,” PlanetScope data is made accessible to research projects via European Space Agency (ESA) platforms, where it complements Sentinel satellites by offering more frequent high-resolution observations (ESA, 2023).

Beyond ecosystem sensing and spatial monitoring, AI is also beginning to transform biodiversity genomics and species-level conservation research. Working with partners such as the Vertebrate Genomes Project, which aims to generate reference genomes for vertebrate species (Vertebrate Genomes Project, 2026), and the Earth BioGenome Project, which aims to sequence and catalog all known cellular organisms (Earth Biogenome Project, 2026), Google is helping scientists accelerate the sequencing and preservation of endangered species genomes before genetic information is lost. These efforts aim to support conservation research through large-scale open genomic datasets.

Collaborative biodiversity monitoring

Crowdsourced and multi-country platforms enable invasive species tracking. Tools like the European Alien Species Information Network (EASIN), which facilitates access to data on invasive species across Europe, are proven platforms. Likewise, Australia's Atlas of Living Australia is a national biodiversity database that features invasive species tracking. WeedScan (Australia) and iMapInvasives (Northern America) (see Proven technology solutions) are mobile apps for real-time invasive reporting, representing more collaborative and ground-up monitoring models. By combining expert, citizen and cross-border data, these platforms not only improve the early detection of invasive species, but also support faster management responses and help conservation agencies track ecological change across larger and more fragmented landscapes.

Innovation examples

The sound of forest restoration in Costa Rica

ETH Zurich Institute of Integrative Biology

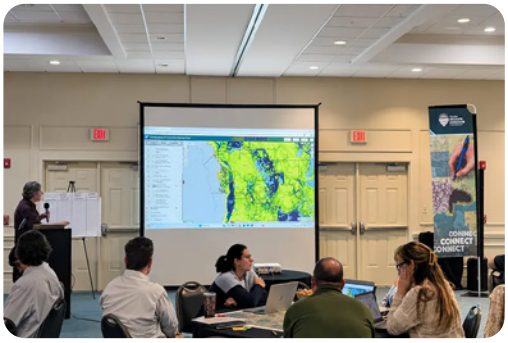


Source: Giacomo Delgado

Researchers at the ETH Zurich Institute of Integrative Biology used over 16,000 hours of passive acoustic recordings to assess how well Costa Rica's Payment for Ecosystem Services (PES) program restores biodiversity. By analyzing soundscapes from 119 sites across the Nicoya Peninsula, they compared degraded pastures, naturally regenerating PES forests and protected reference forests. Forests allowed to regenerate under PES now sound much closer to intact forests than to pasture. This is especially true at dusk when the acoustic profile is almost indistinguishable from that of national parks. This indicates a strong recovery of animal life and ecosystem complexity. In contrast, monoculture timber plantations (mainly teak) show only a partial recovery, exhibiting a quieter and less diverse soundscape. The study relied on passive acoustic monitoring and statistical analysis, enabling non-the invasive measurement of biodiversity through sound. Findings provide empirical evidence that PES schemes can restore more than just tree cover (ETH Zurich, 2026).

Connecting landscapes through data in Florida

Florida Ecological Connectivity Planning Viewer, University of Florida Center for Landscape Conservation Planning, GeoPlan Center

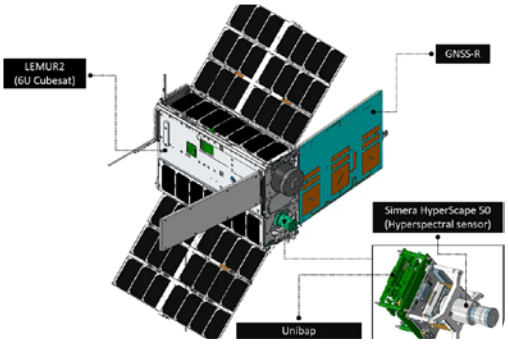


Source: University of Florida Center for Landscape Conservation Planning

Florida's rapid population growth has increased pressure on natural landscapes, making it more challenging to conserve the ecological connections that support biodiversity, clean water, and other ecosystem services. To help address this challenge, researchers at the University of Florida Center for Landscape Conservation Planning, with support from the University of Florida GeoPlan Center, developed the Florida Ecological Connectivity Planning Viewer (EcoCon), a publicly accessible, web-based decision-support tool. EcoCon brings together statewide ecological connectivity models alongside information on conservation lands, water resources, agriculture, land use and other environmental priorities in a single interactive map. This allows users to visualize connected landscapes and understand how proposed land-use changes may affect ecological connectivity. By making decades of conservation science accessible to planners, agencies, conservation organizations and landowners, EcoCon supports more informed and coordinated decision-making. It helps identify opportunities to protect the natural systems that sustain wildlife and people as an integral part of the land use planning and design process. The platform also supports statewide initiatives including the Florida Wildlife Corridor by helping identify and protect the landscape connections that maintain biodiversity and ecosystem resilience (Lockhart, 2026).

Small satellites, big impact on land restoration

King Abdullah University of Science and Technology (KAUST) and Spire Global



Source: King Abdullah University of Science and Technology

The KAUST CubeSat, developed in partnership with Spire Global, is a 6U research satellite designed to collect high-resolution Earth observation data for the purpose of ecosystem monitoring over a three-year mission. Equipped with a hyperspectral imaging sensor (capturing 30+ spectral bands) and GNSS reflectometry (GNSS-R), the satellite can assess vegetation health, soil conditions and environmental variables like soil moisture. Its processing and AI capabilities enable faster analysis. For land restoration, it provides detailed baselines and the continuous monitoring of rangelands, soils and vegetation. It can map degraded areas, track changes in plant cover and evaluate the impact of restoration or land management strategies over time. By combining hyperspectral data with GNSS signals, it provides a fuller picture of ecosystem health than does traditional imaging alone. The satellite supports initiatives like the Saudi Green Initiative by helping researchers measure progress and better target and refine interventions (KAUST, 2023; GPS World, 2021).

The following collection of technologies is divided into three groups: Proven technologies have been on the market for some time and hence are well tested, Frontier technologies are available but relatively new, while Horizon technologies are close to being available but still under development.

Proven technology solutions

Integrated platform for eDNA-powered biodiversity monitoring and nature intelligence

NatureMetrics



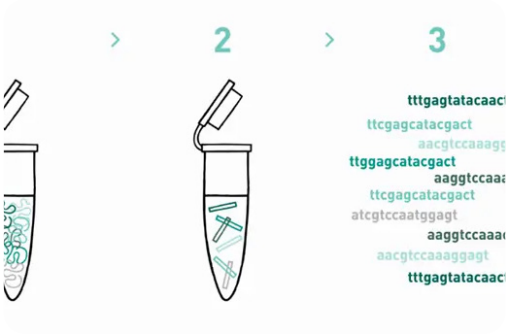
Source: NatureMetrics

NatureMetrics uses environmental DNA (eDNA) technology to monitor biodiversity by analyzing tiny DNA traces left by organisms in water, soil or sediment. Field teams collect samples and send them to NatureMetrics' labs, where DNA metabarcoding and molecular analysis identify hundreds or thousands of species from microbes to mammals without needing direct sightings. This approach reveals hard-to-detect, rare or cryptic species and provides comprehensive biodiversity profiles. The results are fed into the NatureMetrics Intelligence Platform, which turns complex data into standardized biodiversity metrics and indicators that track species presence, habitat health and trends over time. Additional tools like Habitat Insights use geospatial data to assess land cover, habitat connectivity and vegetation condition alongside eDNA results, offering a more complete view of ecosystem function. These solutions support conservation planning, restoration tracking, risk assessment and reporting for regulatory frameworks and corporate sustainability strategies.

- Technological maturity: Proven
- Contracting type: For service contract
- Technology level: High
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

DNA metabarcoding services

AllGenetics



Source: AllGenetics

AllGenetics specializes in DNA metabarcoding of environmental DNA (eDNA) for monitoringbiodiversity across ecosystems. Its service bypasses traditional specimen sorting by extracting DNA directly from environmental samples like water, soil, sediment or bulk organism samples and using high-throughput sequencing to detect many species at once. It amplify universal or custom DNA "barcode" regions and sequences them in order to generate a taxonomic inventory showing what organisms are present and in what relative abundance. AllGenetics also handles the bioinformatics analysis needed to clean, classify and visualize sequence data, while tailoring workflows for different taxonomic groups and sample types. This approach is non-invasive, cost-effective and sensitive enough to detect rare or cryptic species, making it well-suited for scalable ecosystem biomonitoring, conservation and environmental assessment projects.

- Technological maturity: Proven
- Contracting type: For service contract
- Technology level: High
- Place of origin: Spain
- Availability: Worldwide
- Contact: WIPO GREEN Database

Cloud-based map-driven data system to track invasive species

NatureServe



Source: Photo by Alexandre Daoust on Unsplash

iMapInvasives is a cloud-based, map-driven data system used to track and manage invasive species across landscapes. It allows scientists, land managers and citizen-observers to upload georeferenced sightings (often via a mobile device), creating a shared real-time database of where invasive species are occurring. Built on GIS technology, the platform supports mapping, data analysis and reporting, helping identify high-risk areas, track control efforts and prioritize management actions. By integrating observations across regions and enabling rapid data sharing, iMapInvasives improves the early detection of and coordinated response to biological invasions.

- Technological maturity: Proven
- Contracting type: For subscription
- Technology level: High
- Place of origin: United Kingdom
- Availability: Northern America
- Contact: WIPO GREEN Database

Animal movement tracking platform

Max Planck Institute of Animal Behavior



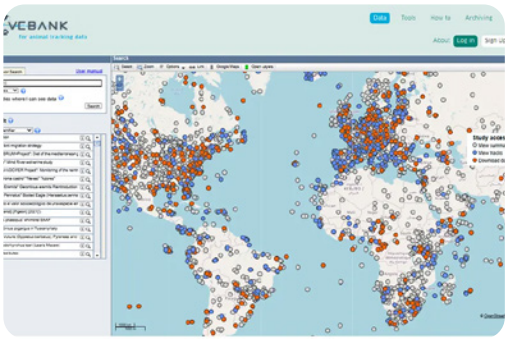
Source: Max Planck Institute of Animal Behavior

Movebank is a global online platform for managing, sharing, analyzing and archiving animal tracking and bio-logging data. Researchers attach GPS tags and other sensors to animals, then upload movement and behavioral data to the platform where it can be visualized, standardized and analyzed across species and regions. The system helps scientists understand migration routes, habitat use, species interactions and responses to environmental pressures such as climate change, habitat fragmentation, biodiversity loss and disease spread. Movebank also enables collaboration between researchers and conservation organizations by providing a shared global database of animal movement data.

- Technological maturity: Proven
- Contracting type: Open access research platform
- Technology level: Medium
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Satellite-based wildlife tracking system

Max Planck Institute of Animal Behavior



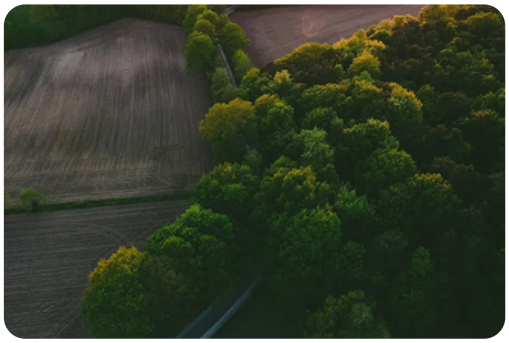
Source: Max Planck Institute of Animal Behavior

ICARUS (International Cooperation for Animal Research Using Space) is a global satellite wildlife tracking system that uses miniature animal-mounted sensors and space-based receivers to monitor animal movements and environmental conditions in near real time across the planet. Small GPS-enabled tags attached to birds, bats, insects, turtles and other species collect data about location, migration, behavior, temperature and atmospheric conditions. As satellites pass overhead, the tags transmit information to space-based receivers, allowing researchers to study migration patterns, habitat use, biodiversity loss, ecosystem change, disease spread and climate impacts at the global scale.

- Technological maturity: Proven
- Contracting type: International scientific research infrastructure
- Technology level: Medium
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Open source connectivity modeling tool

Circuitscape



Source: Photo by Frank Kroeger on Unsplash

Circuitscape is an open-source connectivity modeling tool used in conservation planning to identify how animals, plants, or ecological processes move across fragmented landscapes. It applies principles from electrical circuit theory to ecology by treating landscapes as conductive surfaces: areas that are easy for species to cross have a low "resistance," whereas roads, cities or degraded habitats have a high resistance. The software simulates movement similarly to how an electrical current flows through a circuit, analyzing many possible pathways simultaneously rather than identifying only a single optimal route. This allows researchers to map wildlife corridors, migration routes and habitat bottlenecks, as well as identify restoration priorities. Circuitscape is widely used to support biodiversity conservation, landscape restoration and climate adaptation planning, including identifying areas where habitat connectivity is most vulnerable or where restoration efforts could have the greatest ecological impact.

- Technological maturity: Proven
- Contracting type: Open source
- Technology level: Medium
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Open-source GIS-based conservation planning tool for wildlife corridors

Linkage Mapper



Source: Photo by Y S on Unsplash

Linkage Mapper is an open-source, GIS-based conservation planning tool used to identify and map wildlife corridors between important habitat areas. It works by combining maps of core habitats with “resistance” layers that represent how difficult different landscape features, such as roads, cities, steep terrain or degraded land, are for species to traverse. The software then calculates the least-cost pathways and broader corridors that animals are most likely to use when moving between habitats. Additional modules can identify climate-resilient routes, ecological bottlenecks (“pinch points”) and barriers where restoration or mitigation could most improve connectivity. Some modules integrate with Circuitscape, using circuit theory to model multiple potential movement pathways rather than a single least-cost route. Linkage Mapper is widely used in biodiversity conservation, restoration planning and climate adaptation to help prioritize habitats and ecological connections at the regional scale.

- Technological maturity: Proven
- Contracting type: Open source
- Technology level: Medium
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Soil-plant spectral technology

CIFOR-ICRAF Soil and Land Health Laboratory



Source: Getty Images/Ivan-balvan

The soil–plant spectral technology developed by CIFOR-ICRAF and partners uses infrared and X-ray spectroscopy to rapidly and cost-effectively analyze soil carbon, nitrogen, minerals and plant properties, replacing slower traditional “wet chemistry” methods. Combined with satellite data, it enables high-resolution soil health and land management mapping. Since pioneering large-scale “dry” spectral analysis in Africa through the Africa Soil Information Service in 2009, the Nairobi-based reference laboratory has grown into a global hub supporting more than 30 regional laboratories. The center provides mid-infrared spectral prediction services, open access data, technical consultancy and calibration support, while contributing to international initiatives such as the Food and Agriculture Organization’s Global Soil Laboratory Network (GLOSOLAN). A new 2026 online prediction engine further streamlines national soil analysis systems.

- Technological maturity: Proven
- Contracting type: Fee-for-service
- Technology level: Medium
- Place of origin: Kenya
- Availability: Worldwide
- Contact: WIPO GREEN Database

Low-energy electrokinetic remediation of contaminated soils

EKOGRID Oy



Source: Photo by Danil Shvaika on Unsplash

EKOGRID™ is a patented electrokinetic remediation technology for treating organic pollutants in contaminated soil, groundwater and sediment. The system applies optimized, low-voltage electrical pulses through electrodes, with alternating polarity generating electrokinetic and electro-osmotic movement of pore water and increasing contaminant availability for bioremediation, chemical degradation or removal. Electrochemical reactions at soil-particle surfaces can also generate reactive species and oxygen that contribute to pollutant breakdown. The system is designed to operate with relatively low energy consumption as reactions occur throughout the soil matrix between electrodes, rather than only around the electrodes. The technology can be combined with complementary remediation methods, with treatment monitored through changes in pollutant concentrations, oxidation-reduction potential (ORP) and dissolved oxygen levels.

- Technological maturity: Proven
- Contracting type: For sale or contract
- Technology level: High
- Place of origin: Finland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Moss-based soil and ecosystem restoration

Code of Nature



Source: Code of Nature

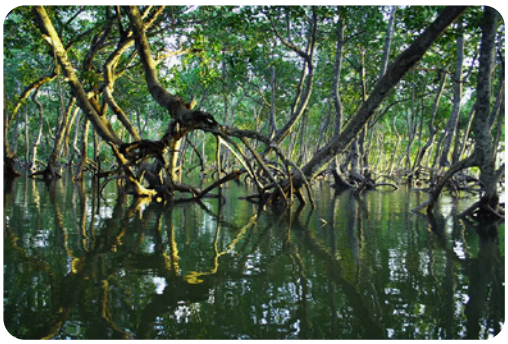
Mosby is a moss-based soil restoration technology designed to support ecological recovery on wildfire-damaged, reclaimed and other degraded soils. The system combines selected moss spores in liquid form with a site-specific nutrient solution, plant growth hormone components and proprietary symbiotic microorganisms. The mixture is diluted and sprayed onto degraded soil surfaces, where the moss is intended to establish during the early stages of restoration. As moss develops, it can help stabilize exposed soil, retain moisture and contribute to the development of conditions suitable for subsequent vegetation establishment. The microbial component is intended to support nutrient cycling and soil fertility during recovery. The technology can be adapted to target-site conditions by adjusting the composition and application rate. It is designed as a relatively simple, spray-based approach to initiating soil and ecosystem recovery.

- Technological maturity: Proven
- Contracting type: For sale or contract
- Technology level: Medium
- Place of origin: Republic of Korea
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier technology solutions

Geospatial AI engine for mangrove restoration

Blue Forest



Source: Photo by Timothy K on Unsplash

Carbon Hawk is a geospatial AI engine that maps and forecasts mangrove forest loss by stacking seven environmental and satellite data layers inside Google Earth Engine using the GEEmap Python interface. It combines satellite imagery (including Landsat 8, Sentinel data, Global Mangrove Forest Distribution, Hansen forest data, and Primary Humid Tropical Forest datasets) with terrain and infrastructure layers such as elevation models, slope and roads. By cross-analyzing these parameters, the system distinguishes mangroves from other forest types with a higher accuracy than legacy maps and identifies patterns linked to degradation risk. The engine updates every 16 days, ensuring near real-time monitoring. This layered, continuously refreshed modeling approach enables the precise detection of "mangroves at risk," allowing for intervention before forest loss occurs.

- Technological maturity: Frontier
- Contracting type: Subscription platform
- Technology level: High
- Place of origin: United Arab Emirates
- Availability: Worldwide
- Contact: WIPO GREEN Database

Digital seed collection and marketplace platform for native restoration seeds

Seedark



Source: Photo by Nataliia Antofii on Unsplash

Squiirrel is a purpose-built mobile app and digital marketplace for seed collection and procurement. The app lets seed collectors capture detailed, GPS-verified data (location, species, photos, etc.) during collection and to store or list their collections for buyers. Each seed record becomes traceable, often via QR codes, improving transparency. Restoration practitioners, nurseries and growers can post seed demand and procure native stock easily through the marketplace, creating a better supply–demand alignment and reducing friction in sourcing seeds for projects. Squiirrel enhances data accuracy, traceability and decision-making across the seed ecosystem.

- Technological maturity: Frontier
- Contracting type: Subscription platform
- Technology level: Medium
- Place of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Biodiversity monitoring software

Okala



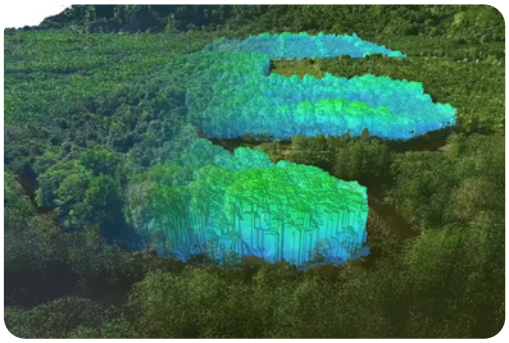
Source: Getty Images/AmericanWildlife

Okala's biodiversity monitoring technology is an AI-driven platform that brings together data obtained from camera traps, bioacoustics, environmental DNA (eDNA), satellite imagery and field surveys into one central dashboard. The system uses machine learning to automate species identification, risk screening and trend analysis, backed by expert ecological review, to enable species and habitat monitoring at scale. It also includes mobile field tools for accurate data collection in remote areas and produces transparent, audit-ready outputs aligned with global standards such as Taskforce on Nature-related Financial Disclosures (TNFD) and European Union Deforestation Regulation (EUDR). The goal of the platform is to simplify complex biodiversity monitoring, speed up reporting and help businesses, governments and NGOs demonstrate environmental impact and meet regulatory requirements.

- Technological maturity: Frontier
- Contracting type: Subscription platform
- Technology level: High
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

3D digital twin biodiversity monitoring

Hexagon/R-evolution



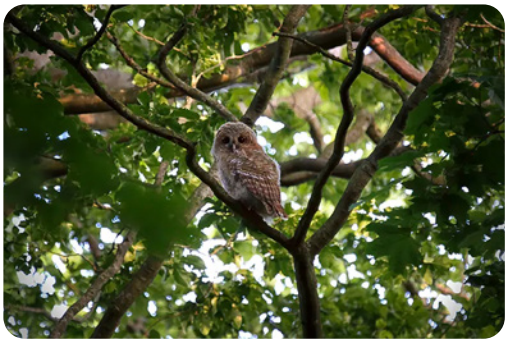
Source: R-evolution

Green Cubes is a biodiversity monitoring solution that creates highly detailed 3D digital twins of terrestrial ecosystems, visualized through a single pane of glass in the Green Cubes platform. Using airborne and terrestrial LiDAR and imaging, acoustic monitoring, camera traps, and AI-powered geospatial analytics and processing, Green Cubes merge and visual multi-dimensional data, making nature visible and valuable. The system tracks biodiversity through ecosystem extent, condition and state of species over time, to help companies, governments and researchers improve biodiversity assessments, validate nature-based projects, and support compliance with global reporting frameworks.such as the Taskforce on Nature-related Financial Disclosures (TNFD).

- Technological maturity: Frontier
- Contracting type: Subscription platform
- Technology level: High
- Place of origin: Sweden
- Availability: Worldwide
- Contact: WIPO GREEN Database

On-site sensor-driven biodiversity monitoring sensors and platform

Hula Earth



Source: Photo by Andy Kennedy on Unsplash

Hula Earth is a biodiversity monitoring and MRV (monitoring, reporting, verification) platform combining proprietary IoT sensors with satellite data and AI analytics to provide continuous, real-time ecosystem insights. The company's key product is the Hula BioT, a solar-powered, low-maintenance IoT biodiversity sensor able to detect wildlife (e.g., bird and insect acoustic activity), air quality and other environmental parameters on site. These field data streams are integrated with earth observation layers obtained from satellites to produce a landscape-wide picture of ecosystem health. This feeds into the Hula Platform dashboard, which provides species reports, metrics, alerts and reporting outputs aligned with global standards.

- Technological maturity: Frontier
- Contracting type: Subscription platform
- Technology level: High
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Open-source smart camera trap system

wildlife.ai



Source: wildlife.ai

Wildlife Watcher is an AI-powered, open source, smart camera trap system designed for wildlife monitoring and biodiversity conservation. The device uses embedded machine learning to automatically detect and identify animal species in real time directly on the camera unit, reducing the need for manual image review and field retrieval. It is specifically designed to monitor difficult-to-study species, such as reptiles, amphibians, insects and small mammals, that are often poorly captured by conventional camera traps. The low-power system combines motion sensing, image recognition and wireless data transmission to send rapid alerts and ecological monitoring data from remote environments. The hardware is designed to be modular and partially 3D-printable, supporting flexible deployment and adaptation for different conservation contexts.

- Technological maturity: Frontier
- Contracting type: Open source
- Technology level: High
- Place of origin: New Zealand
- Availability: Worldwide
- Contact: WIPO GREEN Database

AI-powered bird and bat monitoring platform

Spoor



Source: Photo by Wilmy van Ulft on Unsplash

Spoor is an AI-powered biodiversity monitoring platform designed to track and analyze bird and bat activity around wind energy infrastructure. The system combines high-resolution video cameras with computer vision and machine learning algorithms to automatically detect, track and identify flying species in real time, including at night and in poor weather conditions. The platform generates continuous ecological data on flight paths, movement patterns, species presence, flight heights and turbine interactions, helping wind developers and regulators assess collision risks and biodiversity impacts more accurately than a traditional field survey. Spoor supports environmental impact assessments, permitting, mitigation planning and operational monitoring for onshore and offshore wind projects.

- Technological maturity: Frontier
- Contracting type: Subscription-based SaaS platform
- Technology level: High
- Place of origin: Norway
- Availability: Worldwide
- Contact: WIPO GREEN Database

Surface erosion stabilization (water and dust)

Medusoil



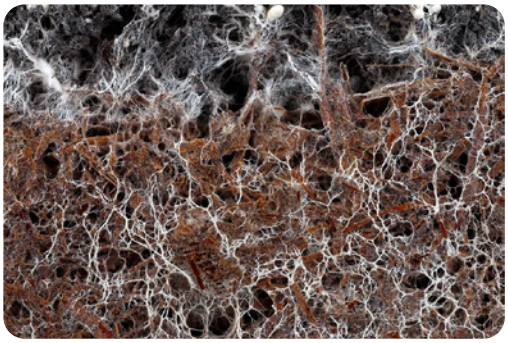
Source: Getty Images/HappyNati

Medusoil develops bio-based soil stabilization and erosion-control technologies using biomineralization and biocementation. Instead of conventional cement or chemical binders, the company uses naturally occurring microorganisms and bio-based mineral agents to bind soil particles together, creating low-carbon alternatives for construction, land restoration, slope stabilization and infrastructure protection. Its technologies can strengthen soils, reduce erosion, stabilize riverbanks and slopes, mitigate dust and improve resilience against landslides and other climate-related risks, while lowering CO_2emissions by more than 50 percent compared to traditional cement-based methods. Medusoil's systems are designed to be minimally invasive, scalable and compatible with circular construction approaches, including the reuse of excavation and demolition materials. The technology has been tested in projects involving erosion control, road reinforcement and ecological restoration across Europe and other regions.

- Technological maturity: Frontier
- Contracting type: For service contract or licensing
- Technology level: High
- Place of origin: Switzerland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Mycorrhizal fungi pellets

Rhizocore Technologies



Source: Getty Images/Andreas Häuslbetz

Rhizocore Technologies harnesses locally-adapted mycorrhizal fungi to improve forest restoration outcomes. Forest soils often lose their natural fungal networks after disturbance, leaving young trees struggling to access nutrients and water. Rhizocore grows and applies site-specific ectomycorrhizal fungi in proprietary RhizoPellets™ that form symbiotic networks with tree roots, boosting nutrient and water uptake, enhancing drought resilience and increasing sapling survival, growth rates and disease resistance. This strengthens overall forest health, accelerates reforestation success, supports soil structure and biodiversity, and increases carbon sequestration. By restoring critical belowground biological networks, Rhizocore enables tree establishment on degraded or challenging lands, helping forests withstand environmental stressors, including prolonged dry periods.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

AI-powered mobile and web app to identify invasive plant species

Centre for Invasive Species Solutions, CSIRO, the Atlas of Living Australia, the NSW Department of Primary Industries and Regional Development and the South Australian, Queensland and Victorian Governments



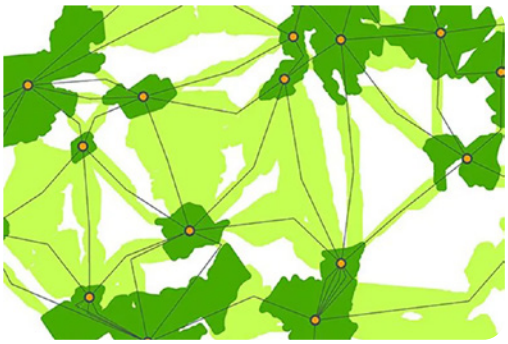
Source: Getty Images/Ulisberg Alves

WeedScan is a free, AI-powered mobile and web application designed to identify, record and manage invasive plant species across Australia. Built using a machine learning model trained on over 120,000 images, it can recognize more than 450 priority weeds by analyzing photos uploaded by users and providing rapid identification with confidence levels. Beyond identification, the app allows users to log sightings, share data and alert authorities to new infestations. It also provides location-specific management guidance, supporting coordinated weed control efforts.

- Technological maturity: Frontier
- Contracting type: Open source
- Technology level: High
- Place of origin: Australia
- Availability: Australia
- Contact: WIPO GREEN Database

Wildlife connectivity toolbox

Conservation Corridor (IUCN, Center for Large Landscape Conservation, Michigan State University)



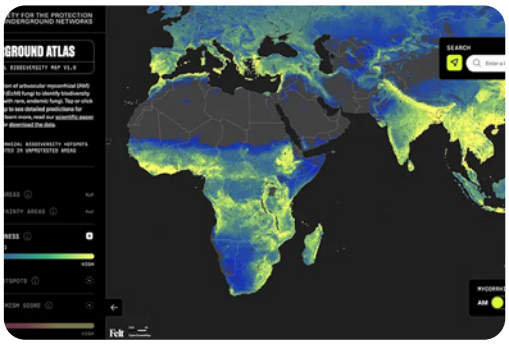
Source: Michigan State University

The connectivity toolbox is a set of geospatial and modeling tools for understanding and preserving how species move across landscapes. It combines spatial data, ecological knowledge and decision-support methods to identify, protect and restore wildlife corridors. Tools include: (1) mapping tools like GIS for defining habitats and barriers such as roads or development; (2) modeling tools that simulate how animals move using concepts like resistance surfaces; (3) corridor identification tools for locating and ranking the most important connections between habitat patches; and (4) decision-support tools for comparing scenarios such as conservation actions or future development. Some tools also incorporate real-world tracking data for validating models and monitoring changes over time.

- Technological maturity: Frontier
- Contracting type: Open source/for sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Global mapping platform for mycorrhizal fungal networks

Society for the Protection of Underground Networks (SPUN)



Source: Society for the Protection of Underground Networks

The Underground Atlas, developed with data partners GlobalFungi and the Global Soil Mycobiome consortium, is a global mapping platform that models the distribution and biodiversity of underground mycorrhizal fungal networks. Using billions of fungal DNA sequences collected from soils across more than 130 countries, combined with machine learning and geospatial analysis, the system predicts fungal biodiversity and identifies ecological hotspots at a high spatial resolution. Underground fungal networks are critical for nutrient cycling, soil formation, carbon storage, water retention and plant health, yet most remain outside protected areas. The platform helps researchers, policymakers and conservation groups identify vulnerable belowground ecosystems and integrate soil biodiversity into restoration, climate adaptation and conservation planning.

- Technological maturity: Frontier
- Contracting type: Open source
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon technology solutions

Seed dart system

Inverto Earth



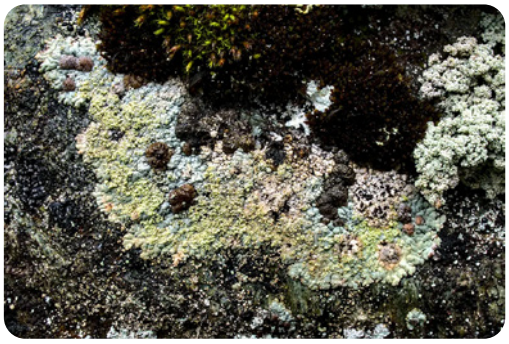
Source: Cameron Dowd

Inverto Earth has developed a patent-pending “seed-dart” system to make coastal restoration (especially mangrove planting) more efficient, reliable and scalable. A seed dart is a biodegradable capsule made of certified marine-friendly material that houses a mangrove seed plus nutrients to support early root growth. The capsule is designed to anchor the seed securely into coastal mud, protecting it at its most vulnerable stage when it would otherwise be washed away by tides, eaten by animals or fail to take root. This significantly improves survival rates compared to direct seeding or traditional nursery-raised approaches. To reach large and often remote areas quickly, Inverto uses drone-mounted launch systems able to plant thousands of seed darts per flight with high precision, cutting time and cost by up to ~50 percent for sites larger than 100 hectares compared to manual planting.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: High
- Place of origin: Switzerland
- Availability: Under development
- Contact: WIPO GREEN Database

Biocrust capsules for degraded-land restoration

Northern Arizona University (NAU)



Source: Photo by Alexey Melechin on Unsplash

Biocrust capsules are a novel delivery technology designed to restore degraded drylands by establishing biological soil crusts (biocrusts) on bare or eroded ground. The technology encapsulates field-collected or cultivated communities of cyanobacteria, mosses, lichens and other microorganisms in biodegradable capsules that protect the inoculum during handling and deployment. Once released, the capsules break down and allow the organisms to establish on the soil surface, where biocrusts can bind soil particles, reduce erosion, retain moisture, capture nutrients and contribute to soil fertility. By rebuilding these living soil communities, the technology can also create more favourable conditions for native plants and support soil biodiversity. A 2026 study tested vegetable-cellulose and tapioca capsules containing biocrust inoculum, seeds and moisture-retaining additives. Field trials are underway in the Sonoran and Mojave Deserts, while testing in additional ecosystems will help assess their effectiveness at broader scales.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: High
- Place of origin: United States
- Availability: Under development
- Contact: WIPO GREEN Database

2.3 Scaling land-based restoration

Why scaling restoration is difficult

Global land restoration ambitions are rapidly expanding. Initiatives such as the United Nations Decade on Restoration, the Bonn Challenge, AFR100, the UNCCD and national restoration targets, together with carbon removal targets spurred by a growing recognition derived from Intergovernmental Panel on Climate Change (IPCC) scenarios that carbon removal will likely be necessary to avert the worst impacts of climate change (see Chapter 1, Introduction), have pushed restoration firmly onto the global agenda. However, scaling restoration remains difficult.

Restoring ecosystems at the planetary scale requires proof that restoration is real, measurable, durable and financeable. It is largely known what to do. This chapter has shown that many land restoration methods already exist. The challenge now is scaling them, which requires finance, coordination, local participation, governance, MRV and long-term management. Restoration outcomes are also inherently difficult to measure. Ecosystems are dynamic, carbon changes are gradual and difficult to detect, biodiversity is multidimensional, impacts vary across landscapes, and permanence is uncertain. Yet carbon and biodiversity finance depend on credibility; investors and markets require proof that outcomes are real.

Restoring ecosystems at the planetary scale requires proof that restoration is real, measurable, durable and financeable

Digital technologies are emerging to address this challenge. As demonstrated throughout other chapters, remote sensing, AI, sensors, modeling, blockchain and integrated monitoring platforms are becoming increasingly prevalent across diverse sectors and ecosystems. To scale ecosystem restoration, these technologies are increasingly being used not only to monitor ecosystems, but also to build trust, support measurement and verification, and enable carbon and emerging biodiversity markets to function at scale. To understand how these systems operate, it is first necessary to understand MRV and carbon market infrastructure.

A quick primer: how carbon markets and MRV work

Measurement, reporting and verification (MRV) is a process used to measure, report and independently verify GHG emissions reductions resulting from climate activities. It ensures that carbon credits represent real, additional and permanent emission reductions, allowing them to be converted into carbon credits (each representing one tonne of CO_2equivalent) with a financial value. MRV is essential for accessing climate finance, supporting carbon markets and tracking progress toward countries' climate targets under the Paris Agreement, although it can be complex to implement (World Bank, 2022). Compliance carbon markets are mandatory systems regulated by governments – for example, the European Union (EU) emissions trading system (ETS) or California's Cap-and-Trade system (Oksen, 2026)– wherein companies are legally required to offset emissions in order to stay below stipulated "caps," although this may be delayed through the awarding of allocated allowances. In contrast, voluntary carbon markets (VCMs) are driven by private companies choosing to buy credits to meet sustainability goals.

Standards act as a "stamp of approval" for credit quality. In compliance markets, primary standards are set by governmental agencies or UN bodies (e.g., the Article 6.4 Mechanism), whereas the VCM relies on independent nonprofits, such as Verra (VCS) and Gold Standard, to certify projects. To ensure these voluntary credits are of a high-quality, oversight bodies like the Integrity Council for the Voluntary Carbon Market (ICVCM) (setting the rules for credits) and the Voluntary Carbon Markets Integrity Initiative (VCMI) (setting the rules for how companies use them) have become the global standard-setters.

It is widely believed by the IPCC, as well as by policymakers, practitioners and experts alike, that transparency is vital to the future success of carbon markets (Okoli and Birkenberg, 2024). Recent investigations into forest carbon credits found that many were significantly overestimated and did not represent real emissions reductions, triggering a broader integrity crisis in VCMs (Johnston-Leek, 2024; Greenfield, 2023; Chuang and Liu, 2025). Issues cited include credits issued without real emissions reductions, weak or inconsistent verification and oversight, lack of additionality, and perverse incentives. This has triggered growing scrutiny of crediting methodologies and ramped up calls for greater transparency and stricter standards. The landscape is moving toward greater integrity through independent benchmarks and digital automation. In response, digital MRV systems and new monitoring technologies are increasingly being promoted as solutions to improve credibility.

In carbon markets, strong MRV lowers the risk of over-crediting, makes additionality and permanence more defensible, and can reduce verification costs to broaden participation. Weak MRV protocols damage credit integrity, and ultimately may hinder restoration efforts from happening at all or from scaling and/or becoming profitable for local communities. Therefore, the sector is increasingly turning toward higher-resolution carbon maps, shared plot databases and digital MRV infrastructures.

The rise of digital MRV

Digital MRV is the next evolution of traditional MRV, using advanced digital technologies such as AI, satellite data, IoT sensors, big data analytics and blockchain to improve how emissions and sustainability impacts are tracked and verified. It aims to make MRV systems faster, cheaper, more transparent and more trustworthy to address long-standing issues of inefficiency, high costs and a lack of credibility. Beyond simply digitizing existing processes, digital MRV represents a system-wide integration of data, standards and stakeholders to support carbon markets and reduce risks like double-counting and greenwashing (Baumann, 2020).

> Digital MRV represents a system-wide integration of data, standards and stakeholders to support carbon markets and reduce risks like double-counting and greenwashing

Digital MRV infrastructures have advanced rapidly over recent years. Across the technologies included in this chapter, several capabilities complement each other. The foundation is based on data collection systems that range from remote sensing (satellites, aerial imagery) and field-based inputs (mobile apps, sensors, geotagging) to automated deployment tools (drones and mechanized restoration). These technologies are then fed into data processing and intelligence layers, where machine learning, ecological models and analytics translate data into measurable indicators such as carbon, biomass and ecosystem health. Digital platforms and management systems are the top-down technologies that integrate various functions and standardize reporting, as well as connecting stakeholders across the diverse parts of the process. Finally, a new wave of technologies is building trust through new verification systems. They include distributed ledgers, audit systems and independent rating or validation tools that ensure transparency and traceability.

How digital land restoration systems work – from planting trees to continuous verification

For land-based restoration, MRV typically combines field plots for calibration with high-resolution satellite imagery and AI-enabled analysis, along with ecosystem-specific tools such as drones, LiDAR, radar, hyperspectral imagery and proximal sensors. Remote sensing, high-resolution satellite imagery and AI are increasingly being used alongside field measurements

to provide more accurate, efficient and near-real-time monitoring at scale (WRI, 2026b). As highlighted in Box 2.7, these technologies can strengthen measurement and monitoring, but they cannot eliminate uncertainty or address the broader governance and system-design challenges associated with MRV.

A restoration project begins by mapping degraded land using satellite imagery and ecological data. Algorithms help identify suitable species and planting locations. Drones or field teams plant trees, and each planting area is digitally logged (sometimes down to the level of individual trees or plots). Over time, satellites and occasional field data track growth, survival rates and biomass. That data is then automatically processed into carbon estimates. Rather than relying solely on periodic field assessments, these systems can provide more frequent updates on restoration performance. Finally, results are verified through a transparent system (sometimes with tamper-proof blockchain records) and carbon credits issued with a full data trail showing where, when and how the carbon was captured. This creates a traceable link between restoration activities on the ground and the carbon credits issued.

Box 2.7 Technology can improve MRV – but not solve everything

Several MRV flaws stem from broader questions of governance and system design. Technology therefore has an important role, but it is not a complete solution. Measurement and monitoring can be improved through satellite remote sensing and AI to help track deforestation, biomass and land use change, while reducing reliance on self-reported and modelled estimates. Digital MRV systems can improve transparency and consistency, while blockchain and registries can reduce double counting. Improved data and modeling can also strengthen baseline estimates, although they cannot eliminate uncertainty. Additionality, however, is not primarily a technical question, but a matter of judgment and governance. Likewise, technology can neither resolve weak incentives nor address concerns that offsets may delay emissions reductions elsewhere.

Soil carbon: the weak link in MRV

Despite rapid advances in digital MRV, soil carbon remains one of the weakest and most uncertain components of restoration monitoring. Estimates can differ by as much as 100 percent when using the popular current method of fixed-depth (FD) sampling, which can wrongly estimate soil carbon changes, because it ignores changes in soil bulk density (Raffeld *et al.*, 2024). Combining Earth observation technologies with *in situ* sampling can be a reliable and cost-effective strategy at the more local scale, but does not deliver the level of accuracy often necessary.

Most soil sampling protocols sample at a too shallow depth; limiting sampling to 30 cm misses a large share of soil carbon and can overlook the redistribution of carbon deeper in the soil. Deeper sampling is more difficult, but sampling at 60 cm captures changes. Also, soil carbon changes are often small, slow and easily obscured – rendering short-term monitoring unreliable. Some researchers recommend using equivalent soil mass (ESM) instead of fixed depth, sampling at deeper levels and increasing sampling intensity to detect real changes, and improving standards and consistency for soil across carbon market protocols (Raffeld *et al.*, 2024).

Soil carbon markets for smallholders are constrained by a trade-off between cost and accuracy, with no single monitoring method performing well on both counts. Scaling soil carbon markets requires blending low-cost technologies with better standards and local engagement (Okoli and Birkenberg, 2024). However, emerging tools, like remote and proximal sensing, can lower costs, but currently lack standardization and trust. Farmer involvement remains critical for adoption and impact (Okoli and Birkenberg, 2024).

The rise of nature technology platforms

Scaling land restoration is becoming less about simply planting more trees and more about building integrated digital systems able to measure, manage, finance and expand restoration efforts more effectively over time. This technology field remains highly fragmented, reflecting

the complexity of the ecosystems themselves. Solutions range from satellite monitoring and eDNA analysis to restoration technologies, ecological modeling platforms and biodiversity market infrastructure. A notable shift is the growing integration of biodiversity and ecosystem data into business decision-making. Restoration platform technologies are increasingly being used not only for conservation, but also for corporate reporting, risk assessment, restoration planning and emerging biodiversity and carbon markets (Planet A. Ventures, 2023).

> Scaling land restoration is becoming less about simply planting more trees and more about building integrated digital systems able to measure, manage, finance and expand restoration efforts more effectively over time

Early platforms (with players like Grow-Trees.com – see Proven technology solutions) focused on digitizing participation and basic tracking. But the field has quickly evolved into integrated systems combining site selection, automated deployment using drones, seed technologies and continuous monitoring. Platforms like Vibrant Planet, Restor, and re.green represent a new class of restoration technology that uses satellite data, remote sensing, AI and ecological modeling to make ecosystems measurable, monitorable and actionable at scale. They range from corporate risk assessment and land-use planning to restoration and ecosystem monetization. Blockchain or similar distributed ledgers are used to prevent double counting and link verification directly with carbon or biodiversity credits. They all translate complex environmental data into usable insights, decisions or financial mechanisms. The contribution they are making is to reduce information gaps, ultimately enabling better decision-making. In some cases, they are also introducing new ways of financing conservation. But they primarily address data and coordination challenges. For the reasons discussed in Box 2.6, AI use by these platforms – and for MRV in general – should be undertaken with due caution.

Another marked trend is that some restoration platforms now manage the entire process from seed selection and nursery production through to planting and long-term monitoring, helping improve consistency and reduce project risks. There is also a growing connection between restoration projects and supply-chain monitoring, with platforms increasingly tracking the broader land-use impacts linked to production and sourcing activities. Overall, restoration is becoming increasingly data-driven and continuously measured and verified, which helps connect restoration projects to financing and investment systems, making it easier to scale them environmentally, economically and institutionally.

Public and multilateral digital infrastructure for ecosystem monitoring

In addition to startups, global public databases and infrastructure are becoming increasingly available. Global Forest Watch is an online platform hosted by the WRI that uses satellite imagery, cloud computing and machine learning to process and deliver near-real-time data on forest cover and change. The platform aggregates satellite imagery, national forest inventories and field observations to map forest cover, loss and gain, as well as fires, using algorithms developed by the University of Maryland and tools like Global Land Analysis and Discovery (GLAD) alerts to detect and flag deforestation events on a near-real-time basis. Users can analyze trends, overlay custom spatial data and export insights for decision-making. Such transparency tool enables governments, companies and researchers to monitor forests and support global initiatives like the UN Reducing Emissions from Deforestation and Forest Degradation (REDD+) Programme and zero-deforestation commitments (WRI, 2026a).

Digital Earth Africa is a pan-African Earth observation platform that transforms open satellite imagery into environmental data ready for analysis by governments and land managers

across Africa. Like other platforms, it uses satellite data obtained from Landsat and Sentinel missions, democratizing access to high-quality Earth observation data and analytics across the continent. This enables countries and practitioners to conduct environmental monitoring and restoration planning without requiring extensive in-house geospatial infrastructure (Digital Earth Africa, 2026).

Other global platforms, like the Copernicus program and SERVIR, function as open, publicly-funded systems that provide free, high-quality Earth observation data and tools to users worldwide. Copernicus delivers continuous satellite data (e.g., from Sentinel missions) on land, atmosphere and oceans (ESA, 2025), while SERVIR translates satellite data into practical tools for governments and practitioners across 50 countries in Africa, Asia and Latin America, supporting various activities like land restoration, climate adaptation and disaster response (Servir Global Collaborative, 2026). These systems form the foundational data infrastructure on which many private MRV platforms and restoration tools depend. They standardize and democratize access to geospatial data and ultimately reduce costs, enabling countries to monitor ecosystems, plan interventions and conduct reporting activities.

Beyond carbon: nature finance and biodiversity credits

The same digital infrastructures described above are now expanding beyond carbon markets into broader forms of nature finance. Biodiversity credits are an attempt to do for nature what carbon credits have done for the climate – create a tradable unit that finances desirable ecological outcomes. A biodiversity credit represents measurable improvement in biodiversity at a specific site (habitat quality, species richness, ecosystem integrity). Unlike carbon (1 tonne CO_2=universal unit), biodiversity is location-specific and multidimensional, which makes standardization much harder.

> Biodiversity credits are an attempt to do for nature what carbon credits have done for the climate – create a tradable unit that finances desirable ecological outcomes

Since 2022, biodiversity credits have gained attention as a tool for scaling private finance for biodiversity gains. But a clear definition has yet to be established. The Kunming-Montreal Global Biodiversity Framework (KMGBF) outlines a plan to stop and reverse biodiversity loss by 2030. One of its 23 targets – Target 18 – calls on governments to cut harmful incentives and expand positive ones that support the conservation and sustainable use of biodiversity (OECD, 2025).

Several questions face the development of biodiversity credits. One of the most important is whether biodiversity can be simplified into tradable units without losing integrity. Nature (see Box 2.8 in relation to the EU proposal) and biodiversity credits, can neither come to fruition nor function without measurement; thus, technology is foundational. Monitoring, as elsewhere, is done using satellite remote sensing, LiDAR, biodiversity sensors (acoustic, camera traps), drones, IoT sensors and AI-driven ecosystem modeling. Biodiversity indicators include species richness, soil health and pollinators. Verification is conducted through digital MRV systems in order to reduce fraud and greenwashing. Ultimately, standardization will be needed to translate complex ecosystems into measurable and comparable units. Like carbon markets, setting baselines is important and digital platforms help in tracking their ongoing changes and the issuing of credits (eventually).

Technology is arguably even more important in this context than it is for carbon alone. CO_2 can be estimated using relatively simple models, whereas biodiversity requires high-resolution and multi-variable data, thus requiring advanced monitoring technology. The main players shaping this emerging idea and working on developing shared definitions, principles and market

governance, are the Biodiversity Credit Alliance, the International Advisory Panel on Biodiversity Credits and the World Economic Forum. The standard setters have been adapted from carbon markets: Verra, Plan Vivo, Terrasos (see Frontier technology solutions) and the Wallacea Trust. They are in the process of defining methodologies, certifying projects and planning the issuing of credits. Box 2.8 discusses the EU's roadmap toward the development of nature credits. In addition to the EU, national pilot programs have taken place in Australia, Colombia and the United Kingdom.

Box 2.8 EU Roadmap toward Nature Credits

The EU estimates that global demand for biodiversity credits could reach USD 180 billion, while the biodiversity funding gap within the EU alone is approximately EUR 37 billion a year. To help mobilize private finance, the EU has developed a framework for "nature credits" that seeks to reward investments in ecosystem restoration and protection. It defines nature credits as representing "an investment into nature-positive actions by a company, a financial institution, a public entity or a citizen, which in return can benefit from cleaner ecosystems, risk reduction, improved reputation and higher social acceptability for its projects" (EC, 2026a). For companies, nature credits are expected to support environmental, social and governance (ESG) reporting and biodiversity commitments, while potentially helping manage supply-chain and environmental risks. For land managers, nature credits could provide an additional revenue stream linked to ecosystem stewardship and restoration activities.

The "EU Roadmap towards Nature Credits (2025–2027)" has launched phase 1 with an expert group to co-develop certification standards, governance rules and pilot projects, and to start market assessments. Phase 2 is focused on developing methodologies and assessing demand, pricing potential and scalability. Phase 3 is slated to help in deciding whether to scale at the EU level and regulate more formally (EC, 2026b;Brancalion and Holl, 2020). The EU is piloting nature credit initiatives in France, Estonia, and Peru. The credits may also support countries in meeting national targets under the EU Nature Restoration Regulation and contribute to the Kunming-Montreal Biodiversity Framework.

Innovation examples

From agroforestry to carbon credits: scaling MRV in Colombia

Rabobank; Solidaridad



Source: Solidaridad Colombia

Acorn, developed by Rabobank with partners like Solidaridad, is a carbon finance program for smallholder agroforestry supported by a digital monitoring, reporting and verification (MRV) system that uses remote sensing, modelling and field data to verify carbon removals. Projects have been implemented across Africa, Latin America, and Asia, often on small farms (0.1–10 ha) where farmers integrate trees into crops like coffee or cocoa. The system takes a hybrid MRV approach, combining satellite imagery, AI and sometimes LiDAR with field data obtained from local partners in order to track tree growth and biomass increase over time. Measurements are converted into carbon removal units (CRUs) with monitoring conducted continuously rather

than through one-off audits. Credits are certified under the Plan Vivo and Verra standard, which ensures additionality, long-term commitments and community benefits. In Colombia, for example, coffee farmers have integrated shade-giving trees into their farms, with data from satellites enabling the low-cost measurement of tree-stored carbon. Farmers typically receive payments after a period of several years, once tree growth is detectable. One farmer sequestered +10 tonnes of CO_2on three hectares of land, generating income alongside coffee production. By linking remote sensing, plot-level traceability and certification, Acorn scales agroforestry activities and channels carbon revenue (up to ~70 percent) directly back to farmers, while supporting land restoration (Solidaridad Network, 2023;Acorn, 2026).

Mangroves meet MRV in Kenya in one of the first voluntary blue carbon credit projects

Association for Coastal Ecosystem Services (ACES), Kenya Marine and Fisheries Research Institute (KMFRI), Plan Vivo Foundation, Kenya Forest Service (KFS)



Source: Mikoko Pamoja Community-Based Organisation (MPCBO)

One of the clearest examples of how restoration technologies, carbon markets and community governance are converging is seen in Kenya's pioneering blue carbon projects, Mikoko Pamoja and Vanga Blue Forest. Developed along Kenya's southern coast, these mangrove restoration initiatives became the world's first community-led blue carbon projects to finance conservation through carbon credits linked to coastal ecosystem restoration. They combine mangrove restoration and protection with increasingly sophisticated monitoring, reporting and verification (MRV) technologies. Carbon accounting integrates field-based biomass inventories, tree measurements, sediment carbon sampling, GPS and GIS mapping, satellite remote sensing, aerial imagery and intensive ground-truthing to estimate carbon storage and monitor ecosystem change over time. Community members play a central role by monitoring forest condition directly on the ground, while spatial technologies track canopy cover, degradation and restoration progress across coastal landscapes. These datasets are incorporated into Plan Vivo-certified MRV systems requiring long-term monitoring, third-party audits and transparent reporting before credits can be issued. Importantly, revenues from carbon credits support local priorities including schools, freshwater infrastructure, health care and community services. These projects therefore represent an early example of "digital blue carbon" systems in which geospatial monitoring technologies and local stewardship are combined to make coastal restoration both measurable and financeable (Mikoko Pamoja, 2026; Plan Vivo, 2026a; b).

Scaling forest carbon in Europe with an integrated platform

Pina Earth, Tree.ly



Source: Photo by James Adams on Unsplash

Europe's forest carbon market has long been fragmented with small projects, different verification standards and limited access for landowners and buyers. The 2025 merger of companies Pina Earth and Tree.ly marks a shift toward a more scalable and integrated model. It will be Europe's first integrated forest carbon platform, combining project development, digital monitoring, certification and sales into a single system. Operating across Austria, Germany, Switzerland, and parts of Central and Southern Europe, the platform manages over 80,000 hectares of forest and has issued more than 500,000 tonnes of certified carbon credits to around 100 corporate buyers. The platform's core innovation lies in integrating software and automation into forest carbon projects. Pina Earth's proprietary forest simulation technology models carbon sequestration and forest growth, while Tree.ly's certification infrastructure supports multiple standards (e.g., ISO 14064-2) and methodologies such as improved forest management and afforestation. It connects landowners directly with buyers and streamlines certification across regions and project types. This means it also contributes to the strengthening of high-integrity credits aligned with emerging EU regulations (XAnge, 2026).

The following collection of technologies is divided into three groups: Proven technologies have been on the market for some time and hence are well tested, Frontier technologies are available but relatively new, while Horizon technologies are close to being available but still under development.

Proven technology solutions

Web-enabled reforestation and tree-planting platform

Grow-Trees.com



Source: Grow-Trees.com

Grow-Trees.com is a web-enabled reforestation and tree-planting platform that lets individuals and organizations plant trees online and track impact. Grow-Trees also works as a project developer for the carbon credit projects at scale. Its core technology integrates a digital tree-planting and tracking system with an AI-driven Monitoring, Reporting and Verification (MRV) platform that leverages geospatial intelligence, satellite-based vegetation indices, and machine learning to monitor restoration projects. Interactive dashboards visualize project boundaries, vegetation health, and changes over time, while geospatial tools support individual tree tracking, predictive modelling, and control-site comparisons to assess ecological trends and project outcomes. Together, these capabilities enable data-driven decision-making, automated reporting, and transparent, evidence-based monitoring of restoration efforts.

- Technological maturity: Proven
- Contracting type: For service contract
- Technology level: Medium
- Place of origin: India
- Availability: India, Tanzania, Uganda, Indonesia
- Contact: WIPO GREEN Database

Online tree plantation platform powered by geotagging and blockchain

SankalpTaru Foundation



Source: SankalpTaru Foundation

SankalpTaru is an IT-enabled environmental NGO that uses a blend of digital and field technologies to enhance transparency, monitoring, and ecological outcomes in tree planting. Each planted sapling is geo-tagged and given a unique digital identity with species, location, and growth data captured. This information is secured on blockchain (via Airchains.io) to create immutable, tamper-proof records of every tree to boost donor confidence and prevent fraud. The organization uses ForeSTation/ IoTree, a proprietary in-house IoT system for real-time soil and environmental parameter monitoring, alongside drone seed bombing for high-elevation terrain and AI-driven species selection These technology layers support better survival rates, smarter interventions, and transparent reporting of environmental impact.

- Technological maturity: Proven
- Contracting type: For service contract
- Technology level: Medium
- Place of origin: India
- Availability: India
- Contact: WIPO GREEN Database

Reforestation management platform

Land Life Company



Source: Getty Images/Daniel Balakov

Land Life technology integrates science, data, automation and field innovations to scale nature-based reforestation. It uses proprietary analysis and prediction models to evaluate sites, forecast carbon capture and determine the optimal mix of native species to fit local conditions. During planting, innovations, such as tree seeding robots, smart-coated seeds and advanced planting techniques, improve speed, survival and resilience. After planting, monitoring combines ground, aerial and satellite data feeding a global database that tracks tree growth, health, survival rates and ecosystem outcomes. This data-driven loop continuously improves design and delivery, while dashboards allow partners to view project impact.

- Technological maturity: Proven
- Contracting type: For service contract
- Technology level: High
- Place of origin: Kingdom of the Netherlands
- Availability: Worldwide
- Contact: WIPO GREEN Database

Aerial ecosystem restoration system

AirSeed Technologies



Source: Photo by Max Mustermann on Unsplash

AirSeed Technologies is an Australian aerial ecosystem restoration company. It combines heavy-lift drones, AI-driven planning, proprietary seed pod biotechnology and digital project management to scale reforestation and land rehabilitation. Its patented seed pods are engineered with nutrients, microbial amendments and protective coatings to boost germination, reduce predation and adapt to varied soils and climates. Custom drones fly autonomously along optimized GPS flight paths and plant the seed pods precisely across remote, steep or fragile landscapes at rates far quicker and more cost-effective than manual planting. The company's Grovia digital platform integrates ecological assessments, species selection, optimized planting plans and real-time monitoring to improve decision-making and track restoration outcomes.

- Technological maturity: Proven
- Contracting type: For service contract
- Technology level: High
- Place of origin: Australia
- Availability: Australia
- Contact: WIPO GREEN Database

Carbon management and advisory platform

Carbon Direct



Source: Getty Images/Fahroni

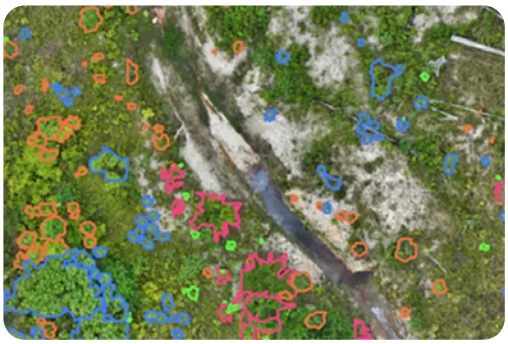
Carbon Direct is a science-driven carbon management and advisory platform that evaluates, rates and guides investment into high-quality forest and ecosystem restoration carbon projects, helping assess whether they meet scientific quality criteria and are likely to deliver durable climate and biodiversity benefits. The platform combines climate science, risk analysis and carbon market expertise to support corporate and governmental clients in sourcing verified carbon removal solutions, conducting due diligence and developing net-zero strategies. Carbon Direct plays a key role in connecting buyers to credible nature-based and engineered carbon removal projects.

- Technological maturity: Proven
- Contracting type: For service contract
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier technology solutions

Forest restoration intelligence platform

MORFO



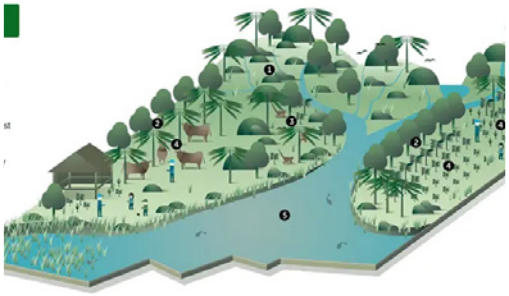
Source: MORFO

MORFO is a science-driven forest restoration platform combining AI, drone technology and ecological methods to restore degraded lands at scale. Its Forest Intelligence system uses satellite and aerial imagery, soil and vegetation diagnostics, and AI-driven models to identify optimal restoration areas, design planting strategies and forecast ecosystem recovery. The Forest Operations component deploys drones and proprietary seedpods to plant native species efficiently, while protecting young seedlings. Finally, Forest Performance continuously monitors restoration outcomes using drones, satellite data and AI analytics, tracking biodiversity, biomass and tree survival, while providing dashboards for transparent reporting.

- Technological maturity: Frontier
- Contracting type: For service contract
- Technology level: High
- Place of origin: France
- Availability: Latin America and tropical regions
- Contact: WIPO GREEN Database

Biotech-enabled ecosystem restoration platform with digital field monitoring

Viridis Terra International



Source: Viridis Terra International

Viridis Terra's Integrated Forest Landscape Restoration (IFLR)® is an ecosystem restoration model. It combines biotechnologies, digital monitoring and scalable field systems to restore degraded forests and agroforestry landscapes with ecological and economic benefits. Advanced biotechnologies include proprietary bioformulations (Sylven®, Microlignum®) that increase both seed germination and plant establishment rates, specialized out-planting substrates (Sustrato®) for higher survival and biofertilizers (TreeBoost®) with microbial inoculants that boost growth in degraded soils. It also uses phenomics and genomic tools, genetic marker-assisted selection and micropropagation to produce high-quality, genetically diverse plant stock. On the digital side, Viridis Terra operates a centralized platform for tracking field operations, carbon capture data, land management models, contracts and SDG progress.

- Technological maturity: Frontier
- Contracting type: For service contract
- Technology level: High
- Place of origin: Canada
- Availability: Latin America and Caribbean
- Contact: WIPO GREEN Database

Blockchain-enhanced digital biodiversity credit issuance and tracking platform

Terrasos



Source: Photo by Giselle Cucunubá Manes on Unsplash

Terrasos has developed a protocol for issuing high-integrity biodiversity credits called Tebu® – digital units that represent a conserved or restored ecosystem area under long-term (20+ year) protection. The Terrasos Protocol defines how these Voluntary Biodiversity Units are quantified, monitored and released based on ecological and management milestones. Projects meeting performance standards are independently validated and listed in official registries. To strengthen traceability and prevent double-counting, Terrasos integrates digital ledger technology (blockchain) into Tebu's traceability framework, embedding credit ownership and history on an immutable platform. This digital backbone supports transparent reporting and market confidence in biodiversity outcomes.

- Technological maturity: Frontier
- Contracting type: For service contract
- Technology level: High
- Place of origin: Colombia
- Availability: Latin America
- Contact: WIPO GREEN Database

Reforestation automation technology

Flash Forest



Source: Flash Forest

Flash Forest uses advanced reforestation automation technology combining drones, AI, GIS, engineering, silviculture and plant science to rapidly restore forests at scale. The system begins with machine learning and GIS mapping to identify optimal planting locations. Specialized heavy-lift drones then deploy proprietary biodegradable seedpods – each containing nutrients, water-retention additives and beneficial microbes – directly into the soil. This aerial approach enables planting that is far quicker and more efficient than traditional methods, including in remote or post-wildfire terrain, while bypassing energy-intensive nurseries. Flash Forest also uses automated manufacturing to mass produce seedpods and supports field operations with complete drone kits and pilots.

- Technological maturity: Frontier
- Contracting type: For service contract
- Technology level: High
- Place of origin: Canada
- Availability: Northern America
- Contact: WIPO GREEN Database

Environmental monitoring and verification platform

Treefera



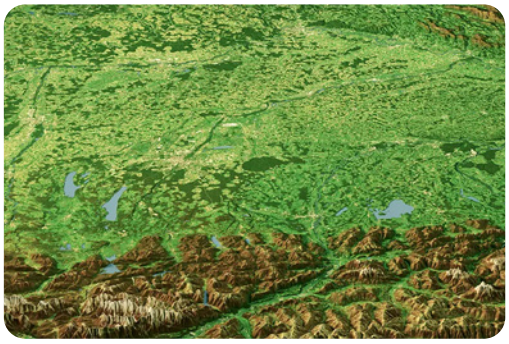
Source: Getty Images/kev303

is an AI-powered environmental intelligence platform combining satellite imagery, drone, sensor, weather and ground data to monitor ecosystems, land use and supply chain origins. Using machine learning and scientific modelling, it converts environmental data into real-time insights on vegetation, deforestation, soil conditions, carbon stocks and ecological risks. The platform specializes in mapping the “first mile” of agricultural and forestry supply chains – where environmental and social risks are often least visible – helping organizations assess and demonstrate whether commodities are sourced from areas associated with deforestation or land degradation risks. Treefera also supports forest carbon and nature-based projects by providing transparent data for monitoring impact, assessing risk, validating carbon claims, and meeting sustainability and regulatory compliance requirements.

- Technological maturity: Frontier
- Contracting type: For subscription or service contract
- Technology level: High
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Blockchain-enabled digital infrastructure for forest carbon projects

Open Forest Protocol



Source: Getty Images/FrankRamspott

Open Forest Protocol (OFP) is a digital infrastructure for forest carbon projects that modernizes monitoring, reporting and verification (MRV) using advanced digital tools and decentralized technology. It combines mobile and web apps with satellite imagery, drones, AI analytics and LiDAR to improve the accuracy of forest and carbon monitoring. Project data is stored and verified on the NEAR Protocol – a decentralized blockchain system that creates secure, transparent and tamper-resistant digital records. Verified by a global network of independent validators, the system can mint carbon credits on-chain with embedded project data, geolocation and verification history.

- Technological maturity: Frontier
- Contracting type: For subscription or service contract
- Technology level: High
- Place of origin: Switzerland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Carbon market platform combining digital MRV and blockchain technology

CYNK



Getty Images/Frazao Studio Latino

CYNK is an end-to-end carbon market platform combining digital MRV (monitoring, reporting, verification), IoT sensors, satellite data and distributed ledger (blockchain) technology. It collects real-time environmental data from projects, verifies emissions reductions and converts them into tokenized carbon credits with a transparent audit trail. The platform then enables these credits to be financed, managed and traded through a built-in marketplace, aiming to reduce costs, increase transparency and connect projects directly with global buyers.

- Technological maturity: Frontier
- Contracting type: For subscription or service contract
- Technology level: High
- Place of origin: Kenya
- Availability: Africa
- Contact: WIPO GREEN Database

Geospatial data platform for land restoration efforts

UNCCD



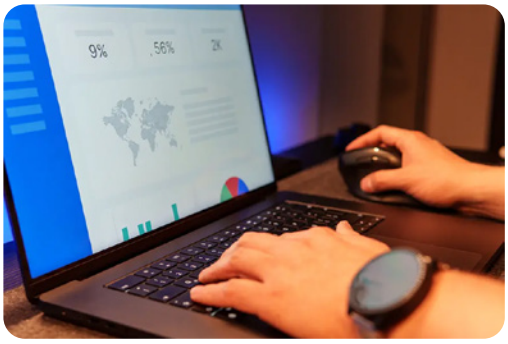
Source: Getty Images/mtcurado

GeoGLI is a geospatial data platform built by the G20 Global Land Initiative to monitor and support global land restoration efforts. It works by aggregating large datasets – satellite imagery, environmental indicators and country-level reports – into an interactive, map-based system. Users can explore trends like land degradation, drought or restoration progress in near real time and generate custom visualizations or reports. The platform's core function is decision support: it helps governments, researchers and NGOs identify priority areas for conservation or restoration by highlighting where ecosystems are either deteriorating or improving. It also tracks national commitments across global agreements (e.g., climate and biodiversity targets).

- Technological maturity: Frontier
- Contracting type: Open access platform
- Technology level: High
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Open access ecosystem restoration data and monitoring platform

Restor



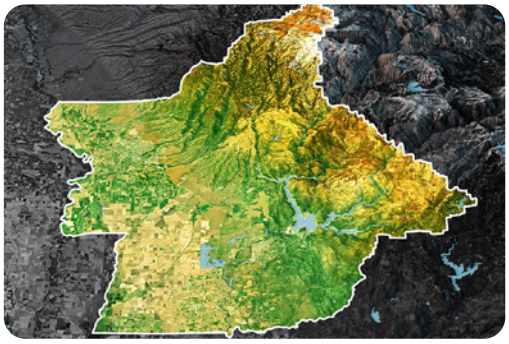
Source: Getty Images/fx-visual

Restor is an open access, geospatial data platform that uses satellite imagery, ecological datasets and machine learning to map, monitor and analyze ecosystem restoration globally. Built on tools like Google Earth Engine, it aggregates high-resolution environmental data such as biodiversity, soil carbon, rainfall and land cover, turning it into location-specific insights for any piece of land. Users can upload their project data, which is then combined with these global datasets to track changes over time, assess restoration impact and compare outcomes across sites. The platform also connects projects to funders and collaborators.

- Technological maturity: Frontier
- Contracting type: Open access platform
- Technology level: High
- Place of origin: Switzerland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Wildfire and landscape resilience intelligence platform

Vibrant Planet



Source: Getty Images/FrankRamspott

Vibrant Planet provides a data-driven decision-support platform designed to help governments, utilities and land managers reduce wildfire risk and improve ecosystem resilience. The technology combines satellite imagery, LiDAR and other geospatial data with AI and advanced wildfire modeling to create detailed maps of landscapes, vegetation and risk. It then simulates different land management scenarios, such as thinning or controlled burning, and predicts the impact on wildfire behavior, carbon storage, water and biodiversity. The platform helps users prioritize where to act and allocate budgets, and coordinate across stakeholders.

- Technological maturity: Frontier
- Contracting type: For subscription
- Technology level: High
- Place of origin: United States
- Availability: United States
- Contact: WIPO GREEN Database

Tech-enabled forest restoration and carbon removal company

re.green



Source: re.green

re.green uses a technology-enabled approach to restore degraded tropical forests at scale. Its platform combines satellite imagery, geospatial analytics and AI-driven modeling to identify priority areas for restoration and design optimal planting strategies. It integrates ecological data with operational data to guide species selection, planting density and long-term forest management. The system also monitors forest growth, carbon sequestration and ecosystem recovery over time using remote sensing and field data. This enables the generation of high-quality carbon credits and the tracking of biodiversity outcomes.

- Technological maturity: Frontier
- Contracting type: For service contract
- Technology level: High
- Place of origin: Brazil
- Availability: Brazil
- Contact: WIPO GREEN Database

Horizon technology solutions

AI-powered forest carbon and biodiversity MRV platform

Kanop, supported by the ESA



Source: Getty Images/FrankRamspott

The Kanop AI-powered Forest Carbon and Biodiversity MRV Platform is an European Space Agency (ESA)-supported demonstration project developing a next-generation digital platform for measuring, reporting and verifying (MRV) nature-based restoration outcomes. The cloud-based platform combines AI with multispectral, radar and LiDAR satellite imagery to automatically estimate forest carbon stocks, tree species composition, canopy height, above- and belowground biomass, and biodiversity indicators. Designed to reduce the cost and complexity of conventional field-based monitoring, the platform generates standardized digital maps and automated MRV reports to support project developers, investors, consultants and regulatory reporting. By integrating multiple Earth observation datasets into a scalable software-as-a-service (SaaS) platform, the technology aims to improve the transparency, efficiency and credibility of carbon accounting, while supporting compliance with emerging sustainability regulations and voluntary carbon markets. The project is currently under development.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: France
- Availability: Under development
- Contact: WIPO GREEN Database

Next-generation framework for MRV of soil organic carbon

GMV Aerospace and Defence S.A.



Source: Getty Images/microgen

MRV4SOC (Monitoring, Reporting and Verification of Soil Organic Carbon and Greenhouse Gas Balance) is a Horizon Europe project developing a next-generation framework for monitoring, reporting and verifying (MRV) soil organic carbon and greenhouse gas balances to support carbon farming and voluntary carbon markets. Coordinated by GMV Aerospace and Defence S.A. (Spain), the project combines remote sensing, high-quality field measurements, ecosystem modeling and digital data integration to create a standardized Tier 3 MRV methodology capable of estimatingfull carbon budgets across diverse ecosystems. The framework accounts for above-andbelowground biomass, soil organic carbon, deadwood, litter and harvested woodproducts, while incorporating carbon and nitrogen cycles. Designed to improve theaccuracy, transparency and cost-effectiveness of soil carbon accounting, MRV4SOCaims to strengthen confidence in carbon credits and support the development ofrobust carbon farming markets.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: Spain
- Availability: Under development
- Contact: WIPO GREEN Database

3 Ocean ecosystems





The ocean is not a simply victim of climate change – it is the planet's strongest defense system. It has protected humanity from the brunt of global warming by absorbing more than 90 percent of the excess heat trapped by greenhouse gases (GHGs) and roughly a quarter of the carbon dioxide (CO_2) emitted by human activity. Since the early 1990s, ocean temperatures and heat content have steadily increased. And the pace of warming has nearly doubled over the past two decades, making it a clear indicator of accelerating global warming (UNESCO, 2026). However, the ocean's climate-regulating role comes at a cost. Those same mechanisms responsible for buffering the climate are fundamentally altering the physics and chemistry of the marine environment, creating three major stressors that threaten marine ecosystems – warming, acidification, and circulation disruption.

> The ocean is not simply a victim of climate change – it is the planet's strongest defense system

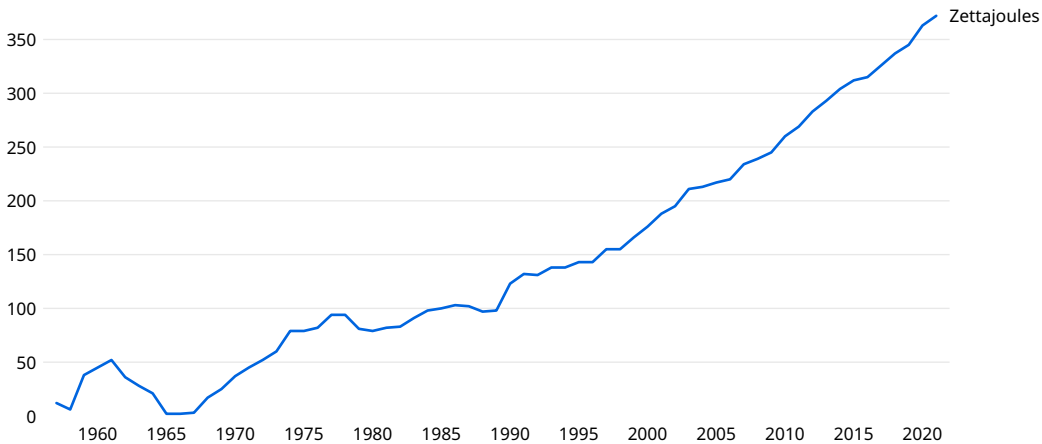
This chapter examines these interconnected pressures and the technologies emerging to better understand and respond to them. New tools are linking environmental monitoring, machine learning and automated systems in support of more adaptive approaches to ocean management. Sensor networks, satellites and autonomous vehicles are able to collect continuous data concerning ocean conditions, which feed digital twins and AI-based models capable of forecasting events such as marine heatwaves, coral bleaching or oxygen depletion weeks to months in advance. These forecasts can help guide restoration and create a continuous cycle between monitoring, prediction and action. Beyond monitoring and prediction, technologies are increasingly enabling large-scale ecosystem restoration. Robotics, AI and advanced materials are making coral propagation and habitat reconstruction more precise, scalable and data driven. Automated reef deployment systems, AI-guided site selection and engineered reef structures are helping restore degraded habitats, while improving survival rates and long-term ecosystem stability.

3.1 Ocean warming

Slowing global warming, but heating and stressing the seas

The ocean helps stabilize Earth's climate by absorbing heat from the atmosphere, thereby moderating global temperatures. To grasp the sheer scale of heat stored in the ocean, consider this: between 1993 and 2022 the ocean absorbed more than 800 times the total amount of energy represented by all the electricity used in the United States in 2022 alone (NOAA, 2026c). The world's average sea surface temperature reached a new record of 21.1°C in August 2026 (Poynting, 2026) Figure 3.1 depicts ocean heat content changes from 1955 to 2024.

Figure 3.1 Ocean heat content changes since 1955 (zettajoules)



Note: The graph shows the rise in heat for the top 2,000 meters of ocean since 1955, when modern record keeping began, as tracked by the National Oceanic and Atmospheric Administration (NOAA). Each data point represents a five-year average. For example, the 2022 value represents the average change in ocean heat for the years 2020 up to and including 2024 compared to the 1955 value.

Source:WOD Team, 2025.

Heat absorption in the ocean is driven by two physical phenomena – *albedo* and *specific* heat capacity (NOAA, 2026c). Because it is dark, the ocean has a low albedo and therefore retains more heat than it reflects. Oceans cover 70 percent of the planet and thus comprise a very large repository for excess heat. Another reason the ocean is such an effective heat reservoir is its high specific heat capacity. It takes much more energy to raise the temperature of water by one degree than it does for air. This means that even small changes in ocean temperature reflect enormous amounts of heat absorbed over time, highlighting the ocean's crucial role in moderating global warming (NOAA, 2026c).

As ocean waters warm, they suffer various detrimental effects. First, warming reduces the amount of dissolved oxygen in seawater. This process is called deoxygenation and leads to the expansion of low-oxygen regions harmful to marine ecosystems. Rising temperatures also increase ocean stratification, meaning that the difference in temperature between surface and deeper waters differs more markedly. This "layering" effect limits vertical mixing, preventing nutrients trapped in deeper waters from circulating upward and supporting marine ecosystems (NOAA, 2026b). In addition, the exchange between the ocean and atmosphere affects how much heat and moisture the air can hold and in turn influences weather, with warmer ocean waters linked to stronger storms and longer-term climatic events such as El Niño and La Niña (NOAA, 2026b).

Ocean on fire: marine and super marine heatwaves

A marine heatwave (MHW) is an extended period of unusually high ocean temperatures relative to the local climate. It is akin to a "heatwave in the ocean," a sustained, abnormally warm event that lasts more than five consecutive days with temperatures above the 90thpercentile of the historical baseline (1 to 2 degrees Celsius higher than the seasonal average) (Gattuso *et al.*, 2015). An MHW typically lasts between five and 15 days, with some areas averaging up to 30 days. Most regions experience between one and two such events a year, though this rate is increasing (Oliver *et al.*, 2018). To better predict MHWs and understand the impacts, we need to learn what causes them and how they develop through the full depth of the ocean. Understanding these dynamics is crucial not just for science, but for guiding technologies and strategies for monitoring, predicting and mitigating the impacts of ocean warming.

Sea surface temperature (SST) refers to the warmth of the ocean's upper layer, usually the top few meters. It is measured through satellite imagery, as well as direct observations taken from ships, drifting and moored buoys, and autonomous surface vehicles. Scientists have found that global average sea surface temperatures reached unprecedented highs in 2023, breaking historical records. The extreme and unusually persistent MHWs in 2023 were so powerful that researchers introduced the term "super-marine heatwaves" to describe sea surface temperatures in excess of the highest values recorded between 1982 and 2022 (NOAA, 2024).

> Extreme and unusually persistent marine heatwaves in 2023 were so powerful that researchers introduced the term "super-marine heatwaves"

Super-marine heatwaves were detected in many regions, including tropical and polar waters. The underlying causes for these record temperature levels are linked to long-term GHG warming, a shift to the warm phase of a Pacific–Atlantic–Arctic climate mode, and a transition from long-lasting La Niña conditions to a strong El Niño. Such extreme MHWs can stress ocean ecosystems and fisheries, coral reefs and marine life, while also influencing weather events such as storms.

Marine heat waves are a fast evolving area of research. At the National Oceanic and Atmospheric Administration (NOAA) Physical Sciences Laboratory, scientists are characterizing MHWs and learning how they form and dissipate in order to predict them better (NOAA, 2026a). Multi-platform systems are emerging that can depict their three-dimensional structure in real-time,

while also improving understanding of the local and remote drivers. There are also more frequent investigations being made into subsurface waves and evolving prediction capabilities (Capotondi *et al.*, 2024).

However, more research is necessary if we are to develop a better assessment of predictability – and understand the large-scale drivers both regionally and during different seasons. One key question is whether the climate models currently in use are able to simulate MHW mechanisms. Some researchers argue that a greater focus is needed on developing higher resolution global and regional models (Capotondi *et al.*, 2024). We are only beginning to understand the consequences for marine life, weather extremes and air–sea CO_2 fluxes. Global observations using satellites and Argo, a global network of autonomous profiling floats that measure ocean temperature and salinity, along with regional observations from moorings, are needed, alongside rapidly deployed real-time monitoring systems and models, to assess how extreme warm events compare to longer-term changes (Capotondi *et al.*, 2024).

Underwater heat stress – coral, fish and ecosystems at risk

Ocean warming is the primary cause of coral bleaching, a phenomenon whereby corals expel symbiotic microscopic algae (*zooxanthellae*) due to thermal stress and turn white (Coral Reef Alliance, 2023). A temperature increase of just 1°C for a period of four weeks can initiate bleaching, although changes in water quality and increased sun exposure can also contribute (Great Barrier Reef Foundation, 2026). Coral cannot survive very long in this state, meaning persistent, elevated temperatures can lead to mass mortality. However, if the stressor is removed in time, *zooxanthellae* can return and recovery is possible.

In 2024, the International Coral Reef Initiative (ICRI) declared the fourth global coral bleaching event, and bleaching continues to intensify worldwide. Between January 2023 and March 2025, severe heat stress causing bleaching affected 84 percent of the world's coral reefs. To put this into perspective, 21 percent of reefs were affected in 1998, 37 percent in 2010, and 68 percent between 2014 and 2017 (ICRI, 2025). Over 50 percent of the world's reefs suffered moderate to severe bleaching during 2014–2017 (Science Daily, 2026), while the Great Barrier Reef has experienced five mass bleaching events during the last eight years (Great Barrier Reef Foundation, 2026). In response, bleaching alert systems have expanded warning scale to include the possibility of losing more than 80 percent of corals on some reefs through prolonged heat stress (Great Barrier Reef Foundation, 2026). Marine heatwaves driving coral reef die-offs threaten habitats that support about a quarter of all marine life. This could have serious economic consequences, especially for small-scale fisheries in tropical regions where millions of people depend on fish for food and income.

> Between January 2023 and March 2025, severe heat stress causing bleaching affected 84 percent of the world's coral reefs

Warmer water alters organism metabolism by increasing oxygen demand (EEA, 2023). As temperatures rise, many fish are becoming smaller, with tropical reef species projected to shrink significantly by mid-century. In some tropical regions, total fish biomass could decline by between 30 and 40 percent by 2100 (WWF-Germany, 2026). Warmer waters also pushing species toward cooler, higher latitudes, shifting ecosystems and leading to the "tropicalization" of temperate seas and the decline of cold water species. While polar regions may see incoming species increase, tropical areas are expected to lose biodiversity, with some local extinctions of key species. Species relocate at different rates, which disrupts established predator–prey relationships (WWF-Germany, 2026). At the same time, fish face physiological stress as the result of warm water holding less oxygen, even as higher temperatures increase metabolic oxygen demand, thus limiting growth and reproduction rates. Warming can also disrupt timing, causing spawning or migration to occur earlier and no longer align with peak prey availability.

Marine heatwaves render ecosystems more vulnerable to additional stressors, including the spread of non-native species. A decline in native species creates ecological gaps that can be quickly occupied by newcomers, and these species can become invasive when they take over available niches (EEA, 2023).

Ocean warming is a major driver of deoxygenation, because warmer water contains less dissolved oxygen. This is worsened by increased stratification, which limits mixing between surface and deeper waters and reduces nutrient exchange, disturbing marine food webs starting with phytoplankton and cascading up through higher trophic levels. In coastal areas, deoxygenation is also driven by eutrophication caused by excess nitrogen and phosphorus from agriculture, together with sewage and runoff, stimulating algal blooms. As the algae die and decompose, microbes consume oxygen, creating hypoxic (low-oxygen) and anoxic (no oxygen) zones that can be deadly for many species (EEA, 2023). Since the 1950s, oxygen-depleted coastal areas have increased fourfold. Globally, ocean oxygen levels are projected to decline by between 3 and 4 percent by 2100 (Bopp *et al.*, 2013).

These changes do not just affect marine life; they influence global fisheries, weather patterns and carbon cycles, with real consequences felt by human communities and economies.

Building ocean resilience with robotics, AI and digital twins

Three clear trends are emerging across those technologies that address ocean warming, namely: automation, biological acceleration and predictive intelligence. First, automation and robotics are scaling reef monitoring and restoration. Autonomous underwater vehicles (AUVs), surface drones, AI-guided deployment systems and 3D scanning tools are replacing diver-based surveys and manual coral planting. These systems collect high-resolution data, plant corals precisely and monitor growth consistently, which speeds restoration and renders it more scalable.

Second, many solutions are focusing on actively rebuilding reef ecosystems rather than just observing decline. Techniques like coral gardening, micro-fragmentation, larval seeding, artificial reef substrates, electrified reef structures and modular reef systems are designed to accelerate coral growth, improve survival, stabilize damaged sea beds and enhance resilience to both warming and acidification. Some approaches even experiment with assisted evolution – or breeding new varieties, including gene editing designed to condition corals to tolerate higher temperatures.

> There is a shift away from reactive conservation toward data-driven ocean restoration combining robotics, AI, predictive modeling and ecological engineering

Third, there is a clear shift toward early warning. As with disaster response (see the *Green Technology Book* Climate disaster response edition), there is a shift away from reactive conservation toward data-driven ocean restoration combining robotics, AI, predictive modeling and ecological engineering in support of marine ecosystems. These tools predict heat stress months in advance, detect biodiversity changes at the molecular level, and help guide where intervention will be most effective. High-resolution satellite monitoring, MHW forecasting, AI-based bleaching prediction, digital twin ocean models, acoustic monitoring and environmental DNA (eDNA, see Box 3.1 for explanation) sampling are enabling the near-real-time tracking of ocean conditions.

Digital twins of the ocean are virtual representations of marine systems that integrate satellite observations, sensor networks, AI, and ocean models to create a near-real-time simulation of the entire ocean. Emerging digital twin platforms incorporate autonomous sensing and advanced

analytics to produce detailed 3D maps. Collaborative initiatives, such as the European Union (EU) Iliad project, aim to establish interoperable, data-intensive and cost-effective Digital Twins of the Ocean (DTOs). The Iliad DTOs combine a large volume of data to enable simultaneous communication with real world models, and integrate all existing EU Earth observing and modeling digital infrastructure and facilities to promote additional applications to be accessed at the Iliad Marketplace. They include plug-ins interfaces, raw data, citizen science data, and synthesized information. It is anticipated that Iliad DTOs will contribute to the achievement of the UN Ocean Decade (European Commission, 2026).

Likewise, Fujitsu's advanced digital twin system uses AUVs equipped with LiDAR, cameras and sensors to scan coral reefs and seaweed beds. Drones are able to collect data even in a strong current, which are then processed through AI models to identify organisms, map structures and estimate specific properties like carbon absorption (Boreham, 2024).

Systems such as NOAA's Coral Reef Watch use satellite data and physical climate models to calculate indicators such as HotSpot and Degree Heating Weeks in order to estimate bleaching risk (NOAA, 2021). Other NOAA research systems incorporate AI and expert-system forecasting tools combining multiple environmental datasets to generate ecological forecasts (Gramer *et al.*, 2026).

The Allen Coral Atlas, managed by Arizona State University, illustrates how AI and satellite monitoring are together transforming coral reef conservation. Using machine learning and high-resolution satellite imagery, it has produced the first comprehensive map of benthic habitats and reef geomorphology, enabling managers to monitor reef condition at unprecedented scale (Coral Reef Alliance, 2026). The platform's "Reef Threats" system tracks bleaching risk, water turbidity and other stressors, while a bleaching alert system combines Sentinel-2 imagery with NOAA's Coral Reef Watch data to provide near-real-time alerts at 10 meter resolution. These capabilities support the earlier detection of reef decline and a more targeted conservation and restoration response (Coral Reef Alliance, 2026).

Scaling ecosystem restoration and ecological engineering

Environmental DNA refers to genetic material shed by organisms into water, sediment or air. Sampling eDNA allows scientists to detect species presence, track biodiversity changes and monitor ecosystem health without the need to capture organisms directly. These analyses are therefore a quick and cost-effective way of detecting the presence of species and assessing wildlife communities and biodiversity (IUCN, 2026). See Box 3.1 to read more about the power of eDNA.

> Innovations are shifting coral restoration from small-scale conservation toward scalable, industrialized systems combining coastal engineering, robotics, AI, evolutionary biology and advanced materials

Automation and AI are transforming coral husbandry. The CHARM system automates coral care, with autonomous underwater robots feeding and monitoring farmed corals, and AI-guided vessels ensuring precise seeding and long-term tracking. Biological acceleration techniques, including microfragmentation, assisted evolution and coral paint (larval hydrogel combined with modular reef mesh), can speed coral growth and settlement. Complementary interventions, such as low-voltage electrified reef structures (Biorock) and mesh structures (e.g., Kajima Corporation), improve coral survival, promote natural recruitment and increase bleaching resistance.

Biorock works by passing a low-voltage electrical current through a submerged structure, thereby stimulating the deposition of limestone-like minerals from seawater and creating favorable conditions for coral attachment and skeletal growth. By facilitating calcium carbonate formation, proponents argue that corals can devote less energy to calcification and more to growth and recovery. Coral and other reef organisms on powered Biorock structures can grow 2–10 times faster than under natural conditions (GCRA, 2022). Corals growing on Biorock reefs in Indonesia experienced significantly reduced bleaching, higher survival rates and faster recovery after severe heat events (including in 2016 and 2020), with many fully recovering while nearby natural reefs underwent extensive mortality (GCRA, 2020). These electrified structures also act as habitat for fish and other marine life and promote biodiversity. They also help reduce beach erosion by slowing wave energy. AI-designed artificial reef substrates can be tailored to local ecosystems to enhance colonization and habitat complexity. These innovations are shifting coral restoration away from small-scale conservation and toward scalable, industrialized systems combining coastal engineering, robotics, AI, evolutionary biology and advanced materials.

The *Greeen Technology Book* Adaptation edition features several innovative technologies for coral restoration. Reef balls, for example, are hollow concrete structures that reduce wave energy and create marine habitat. Archireef, working alongside researchers at the University of Hong Kong, is developing modular, 3D-printed terracotta reef tiles that mimic natural reef chemistry. See also the *Green Technology Book* Climate disaster response edition for more artificial reef technologies. A smaller technological frontier intervenes more directly using technologies, such as localized reef cooling pod system (oPod), or techniques to counter deoxygenation, such as experimental ocean reoxygenation using industrial by-products (see Innovation examples), though they remain at an early stage.

Box 3.1 eDNA reveals biodiversity

Environmental DNA (eDNA) refers to genetic material shed by organisms in the environment. Sampling eDNA allows scientists to rapidly detect species presence and monitor biodiversity. Applied Genomics (see Proven technology solutions) conducted a study to evaluate whether eDNA sampling could more effectively monitor biodiversity and detect ecosystem change compared to traditional scientific trawling methods (Applied Genomics, 2026). The company analyzed 460 seawater samples using both small- and high-volume sampling methods. Results showed that high-volume eDNA collected 20 times more DNA than smaller volume samples and detected more biodiversity than trawling, identifying 1,525 additional species overall. eDNA also demonstrated greater sensitivity to subtle ecosystem changes. Most significantly, the study revealed a decline in overall fish biodiversity, with marked reductions in bottom feeders, fish-eaters and generalist feeders, indicating a loss of marine food web complexity and declining ecosystem health.

Speculative ocean intervention: reoxygenation and upwelling

Artificial ocean reoxygenation is an emerging ocean intervention aimed at mitigating hypoxia and dead zones. It involves the intentional addition of oxygen to low-oxygen (hypoxic) or oxygen-depleted (anoxic) seawater, typically in areas where warming, nutrient pollution or stratification is reducing dissolved oxygen. While it has potential benefits – such as maintaining viable habitats for fish, plankton and benthic organisms, reducing harmful algal blooms and mitigating dead zones – it requires careful monitoring, deployment and long-term environmental assessment. Technologies include oxygen injection – often using oxygen co-produced from offshore hydrogen electrolysis – and mechanical or bubble-based oxygenation systems. Challenges include overcoming stratification to ensure oxygen reaches a necessary depth without causing harmful circulation effects. A key limitation is scale: although reoxygenation can be applied in localized hypoxic areas, the vast volumes of water involved make broader deployment across large marine ecosystems technically challenging and energy intensive. That the process is energy-intensive means it can also have unintended chemical impacts, for example, altered nitrogen, iron and sulfur cycles.

Artificial upwelling and downwelling are experimental ocean engineering approaches that bring deep, cold, nutrient-rich water to the surface (upwelling) or transport warm surface water to deeper layers (downwelling) in order to influence local temperature, nutrient availability and ocean circulation. Upwelling may enhance biological productivity and carbon uptake, while downwelling is being explored as a way of reducing local heat stress and delivering oxygen-rich surface water to deeper waters. However, these approaches remain at an early research stage, with effectiveness, scalability and the potential ecological side-effects uncertain.

Tracking marine wildlife in a warming ocean

Ocean warming is affecting marine life in three major ways: first, by shifting species distribution; second, by altering performance and survival; and third, by changing food webs and ecosystem interactions.

> Ocean warming is reshaping species distribution, migration patterns and ecosystem interactions

Salmon is cold-water fish that spends part of its life in rivers and part in the ocean. It is widely regarded as a sentinel species – an early indicator of broader ecosystem change and climate impacts – because it depends on not only on freshwater, but also coastal and open-ocean ecosystems throughout its life cycle (Crozier *et al.*, 2021). Ocean warming is increasingly affecting salmon during the marine phase when most of the energy needed for reproduction is obtained. Rising sea temperatures alter food web structure, prey distribution, predator–prey interaction and broader ecosystem dynamics (NOAA, 2022; Crozier and Siegel, 2023). Marine heatwaves, such as the 2014–2016 Northeast Pacific "Blob," have disrupted food webs and reduced juvenile salmon survival by decreasing prey availability and ecosystem productivity (Connors *et al.*, 2025). Researchers are also observing a shift toward cooler northern waters, changes in feeding grounds, altered depth use and modified migration routes as salmon respond to changing ocean conditions (Connors *et al.*, 2025;Crozier and Siegel, 2023).

Large whales are also indicators of climate impacts on marine ecosystems, because migration is closely tied to the distribution of prey and broader oceanographic conditions (Meyer-Gutbrod *et al.*, 2021; Record *et al.*, 2019). Ocean warming is altering the abundance and location of plankton and small forage species, causing some whale populations to shift their feeding and migration ranges (Meyer-Gutbrod *et al.*, 2021; Record *et al.*, 2019). One of the best documented examples is the North Atlantic right whale, whose primary prey has moved northward as ocean conditions have changed. This shift into new areas has increased the exposure of right whales to ship strikes and fishing-gear entanglement in regions where management measures are not designed to protect them (Davies and Brillant, 2019; Meyer-Gutbrod *et al.*, 2021; Record *et al.*, 2019).

Similar climate-related changes have been observed in humpback whales. Long-term climate tracking reveals that warming ocean temperatures, MHWs and disappearing polar sea ice are directly degrading humpback whale habitats (NOAA Fisheries, 2026). One of the most significant impacts of this is a disruption to food supply. As sea ice melts, foundational prey species like Antarctic krill either shift location or decline, causing humpback whales nutritional stress and reducing calving rates (Dunlop *et al.*, 2025). Consequently, visual and acoustic data show humpback populations shifting historical migration schedules and returning from breeding grounds up to three weeks earlier than previously (Dunlop *et al.*, 2025). This is also instigating a departure from traditional routes in favor of foraging in heavily trafficked coastal areas.

Tuna are highly sensitive to ocean temperature and oxygen conditions, making them particularly responsive to ocean warming and MHWs. With suitable habitats shifting, tuna distribution, migration routes and fishing grounds are changing across many ocean regions. Warming oceans are also driving a poleward shift in tuna distribution and altering the location of productive fishing grounds, with implications for national fisheries, coastal economies and international fisheries governance.

These examples illustrate how ocean warming is reshaping species distribution, migration patterns and ecosystem interactions. In response, a growing suite of technologies is being developed to monitor temperature, animal movements, behavior, health and ecosystem change. Increasingly, marine animals themselves are becoming part of ocean observing systems through electronic tags to record movement, depth, temperature and habitat use, turning animals into mobile ocean sensors. Autonomous vehicles and smart sensors are enabling the continuous near-real-time monitoring of marine ecosystems. AI is transforming marine monitoring by automating the identification of species, analyzing acoustic recordings and imagery, detecting animals in satellite observations, and forecasting ecosystem change at a large scale. Modern monitoring platforms combine satellite observations, underwater acoustics, environmental DNA, oceanographic sensors and AI analytics into integrated systems.

Increasingly, marine animals themselves are becoming part of ocean observing systems through electronic tags that record movement, depth, temperature and habitat use, turning animals into mobile ocean sensors

Whales, dolphins and other marine mammals communicate acoustically. New marine mammal acoustic monitoring systems use hydrophones, AI-powered sound recognition and real-time species detection to identify whale presence, migration changes and behavioral responses to warming and shipping noise (Box 3.2). Acoustic telemetry tracks fish movements through acoustic tags attached to fish such as salmon, tuna, cod and shark. Networks of underwater receivers are then able to track migration routes and monitor changes in spawning behavior.

Unmanned aerial vehicles and remotely operated vehicles (ROVs) – already used for ocean monitoring – also collect valuable data on marine life. This enables monitoring in remote areas, while reducing the disturbance associated with diver-based surveys. Increasingly, cameras rather than people are monitoring marine life, contributing to fish counting, species identification, health monitoring and stress detection, and migration analysis. Commercial platforms such as Ocean Infinity use autonomous robotic vessels to collect large-scale ocean and habitat data.

These tools are complemented by whale-specific detection and warning systems to reduce vessel strikes and other human–wildlife conflicts. For tuna, researchers and fisheries managers use AI-enabled distribution models and dynamic ocean management systems to track movement and plan conservation efforts. They also use satellite-linked echo-sounder buoys, a fishing technology originally designed to help fishing fleets locate tuna. These buoys are now being repurposed into low-cost real-time ocean biodiversity monitoring systems (Lebrato *et al.*, 2026). SatLink's ReCon project is repurposing smart echosounder buoys with sonar technology to measure the distribution and abundance of marine life (see Innovation examples).

Box 3.2 Turning whales into ocean sensors

The MRI Whale Unit is a leading African cetacean research program based at the University of Pretoria. Since 2021, the Unit has deployed satellite-linked telemetry tags on southern right whales to track migration routes, feeding areas and responses to climate-driven changes in the Southern Ocean. Each tag can transmit location data for up to a year, providing insights into whale movements across ocean regions. More recently, the program has deployed CTD (conductivity–temperature–depth) tags, transforming whales into mobile ocean-observing platforms. In addition to tracking whale movements, these tags collect data on water temperature, salinity and diving depth, generating oceanographic observations from

remote regions that are difficult and costly to monitor using ships or fixed instruments. The project combines satellite telemetry, animal-borne sensors, GIS mapping and oceanographic monitoring to improve understanding of whale ecology and climate impacts. It is conducted through international collaboration involving NOAA, the University of Washington, MarEcoTel and other research partners.

Source: MRI, 2026; SAPRI, 2025.

Reforesting the ocean: kelp under climate stress

Kelp forests occur along approximately 25 percent of the Earth's coastline, providing habitat, food and ecosystem services that support a wide range of marine species (Box, 2022). They are among the most productive and biodiverse marine ecosystems, and also act as a significant blue-carbon sink, removing CO_2 from seawater and sequestering an estimated 61–268 million tonnes of carbon a year globally (Live Ocean, 2026). Ocean warming, however, poses a significant threat to their long-term viability.

Warming reduces the quantity of cold and nutrient-rich water on which kelp depends. Rising ocean temperatures and MHWs reduce growth, cause tissue degradation and incur large-scale loss. Ocean warming has already led to local extinction and range contraction in many kelp species, particularly at lower latitudes where kelp populations are most vulnerable to thermal stress. Indirect effects include increased sea urchin grazing, competition from turf algae and invasive species, altered nutrient availability and changes in disease and ecological interaction, further accelerating decline (Smale, 2020). Warming can trigger a shift from a kelp forest to a turf algae-dominated ecosystem. Once established, turf algae can inhibit kelp recovery through competition and chemical feedback, creating a self-reinforcing ecological shift. Although some high-latitude kelp populations are expanding as Arctic waters warm and sea ice retreats, overall evidence suggests that continued ocean warming and more frequent MHWs are likely to drive further redistribution and global kelp forest loss (Smale, 2020).

Kelp forest restoration is consequently a rapidly growing global field with a history spanning more than 300 years and projects in at least 16 countries (Eger *et al.*, 2022). Restoration efforts aim to rebuild degraded kelp ecosystems through sea urchin control, kelp seeding and transplantation, artificial reef deployment and water quality improvement (Live Ocean, 2026). Artificial reefs can provide new hard substrates for kelp attachment and recovery, while innovative restoration techniques such as Green Gravel – a scalable out planting method in which juvenile kelp are cultivated on small stones and dispersed directly onto degraded reefs – are enabling restoration at larger spatial scales (Fredriksen *et al.*, 2020). Alongside restoration, monitoring technologies are becoming increasingly important. Satellite observations, ocean sensors, AI-enabled image analysis and genetic monitoring are being used to map kelp forests, track ocean conditions and monitor the health and genetic diversity of surviving populations. Looking further ahead, researchers are exploring the development of climate-resilient kelp strains. For example, scientists in New South Wales are working to identify the genetic traits associated with heat tolerance and develop gene-editing tools that could eventually enhance the resilience of kelp species such as golden kelp (*Ecklonia radiata*) to ocean warming (NSW Government, 2026). Box 3.3 highlights a community-led initiative in New Zealand combining kelp restoration with the development of climate-resilient kelp strains.

Box 3.3 Community-led kelp restoration in New Zealand

Māra Moana, a kelp restoration initiative in Whakaraupō (Lyttelton Harbour), New Zealand, aims to respond to the marine heatwaves that have been the cause of a widespread loss of native kelp forests. The project combines ecological restoration, Indigenous stewardship and climate adaptation by reseeding native giant kelp (*rimurimu*), removing invasive species and developing climate-resilient kelp strains better able to withstand warming oceans. Led by researchers at the University of Otago in partnership with Ngāi Tahu communities, the project is also creating practical restoration toolkits for local communities to support the long-term recovery of kelp ecosystems and the biodiversity, fisheries habitat and ecosystem services they provide.

Scaling seagrass recovery

Like kelp forests, seagrass meadows are foundation ecosystems that support biodiversity, fisheries and coastal protection. They are also among the planet's most important blue-carbon ecosystems, capable of sequestering carbon at rates that exceed those of many terrestrial forests and storing it in sediments for centuries to millennia (Seaside Sustainability, 2023).

Unlike some marine ecosystems that may experience localized gains and losses, a 2023 global modeling study found a net decline in seagrass abundance and diversity across all climate scenarios examined, indicating that warming oceans pose a serious threat to seagrass ecosystems globally (Stanford Report, 2023). They are currently declining rapidly due to an array of factors, including climate change, pollution, coastal development and boating impacts (Seaside Sustainability, 2023).

Seagrass meadows are among the world's most important blue-carbon ecosystems, capable of sequestering carbon at rates that exceed those of many terrestrial forests and storing it in sediments for centuries to millennia

Restoration efforts such as seagrass transplantation, water-quality improvement, marine protected areas and community-based monitoring have demonstrated that degraded meadows can recover once key stressors are reduced. Unlike kelp restoration, which focuses on rocky reefs and open water out planting, seagrass technologies are engineered to handle soft, muddy or sandy sediment and meet the challenges of harvesting underwater flowering grass seeds. Manually picking reproductive shoots underwater is tiring, which limits large-scale restoration. New technologies automate the first step in this process. Towed seabed harvesters glide along the seafloor on skids, cutting seed-bearing shoots and transporting them to the surface using a gentle suction system, potentially increasing seed collection rates by up to 100-fold compared with manual diver collection.

Recent innovation is increasingly focused on mechanizing the entire restoration process from seed collection and processing to storage, planting and site stabilization (Unsworth and Rees, 2025). Buoy-deployed seeding (BuDS) is a system that suspends seed-bearing shoots in mesh bags beneath buoys positioned over a restoration site, allowing seeds to be naturally released as they mature. The DIS Wheel is a mechanized version of the handheld Dispenser Injection Seeding (DIS) method which injects seeds directly into sediment and can plant seeds approximately 26 times quicker than a manual injection system (Unsworth and Rees, 2025). Restoration is also moving upstream into seed collection, processing, storage and logistics, and is not limited to simply planting. Automated seed separation systems, such as automated stirring, drum filtration and seed aspiration, are reducing the labor required for processing and storage.

Technologies that restore former ecological conditions rather than plant seagrass directly are also gaining traction. They include sand capping to stabilize sediments, biodegradable matting to reduce erosion and improve seedling establishment, and hydrodynamic shields that reduce the wave and current stress on restoration sites (Unsworth and Rees, 2025). Seed coatings, hormones, microbial inoculants and microbiome engineering are promising emerging technologies for improving germination and survival (Unsworth and Rees, 2025).

Innovation examples

Forecasting bleaching before it begins in Florida

University of Miami, Florida



Source: Rosenstiel scientist Fabrizio Lepiz-Conejo surveys a colony of staghorn corals on Yung's Reef after the 2023 marine heatwave. Photo: Cailyn Joseph

Florida and Caribbean reefs are undergoing increasingly frequent heat-stress events. These are causing coral bleaching, prompting an urgent need for early warning tools. Scientists at the University of Miami have developed an AI model for forecasting moderate heat stress along Florida's Coral Reef up to six weeks in advance, with predictions generally accurate within one week. The machine learning model, XGBoost, was employed at three reef sites using environmental data from 1985–2024, including sea surface temperature anomalies, accumulated heat metrics, air temperature, wind, solar radiation and larger oceanic indicators like the Loop Current and El Niño conditions. Researchers also used explainable AI methods, which identify the factors most influencing model predictions, to determine which environmental variables most strongly influenced each prediction, allowing them to analyze how the drivers of heat stress vary according to reef location and forecast lead times. Surface air temperature consistently emerged as one of the most influential predictors in the model. The researchers emphasize that while this tool will not replace large, operational systems like NOAA's Coral Reef Watch it complements them by providing local guidance to reef managers and restoration practitioners in planning and response efforts (Udel, 2026).

Reviving coastal waters with hydrogen byproducts

Lhyfe, Flexens, Department of Ecology, Environment and Plant Sciences (DEEP) at Stockholm University



Source: Lhyfe

Oceans have been losing oxygen in recent decades due to warming and water pollution. Nutrients in coastal runoff cause excessive algae growth. Bacteria breaking down these algae consume oxygen, creating hypoxic conditions associated with eutrophication. With low oxygen, bacteria release phosphorus stored in sediments, promoting new algae growth and continuing the cycle. Reintroducing oxygen into these dead regions is being explored in the Baltic Sea Oxygenation and Super Green Hydrogen Economy (BOxHy) project launched by Lhyfe, Flexens and Stockholm University in 2023. As a green hydrogen producer, Lhyfe plans to produce

hydrogen alongside offshore wind farms, using water electrolysis. During water electrolysis, water molecules are split to produce hydrogen and oxygen, the latter of which can be injected into hypoxic waters to restore dissolved oxygen and support marine life. A pilot assessed 19 coastal sites in the Baltic Sea for suitability. A follow-on pilot, BOxIn (Baltic Sea Pilot for Pure Oxygen Injection), is planned for a duration of six years, including baseline monitoring, multi-year oxygen injection, and post-project observation. Backed by the UN Ocean Decade, the project fosters collaboration between industry and academia and engages European marine enrichment initiatives. BOxHy/BOxIn represents one of the first structured attempts to adapt industrial oxygen co-production and strategic site selection for long-term marine ecosystem restoration (Lhyfe, 2024).

Repurposing fisheries technology ocean and community resilience

Satlink



Source: BCSS deploying ReCon buoy for Ocean Observation @BCSS

Satlink's ReCon (Recovering and Connecting Habitats) initiative demonstrates how existing technology can be repurposed to support marine conservation and restoration. Satlink's smart echosounder buoys were originally developed for the tuna fishing industry. They use acoustic sensors to estimate fish biomass underneath fish aggregating devices. Through ReCon, recovered devices are reconditioned and adapted to new environmental, scientific and social applications. Active across 25 countries and territories and covering more than 75,000 km of coastline, the project works with local partners to adapt the buoys to the needs of each region. Some of these applications are particularly relevant to ocean warming. In Mozambique, Project ReCon partnered with the Bazaruto Center for Scientific Studies (BCSS) to integrate the buoys into its Ocean Observatory, supporting long-term monitoring of ocean temperature, seawater chemistry, ocean acidification and marine biomass. In Pacific Island communities, the same technology can be deployed on anchored fish aggregating devices used by artisanal fishers. As warming waters and changing ocean conditions affect the distribution of tuna and other pelagic species, the buoys can provide information on fish biomass, position and oceanographic conditions, helping fishing communities adapt while also contributing valuable ocean observations(Satlink, 2026;2024).

China and Mauritius are working together to protect coral reefs through real-time monitoring

Huawei (Mauritius) Technology Co., Ltd; EcoMode Society



Source: Nadeem Nazurally

As part of Huawei's TECH4ALL initiative, Chinese and Mauritian partners have implemented a digitally connected coral restoration system enabling the continuous, real-time monitoring of underwater coral nurseries. Developed with digital technologies provided by Huawei (Mauritius) Technology Co., Ltd., the system integrates underwater cameras and environmental sensors to monitor coral growth, water quality, surrounding environmental conditions, marine biodiversity and potential threats such as coral predators. Solar-powered offshore platforms enable the continuous operation of monitoring equipment deployed at multiple depths. Images and sensor data are transmitted via 4G/5G connectivity to a cloud platform, where they are processed and analyzed in near real-time, allowing restoration teams to remotely observe coral health and intervene rapidly without the need for frequent diving inspections. By reducing underwater fieldwork while improved response speed, the system increases the efficiency of coral cultivation and transplantation. Since the project began in 2020, more than 25,000 coral fragments have been propagated and then transplanted onto degraded reefs at Pointe-aux-Feuilles, helping restore one of Mauritius's most biodiverse reef systems. Monitoring data are also shared with researchers to improve the understanding of coral bleaching, ecosystem dynamics and marine biodiversity (Huawei, 2024; Xinhua, 2024).

The following collection of technologies is divided into three groups: Proven technologies have been on the market for some time and hence are well tested, Frontier technologies are available but relatively new, while Horizon technologies are close to being available but still under development.

Proven technology solutions

eDNA-based marine ecosystem monitoring

Applied Genomics



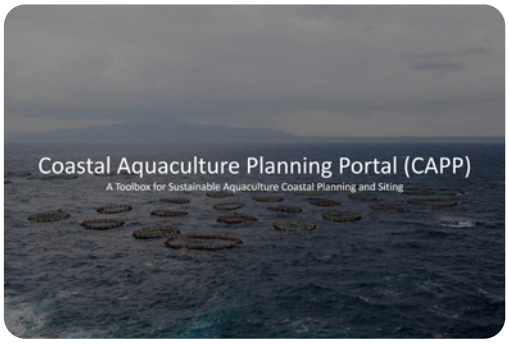
Source: Getty Images/CasarsaGuru

Applied Genomics develops environmental DNA (eDNA) technologies enabling non-invasive biodiversity monitoring and ecological assessment in terrestrial, freshwater and marine environments. The company develops proprietary eDNA sampling kits and large-volume water filtration systems designed to capture genetic material shed by organisms into the environment (e.g., seawater). Samples are then analyzed in a lab using genomics and bioinformatics to detect species presence, community composition and changes in biodiversity with high molecular precision. This approach is especially powerful in marine settings, where eDNA can reveal fish, invertebrate and mammal diversity more comprehensively and efficiently than traditional methods like trawling or visual surveys. Applied Genomics' technology also supports long-term time-series monitoring, invasive species surveillance, marine protected area assessment and other applications informing conservation, sustainability reporting and environmental management.

- Technological maturity: Proven
- Contracting type: For service
- Technology level: High
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

High-resolution model

National Oceanic and Atmospheric Administration (NOAA)



Source: NOAA

Coral Reef Watch (CRW) is a program run by NOAA providing near-real-time monitoring and forecasting of sea surface temperatures and coral bleaching risk worldwide. Its satellite-based system tracks ocean temperatures, heat stress and the anomalies that can trigger coral bleaching events. CRW uses satellite remote sensing and ocean models to generate high-resolution maps of thermal stress over coral reef areas. It produces Degree Heating Weeks (DHW) metrics that quantify cumulative heat stress and predict the likelihood of bleaching. Data is accessible online, allowing reef managers, scientists and policymakers to take timely decisions such as restricting human activity or prioritizing restoration interventions.

- Technological maturity: Proven
- Contracting type: Open access
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Coral seeding and CRIBs

Secore international



Source: SECORE international

SECORE International develops innovative coral reef restoration technologies that accelerate reef recovery. Its flagship approach, Coral Seeding, collects coral spawn during natural mass spawning events, fertilizes eggs and sperm, and rears larvae under controlled conditions. Larvae are then settled onto specialized substrates, such as tiles or self-stabilizing units, before being out planted onto degraded reefs. To reduce costs and increase scalability, SECORE pioneered Coral Rearing In-Situ Basins (CRIBs) that allow coral larvae to grow and settle directly in the ocean, minimizing reliance on land-based nurseries. Supporting tools, including Coral Trees and custom settlement substrates, improve survival rates and simplify large-scale deployment. By combining methods, SECORE is able to restore coral genetic diversity and resilience. The technology is shared globally with partners, making coral restoration more efficient, scalable and scientifically grounded.

- Technological maturity: Proven
- Contracting type: For collaboration and partnership
- Technology level: Medium
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Passive acoustic monitoring system

Jasco



Source: Getty Images/CasarsaGuru

OceanObserver is a real-time passive acoustic monitoring system developed to detect and monitor marine mammals, including whales, using underwater sound. The system combines hydrophones with onboard processing software that analyzes acoustic data directly on autonomous vehicles, buoys and other ocean platforms. By detecting whale vocalizations as they occur, OceanObserver can provide near-real-time information on whale presence and movement (even in remote areas), at night or during poor weather when visual surveys are difficult. The technology supports marine conservation by helping researchers understand habitat use and migration patterns, while also enabling shipping, offshore energy and other marine activities to reduce the potential impact on whales.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Marine robotics and autonomous ocean monitoring platform

Ocean Infinity



Source: Photo by Francesco Ungaro on Unsplash

Ocean Infinity is a marine robotics company that develops and operates fleets of autonomous and remotely operated ocean vehicles for large-scale marine data collection. Its technology ecosystem combines uncrewed surface vessels (USVs), AUVs, ROVs, advanced sensors, AI-enabled data processing and shore-based command centers. Through its Armada fleet, robotic vessels can be operated remotely and deploy underwater robots to collect geophysical, environmental, hydrographic and oceanographic data in deep and remote ocean regions. Ocean Infinity's purpose-built software enables the real-time command and control of robotic systems from onshore operations centers, reducing the need for large crews at sea, while extending monitoring coverage and endurance. The platform supports applications ranging from seabed mapping and ocean exploration to environmental monitoring and marine ecosystem assessment.

- Technological maturity: Proven
- Contracting type: For service
- Technology level: Medium
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Drone-based whale health monitoring system

Ocean Alliance



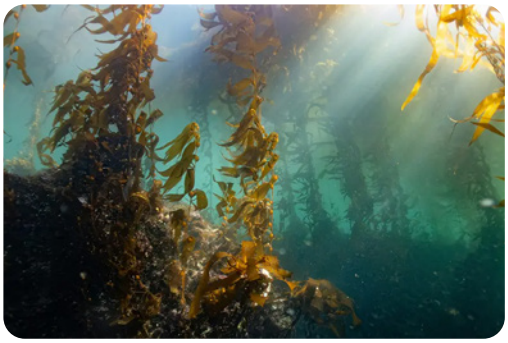
Source: Christian Miller/Ocean Alliance

SnotBot is a drone-based whale health monitoring system. The technology uses modified consumer drones equipped with sterile collection plates that fly through a whale's exhaled blow (or "spout") to collect respiratory samples without disturbing the animal. Samples contain valuable biological information, including DNA, hormones, microbiomes and other indicators of health, stress, reproduction and exposure to environmental pressures. In addition to sample collection, SnotBot drones can be used for photogrammetry, body-condition assessment, tagging and disentanglement operations. By replacing more invasive methods, such as tissue biopsies, the system enables the safer and more frequent monitoring of whale populations at a lower cost.

- Technological maturity: Proven
- Contracting type: For service
- Technology level: Medium
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Large-scale kelp restoration system

SeaForester



Source: Photo by Erick Morales Oyola on Unsplash

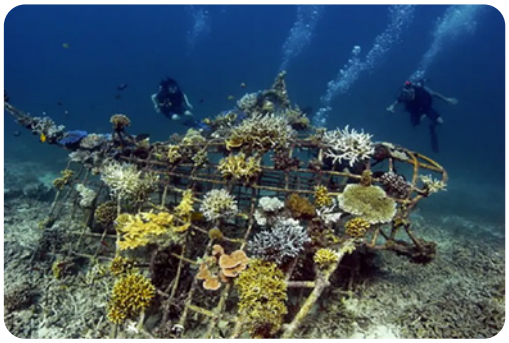
SeaForester is a large-scale kelp restoration approach combining seaweed nurseries with “seaforestation” techniques to re-establish degraded kelp forests. The system works by cultivating kelp spores on small stones (“green gravel”) under controlled conditions and then deploying them onto degraded reefs, where the kelp continues to grow, reproduce and gradually rebuild underwater forests. SeaForester complements restoration with monitoring and community-based implementation, aiming to restore biodiversity, strengthen fisheries, improve water quality, enhance carbon sequestration and increase ecosystem resilience. The approach is designed to be low-cost, scalable and adaptable to different regions through mobile seaweed nurseries and climate-resilient kelp strains.

Technological maturity: Proven

- Contracting type: For service
- Technology level: Medium
- Place of origin: Portugal
- Availability: Portugal, Norway
- Contact: WIPO GREEN Database

Biorock (electrified reef) technology

Gili Eco Trust



Source: Gili Eco Trust

Gili Eco Trust employs Biorock® technology, a reef restoration method that uses low-voltage electrical currents passed through underwater steel structures to accelerate coral growth and ecosystem recovery. Originally developed by Prof. Wolf Hilbertz and Dr. Thomas J. Goreau, the process relies on electrolysis in seawater, which causes dissolved minerals like calcium carbonate to precipitate and coat a metal framework, creating a limestone-like substrate ideal for coral attachment and growth. Coral fragments are then attached to these structures, where they grow up to 2–8 times faster than on a natural reef surface and have a much higher survival rate, even during thermal stress and bleaching events. Biorock reefs also provide habitat for fish, sponges and other marine life, and can help protect shorelines by dissipating wave energy. The technology is powered safely using low electricity, increasingly sourced from renewable energy like marine turbines, making it sustainable and replicable in remote coastal locations.

- Technological maturity: Proven
- Contracting type: For collaboration and partnership
- Technology level: Medium
- Place of origin: Indonesia
- Availability: Worldwide
- Contact: WIPO GREEN Database

Smart enhanced reefs (SERs)

Underwater Gardens International



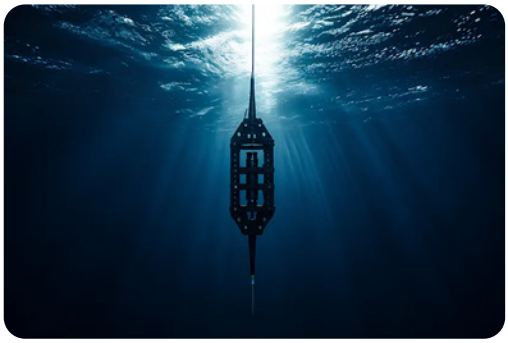
Source: Underwater Gardens International

Underwater Gardens International develops ocean regenerative solutions designed to restore damaged marine ecosystems and boost biodiversity in support of climate resilience. Its core innovation is the Smart Enhanced Reef (SER®), a modular artificial reef system designed using ecological data and proprietary reefhopper® software. Rather than using a standard reef structure, SER® installations are tailored to local environmental conditions and restoration goals. The structures provide complex habitat for corals, fish, algae and other marine organisms, creating surfaces suitable for settlement and encouraging natural recruitment and ecosystem recovery. SER® systems can be deployed in shallow, mesophotic or deep-water environments and are intended to support long-term reef growth through natural biological processes. Underwater Gardens combines its SER® technology with digital monitoring, citizen science initiatives and socioeconomic programs, while its Blue Innovation Hub promotes marine education and climate awareness.

- Technological maturity: Proven
- Contracting type: For collaboration and partnership
- Technology level: High
- Place of origin: Spain
- Availability: Worldwide
- Contact: WIPO GREEN Database

Underwater acoustic digital twin system

blueOASIS



Source: blueOASIS

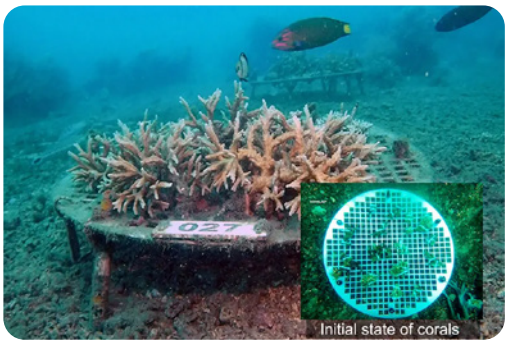
Hydrotwin is an AI-powered underwater acoustic intelligence platform that creates a dynamic digital twin of the marine soundscape. By combining artificial intelligence, IoT, edge computing, and cloud-based analytics, the platform transforms underwater acoustic data into actionable environmental and operational intelligence. Designed as a platform-agnostic solution, Hydrotwin seamlessly integrates with a wide range of hydrophones, autonomous monitoring buoys (from Sofar), unmanned surface and underwater vehicles, fixed observatories, and third-party sensing infrastructures, enabling flexible deployment across diverse marine environments. The platform continuously acquires underwater acoustic data and processes it at the edge to enable real-time detection, classification, localization, and tracking of both natural and anthropogenic sound sources, including vessels, underwater vehicles, dolphins, whales, and other marine species. At the core of Hydrotwin are advanced AI and machine learning models that automatically identify sound patterns, classify species and vessels, detect anomalies, and generate predictive insights. The platform supports interoperability through open APIs and standardized data interfaces, allowing integration with oceanographic monitoring systems, meteorological services, AIS vessel tracking, satellite observations, GIS platforms, environmental databases, and enterprise management systems.

- Technological maturity: Proven
- Contracting type: For collaboration and partnership
- Technology level: High
- Place of origin: Portugal
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier technology solutions

Coral net

Kajima Corporation



Source: KAJIMA Technical Research Institute

CORAL NET is a mesh-based coral restoration structure designed to reduce sedimentation, improve water circulation and create favorable conditions for coral settlement and growth. The mesh structure placed at a certain height from the seafloor provides adequate water-flow and light, as well as some shade area on its bottom surface for larval settlement and a nursery. Two types are available depending on environmental conditions: one is durable (made from stainless metal) for harsh wave conditions, while the other is biodegradable for calmer environments.

- Technological maturity: Frontier
- Contracting type: For collaboration and partnership
- Technology level: Medium
- Place of origin: Japan
- Availability: Worldwide
- Contact: WIPO GREEN Database

Acoustic telemetry system

Innovasea



Source: Photo by Sebastian Pena Lambarri on Unsplash

NexTrak is an advanced acoustic telemetry system that tracks the movements and behavior of aquatic animals across rivers, lakes and oceans. The system combines acoustic tags attached to fish or other marine species with underwater receivers that detect and record the unique sound signals emitted by the tags. NexTrak improves upon previous generations by increasing detection range by up to 40 percent and doubling detection rates, enabling researchers to monitor animals over larger areas with fewer receivers. A feature called increased residency (IR) programming reduces signal interference when many tagged animals are present, allowing up to 10 times more detections in high-density study areas. The system also possesses remote retrieval capabilities and includes cloud-based data management software. By providing more accurate and extensive movement data, NexTrak helps scientists understand migration patterns, habitat use and ecosystem connectivity.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: Medium
- Place of origin: United States/Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

AI-powered marine biodiversity platform

Monterey Bay Aquarium Research Institute (MBARI)



FathomNet

FathomNet is an open-source marine biodiversity platform using AI, computer vision and a global database of annotated underwater imagery to automate the identification and monitoring of marine life. Developed by the Monterey Bay Aquarium Research Institute (MBARI) and partners, it aggregates millions of labeled images and video observations from research organizations worldwide to train AI models capable of recognizing marine organisms and habitats. Through tools, such as the FathomNet Database, FathomNet Portal and the citizen science app FathomVerse, the platform accelerates the analysis of underwater imagery collected by ROVs, autonomous vehicles, cameras and other observing systems. By enabling the rapid detection of species distribution, biodiversity change and ecosystem conditions, FathomNet supports marine conservation, ecosystem restoration and the long-term monitoring of climate impacts on ocean ecosystems.

- Technological maturity: Frontier
- Contracting type: Open access platform
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Kelp restoration technique

Green Gravel Action Group



Source: Green Gravel Action Group

Green Gravel is a low-cost, scalable kelp restoration technique that involves seeding variety of substrates like lines, rocks, small stones or gravel with kelp spores in a laboratory or nursery, allowing juvenile kelp to grow under controlled conditions before they are dispersed onto degraded reefs. Once deployed, the kelp continues growing from the substrate and eventually attaches to the surrounding reef, helping re-establish kelp forests. In case of small sized substrates like seeded gravel, they can simply be dropped from boats, the approach avoids the need for extensive diving operations and can be applied over large areas.. Green Gravel has also been proposed as a way to introduce more heat-tolerant kelp genotypes into vulnerable ecosystems, improving resilience to ocean warming and marine heatwaves.

- Technological maturity: Frontier
- Contracting type: Open access
- Technology level: Low
- Place of origin: Australia
- Availability: Worldwide
- Contact: WIPO GREEN Database

Commercial kelp cultivation and ocean restoration platform

Kelp Blue



Source: Kelp Blue

Kelp Blue is a large-scale ocean restoration and sustainable aquaculture initiative that cultivates giant kelp (*Macrocystis pyrifera*) on offshore structures to restore marine ecosystems, enhance biodiversity and sequester carbon. The cultivated kelp is harvested sustainably, with only the upper canopy removed to allow continued growth and carbon storage, and is processed into products such as agricultural biostimulants, animal feed ingredients and other bio-based materials. By combining kelp cultivation with ecosystem restoration, Kelp Blue aims to create a commercially viable model in support of climate mitigation, ocean health and sustainable economic development.

- Technological maturity: Frontier
- Contracting type: For service
- Technology level: Medium
- Place of origin: Kingdom of the Netherlands/Namibia
- Availability: Worldwide
- Contact: WIPO GREEN Database

Seagrass and coral planting robot

Reefgen



Source: Photo by Oleksandr Sushko on Unsplash

Reefgen uses underwater robotics to scale the restoration of seagrass meadows and coral reefs. Its flagship technology, the Grasshopper robot, automates the planting of seagrass seeds and shoots on the seafloor, reducing the cost, risk and labor associated with diver-based restoration. Operating under a robotics-as-a-service (RaaS) model, Reefgen provides restoration practitioners, governments and conservation organizations with robotic planting services instead of selling the robots themselves. The system combines robotic deployment, monitoring and data collection to enable large-scale ecosystem restoration in coastal environments. By mechanizing restoration, Reefgen aims to accelerate seagrass and coral recovery, enhance biodiversity, improve coastal protection and increase blue-carbon sequestration.

- Technological maturity: Frontier
- Contracting type: For service
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

AI-powered whale detection platform

Whale Seeker



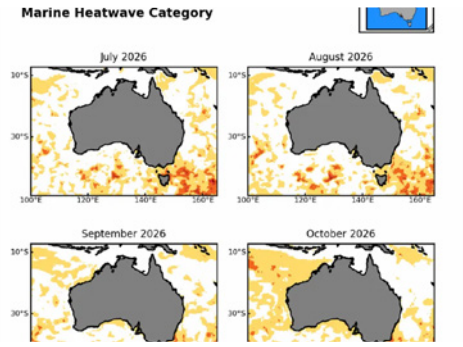
Source: Whale Seeker

Cetus is an AI-powered whale detection platform that uses very-high-resolution satellite imagery to identify and monitor whales across large ocean areas. The system applies computer vision and machine-learning algorithms to the analysis of satellite images and automatically detects whales located at the ocean surface. By processing imagery at scale, Cetus can survey remote and expansive marine regions that are difficult or costly to monitor using ships or aircraft. The platform generates geospatial data on whale distribution, abundance and habitat use, supporting conservation planning, marine spatial management and the assessment of climate-driven shifts in migration and feeding areas. Because it relies on satellite observations, Cetus enables repeat monitoring over broad geographic areas and can complement traditional aerial surveys, vessel-based observations and acoustic monitoring programs. Its combination of Earth observation and AI represents a new approach to large-scale marine mammal monitoring.

- Technological maturity: Frontier
- Contracting type: For service
- Technology level: High
- Place of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Ocean temperature long-range forecasts

Fisheries Research and Development Corporation (FRDC), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the Australian Bureau of Meteorology (BoM)



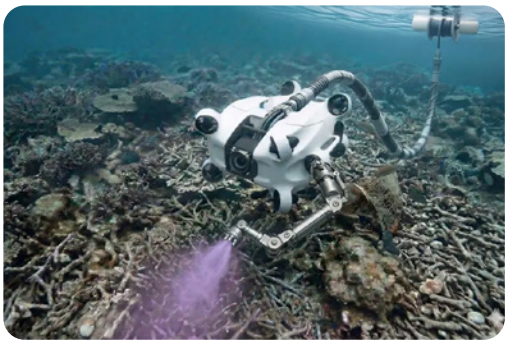
Source: Australian Bureau of Meteorology

The long-range ocean temperature forecast provides information on the likelihood, location, and predicted severity of marine heatwaves across the Australian region up to four months ahead. The forecasts were developed in partnership by the Australian Bureau of Meteorology (BOM) and CSIRO, and funded by the Department of Climate Change, Energy, the Environment and Water (DCCEEW), the Fisheries Research and Development Corporation (FRDC), and CSIRO. The forecast uses sea surface temperature forecast data from the BOM's Australian Community Climate Earth-System Simulator – Seasonal V2 (ACCESS–S2) model. The tool is updated three times a week and shows regional maps indicating the likelihood and category (moderate to extreme) of a marine heatwave. Views are available by state and across all Australian waters. Marine heatwaves pose a significant threat to the long-term health and resilience of coral reef and other marine ecosystems. Long-range marine heatwave and ocean temperature forecasts support decision-making across marine management, aquaculture, fisheries, conservation and ocean research by providing early warning to help users plan and prepare for ecological and industry impacts.

- Technological maturity: Frontier
- Contracting type: Open access
- Technology level: High
- Place of origin: Australia
- Availability: Australia
- Contact: WIPO GREEN Database

Ultra large scale coral reef restoration method using autonomous underwater vehicles and coral tissue embedded in hydrogel

CORAlliance



Source: CORAlliance

CORAlliance (Coastal & Ocean Regeneration Alliance) offers a patented, scalable system for large-scale coral reef restoration that moves beyond traditional small-scale outplanting. At the heart of its approach is the Coral Paint, a bio-based hydrogel infused with crustose coralline algae, coral polyps, and coral larvae that primes degraded reef areas and promotes rapid settlement and growth, enabling restoration up to hundreds of times faster than manual transplantation. Supporting this is the Modular Living Coral Mesh, large metal grids coated with Coral Paint that stabilize rubble fields and facilitate reef recovery. On-site rearing facilities (containerized wet labs and floating sea tanks) ensure ecological fit and reduce transport impacts. CORAlliance also uses advanced delivery tools – from diver-held spray lances to autonomous underwater vehicles -- to apply materials precisely, and an AI-driven monitoring platform tracks biodiversity, coral cover, and growth.

- Technological maturity: Frontier
- Contracting type: For collaboration and partnership
- Technology level: High
- Place of origin: Switzerland
- Availability: Maldives, Palau and Seychelles
- Contact: WIPO GREEN Database

oPod for reef cooling

Blue Carbon



Source: Blue Carbon

Blue Carbon's oPod™ technology is a wave- and solar-powered system designed to support coral reef restoration, monitoring, and environmental management. By circulating seawater and, where appropriate, drawing cooler water from deeper depths, the system can help reduce localized heat stress around coral restoration sites and create more favorable conditions for coral survival and growth. The technology has undergone trials and pilot deployment, and early commercial use began in 2025–2026. While the oPod™ system is now entering the market, it is still very new, with broader commercial availability just starting.

- Technological maturity: Frontier
- Contracting type: For collaboration and partnership
- Technology level: High
- Place of origin: Australia
- Availability: Australia
- Contact: WIPO GREEN Database

Horizon technology solutions

AI-assisted marine robotics system

Australian Institute of Marine Science (AIMS)



Source: AIMS, Chris Bartlett

The Australian Institute of Marine Science (AIMS), in conjunction with other organisations, is developing AI-assisted marine robotics systems supporting the development of at-scale up coral reef restoration, particularly on the Great Barrier Reef. The system, called the Deployment Guidance System (DGS), is currently in the research and field testing stage. It combines robotics, GPS guidance, cameras, and AI to plan, deploy, and monitor coral seeding devices holding juvenile corals. AI models analyze reef data to identify optimal deployment sites, while the robotic system ensures precise placement. Each deployment is recorded with GPS so scientists can revisit and monitor coral growth. By automating planning, positioning, and tracking, the system allows reef restoration efforts to cover larger areas more consistently and safely than manual methods.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: Australia
- Availability: Under development
- Contact: WIPO GREEN Database

Sea simulator for coral seeding

Australian Institute of Marine Science (AIMS)



Source: AIMS , Marie Roman

The National Sea Simulator (SeaSim) is a large-scale marine research infrastructure that supports the development and evaluation of coral seeding technologies through the replication of both present-day and future ocean conditions in controlled experimental seawater systems. This capability enables rigorous investigation of coral reproduction, settlement, growth and survival, as well as broader coral reef ecosystem responses under a range of environmental scenarios. SeaSim's advanced industrial process automation platform also provides a foundation for the development of scalable coral production workflows, including the integration of image analysis, process control and robotics. Within this framework, coral colonies collected prior to spawning can be induced to spawn, fertilised, reared through larval stages, and settled onto substrates for subsequent attachment to seeding devices designed to improve survival and support targeted, cost-effective deployment to reefs. Early trials have demonstrated promising survival outcomes for coral recruits established on these devices. These capabilities position SeaSim as a unique platform for advancing coral seeding from experimental development toward scalable application.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: Australia
- Availability: Under development
- Contact: WIPO GREEN Database

Underwater seagrass seed harvester

Tandem Ventures



Source: Tandem Ventures

The Seagrass Harvester, developed by Tandem Ventures in collaboration with Project Seagrass and Swansea University, is a boat-towed mechanical harvesting system designed to automate the collection of seagrass seeds for restoration projects. Traditionally, divers collect seed-bearing shoots by hand using scissors, a slow and labor-intensive process that limits restoration scale. The Harvester moves over the seabed on skids, cutting the upper portions of seagrass shoots that contain mature seeds and transporting them to the surface through a suction and filtration system for collection. Developers estimate the technology could be up to 100 times faster than manual harvesting, potentially enabling restoration at much larger scales. The design is intended to be open source, allowing researchers and restoration organizations worldwide to adapt and replicate the technology for local conditions.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: United Kingdom
- Availability: Under development
- Contact: WIPO GREEN Database

Autonomous seagrass restoration robot

Ulysses Ecosystems Engineering



Source: Photo by Benjamin L. Jones on Unsplash

MAKO is an autonomous underwater restoration system developed by Ulysses Ecosystem Engineering combining robotics, AI, computer vision and precision deployment technologies to restore seagrass meadows at scale. The robot navigates across the seabed, identifies suitable habitat conditions, and plants either seagrass propagules or seeds with high spatial accuracy. By automating tasks that traditionally require a large team of divers, MAKO aims to accelerate restoration, reduce costs and improve consistency across large restoration sites. The system also collects environmental and habitat data during operations, supporting monitoring and adaptive management.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: United States
- Availability: Under development
- Contact: WIPO GREEN Database

Robotic system for coral reef mapping and monitoring

Arizona State University



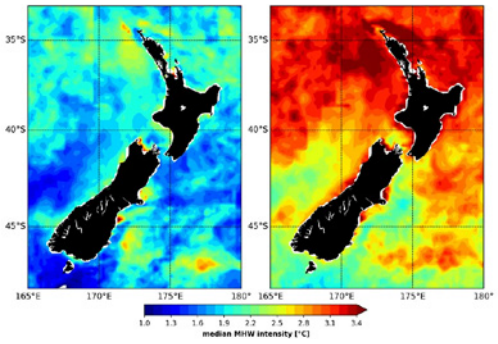
Source: Photo by Daniel Pelaez Duque on Unsplash

The Coral Collaborative Robotic Aquatic Laboratory (CoRAL) is an advanced robotic system for better monitoring, mapping and sampling of coral reefs. It combines multiple robotic components – such as an autonomous surface vessel, an underwater drone and multi-spectral imagers – to collect high-resolution visual data and environmental samples more safely, frequently and at a larger scale than traditional diver-based surveys. The system is also capable of supporting intervention tasks like collecting water samples, planting new corals or aiding artificial reef structures. It aims to reduce cost and risk ,while improving the scientific understanding of reef health.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: United States
- Availability: Under development
- Contact: WIPO GREEN Database

AI-driven marine heatwave forecasting system

NIWA; Earth Sciences New Zealand



Source: Earth Sciences New Zealand

The marine heatwave forecasting system is an AI-driven early warning tool designed to predict extreme ocean temperature events – known as marine heatwaves – well in advance. It aims to generate publicly accessible forecasts spanning several months for New Zealand's surrounding oceans by combining historical models, fine-scale ocean and atmospheric data, and machine-learning approaches. The project adapts an ocean "emulator" model originally developed by the University of California, Santa Cruz, to infer future conditions such as sea surface temperature and heat extremes on scales of a few kilometers. These forecasts are intended to help marine businesses, *iwi* (Māori communities) and regulators prepare for impacts like ecosystem stress, fishery disruptions and aquaculture risk, enabling climate-resilient planning decisions to be made. The system represents a cost-effective alternative to traditional numerical ensemble forecasting systems.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: New Zealand
- Availability: Under development
- Contact: WIPO GREEN Database

AI-enabled marine ecosystem digital twin

Fujitsu



Source: Getty Images/Andrew Stowe

Fujitsu has developed a technology that uses AUVs, LiDAR sensors and AI to create high-resolution 3D digital twins of underwater ecosystems. The drones scan marine environments, such as coral reefs, seaweed beds and offshore infrastructure, capturing centimeter-scale data even in murky water or strong currents. AI-based image enhancement restores color and sharpens contours in underwater images, allowing the accurate identification and measurement of organisms and structures before converting the data into detailed 3D models. These models form an ocean digital twin, enabling researchers to analyze ecosystems, simulate environmental changes and test conservation strategies. Initial field trials near Ishigaki Island, Japan, successfully mapped coral reefs in real time. Fujitsu plans to expand the system to model seaweed ecosystems and estimate blue carbon storage.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: Japan
- Availability: Under development
- Contact: WIPO GREEN Database

3.2 Ocean acidification

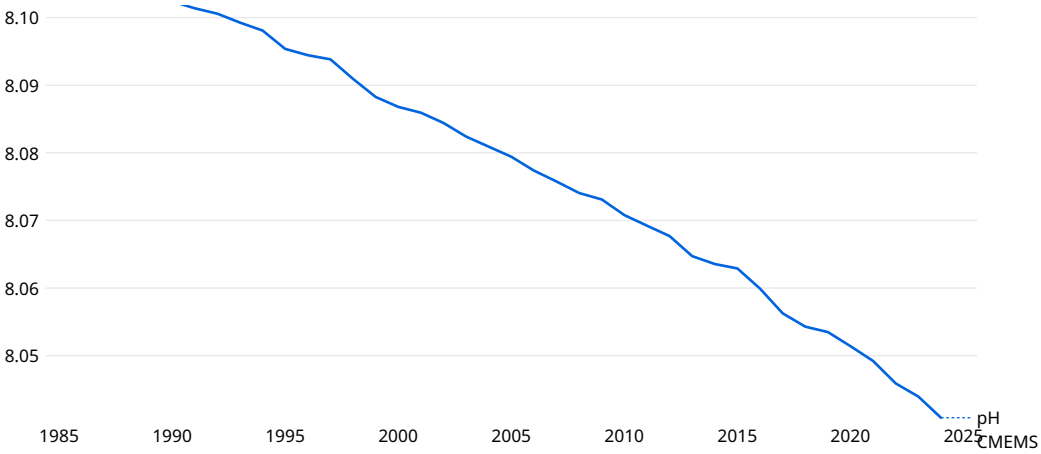
The emissions driving climate change are not just warming the air and the ocean – they are altering ocean chemistry by increasing acidification, with serious consequences for marine ecosystems.

From air to acid: the ocean in peril (or "the second deadly pressure")

At least a quarter of the CO_2 released into the atmosphere dissolves in the ocean. Since the start of the industrial era, the ocean has absorbed roughly 525 billion tonnes of CO_2, currently amounting to about 22 million tonnes each day (Smithsonian Ocean Portal, 2026). Ocean water has become 30 percent more acidic during this period – a rate of change faster than anything known in ocean chemistry over the past 50 million years (Smithsonian Ocean Portal, 2026). Ocean acidity is projected to double or even triple by 2100, unless we reduce CO_2 emissions (Masson-Delmotte *et al.*, 2021).

Figure 3.2 shows ocean pH having decreased by about 0.1 units since 1985. Since pH is measured on a logarithmic scale, a small unit decrease in pH represents a large increase in acidity. Between 1985 and 2024 alone, ocean acidity increased by 17.5 percent (Copernicus Marine Service, 2026).

Figure 3.2 Yearly mean surface seawater pH reported on a global scale (pH), 1985–2024



Note: Decline in ocean pH measured at the Aloha station and yearly mean surface seawater pH reported on a global scale (Copernicus Marine Service).

Source:EEA, 2025

When CO_2 is absorbed by seawater a series of chemical reactions is triggered that increases hydrogen ion concentration. This lowers the pH, making the water more acidic and reducing the relative abundance of carbonate ions. Carbonate ions are a key component of calcification, the biological process of building calcium carbonate structures such as shells, skeletons and other hard parts. A decline in carbonate ions makes it harder for calcifying organisms – including oysters, clams, sea urchins, shallow and deep-water corals – and calcareous plankton to build and maintain such structures (NOAA, 2012). The effect of increasing ocean acidification is to slow growth and weaken the structure of corals, mollusks and some plankton, and it can also reduce population resilience and ecosystem stability.

Scientists once assumed rivers supplied enough minerals to keep the world's ocean pH stable through a process called buffering. But CO_2 is now entering the ocean so quickly that natural buffering is unable to keep up – and marine life has had scant time to adjust. The shells of some organisms are already dissolving, although a few species living in naturally variable estuarine environments appear to be developing a greater tolerance to lower pH conditions (NOAA, 2012).

> Since the start of the industrial era, the ocean has become 30 percent more acidic – a rate of change faster than anything known in ocean chemistry over the past 50 million years

The effects of rising CO_2 on marine ecosystems are expected to be severe, especially for tropical coral reefs, as well as high-latitude marine invertebrates such as snails, crabs, starfish and so on (Fabry *et al.*, 2009;Yamamoto-Kawai *et al.*, 2009;Hofmann *et al.*, 2010). Some models suggest that even if atmospheric CO_2 were to be stabilized at 450 ppm – as of early 2026 it is already well above 420 ppm (NOAA GML, 2026) – only about 8 percent of coral reefs would remain in seawater favorable for calcification (Cao and Caldeira, 2008). Arctic surface waters are already showing signs of aragonite undersaturation (a chemical condition in seawater where the concentration of carbonate ions is too low to support the formation or maintenance of aragonite, a crystalline form of calcium carbonate that many marine organisms use to build shells and skeletons), particularly in those regions affected by rapidly melting sea ice. Conditions are likely to become corrosive (low pH, low aragonite saturation) if atmospheric CO_2 exceeds 450 ppm (Yamamoto-Kawai *et al.*, 2009). As acidification worsens, ecosystems are likely to shift toward macroalgal dominance, resulting in simplified habitats and declining biodiversity in both temperate and tropical marine regions (Hall-Spencer and Harvey, 2019).

Impact of acidification on fish populations and marine life

Shellfish hatcheries – especially oyster, clam and mussel hatcheries – draw in seawater from coastal areas. When that seawater turns corrosive, larvae experience a high rate of mortality. This is common in parts of Europe, the Pacific Northwest United States, and parts of Australia. Beyond aquaculture, ocean acidification also affects coastal communities whose economies depend on reef-based tourism, Globally, acidification has been estimated to incur annual economic losses of USD97–301 billion (in 2014) (Myers and Subban, 2022).

Hatchery buffering systems are localized adaptation technologies applied in marine and estuarine aquaculture facilities. Systems such as the Burke-o-Lator developed by Burke Hales for Pacific shellfish hatcheries (and used in the United States and Canada) provide real-time carbonate chemistry data to help optimize buffering and water conditions in order to improve larval survival under more acidic conditions. Burke-o-Lators measure ocean pH, the quantity of CO_2dissolved, non-organic carbon from non-organic sources, and aragonite concentration (Canada OA CoP, 2018).

The Central and Northern California Ocean Observing System uses Burke-o-Lators to track seawater chemistry in real time. Observations show coastal pH often falls below 7.75, a level at which the aragonite saturation state (Ω_{ara}g) approaches 1. When Ω_{ara}g is around or below 1, seawater becomes chemically corrosive to calcium carbonate minerals (California Sea Grant, 2026).

Technologies and tools for ocean acidification action

The International Alliance to Combat Ocean Acidification (OA Alliance) is a global coalition of governments and organizations that has more than 120 members. In its submission to the UNFCCC Ocean and Climate Change Dialogue (2022) titled "Advancing Ocean & Coastal Adaptation" (OA Alliance, 2022), it cited the need to increase and ease access to climate financing for ocean and coastal climate monitoring and research, risk assessment and remediation or adaptation measures. Nature-based recommendations to address ocean and coastal adaptation measures included:

- remediation and amelioration of coastal acidification through aquatic ecosystems such as mangroves, seagrass beds, salt marshes and kelp forest;

- improving water quality, limiting coastal erosion and providing protection from extreme events;
- facilitating the movement and protection of species (refugia);
- supporting adaptive management and promoting resilience strategies for highly vulnerable species; and
- reducing those land-based/terrestrial sources of pollution that exacerbate local OA conditions.

In a proposed Toolkit, the OA Alliance outlined six actionable areas together with the associated technologies or methods. Table 3.1 lists the various technologies in support of these actionable areas. Note that action area 1 is to reduce atmospheric CO_2 emissions, which lies outside the scope of this edition of the *Green Technology Book*, as technologies featured here are intended to restore ecosystems and not to mitigate climate change writ large. However, this area is included in order to highlight the indirect benefits that blue carbon ecosystems can have in reducing ocean acidification.

Table 3.1 Action areas and associated technologies and methods (recommendations for formulating an OA action plan)

Action area	Technology (or method) examples	Relevance to OA
1.Reduce atmospheric CO_2 emissions	Blue carbon ecosystem management & carbon accounting (mangroves, seagrass, salt marshes)	Sequesters CO_2, indirectly reducing ocean acidification
2.Advance scientific understanding	Ocean pH sensors, autonomous buoys, satellite-based ocean chemistry data	Measures acidification rates and trends
	Predictive models for OA, aragonite saturation, species vulnerability	Supports adaptive management and policy decisions
	Laboratory and field experiments on species and ecosystems	Determines biological thresholds and resilience
	Data integration platforms	Facilitates decision-making and research sharing
3.Reduce local pollutants	Wastewater and stormwater treatment technologies, vegetated buffer zones	Reduces nutrient-driven eutrophication and local acidification
	Land-use management tools (GIS runoff mapping, sediment monitoring, water quality sensors)	Limits coastal contributions to OA
4.Build adaptation and resilience	Buffered/aerated hatcheries, selective breeding, shell addition	Protects shellfish and aquaculture species from OA stress
	Submerged aquatic vegetation restoration (kelp, seagrass, mangroves)	Enhances local carbonate buffering and habitat resilience
	Marine spatial management: MPAs, LMMAs, marine spatial planning software	Protects biodiversity and supports adaptive fisheries
5.Expand public awareness	Digital curricula, citizen science apps, interactive OA dashboards	Engages communities and stakeholders in OA mitigation/adaptation
	Stakeholder workshops, webinars, panels	Informs policy, industry, and public on OA risks and responses
6.Sustain international support	International collaboration networks (GOA-ON, OA-ICC, OAIE)	Standardizes OA monitoring and knowledge exchange
	Policy and reporting platforms for NDCs, CBD/UNFCCC integration	Ensures OA is included in global climate strategies

Source: Adapted from Ocean Acidification Alliance Action Plan Toolkit (OA Alliance, 2024).

Within the respective actionable areas, strategies that build adaptation and resilience are particularly relevant for ecosystem restoration. One such approach is the use of Marine Protected Areas (MPAs) to reduce local stressors, such as overfishing and pollution, and create conditions that help marine ecosystems better withstand ocean acidification. While not itself a technology, an MPA functions as an adaptive management tool able to enhance ecosystem resilience. The OA Alliance recommends identifying existing MPAs or locally-managed marine areas for potential locations for expanding ocean acidification monitoring and research, as these sites are often suitable for long-term ecological observation (OA Alliance, 2024).

Aeration and circulation systems: tools to reduce CO_2 and acid stress in aquaculture

Seawater aeration and water circulation systems are important technologies for managing OA in localized environments such as marine laboratories, coral restoration sites and aquaculture facilities. By increasing gas exchange and water movement, they can reduce localized CO_2 accumulation and improve the saturation state of calcium carbonate (Myers and Subban, 2022).

Water circulation can improve mixing between water layers and help prevent the localized buildup of high CO_2-rich water (Comeau *et al.*, 2014). For example, boundary layer control via increased water flow may alter the chemical boundary layer around corals, thereby moderating the pH level (Cornwall *et al.*, 2014; Chan *et al.*, 2016), though some research has found only a weak to moderate effect (Martins *et al.*, 2024). Enhanced circulation helps mitigate the impacts of extremely low pH on coral larvae, and subsurface aeration systems can reduce oxygen depletion and prevent the accumulation of concentrated acidic anaerobic byproduct, particularly in coastal areas.

Autonomous systems, smart sensors and data platforms transforming ocean acidification monitoring

The measurement and tracking of carbonate system variables is crucial for monitoring the progression of ocean acidification and understanding the ocean's role as a carbon sink. Effective ocean acidification monitoring requires continuous, long-term time series obtained from moorings and autonomous sensors sustained over many years. Acidification trends unfold gradually, but short-term variability can be rapid and intense, therefore both must be captured in order to understand ecosystem exposure.

Box 3.4 discusses how high-frequency sampling, such as measurements being taken every few hours rather than a monthly average, can significantly alter estimates of carbon flux, shift the classification of a region as being either a CO_2 source or a sink, and better reflect the chemical conditions experienced by organisms. Because marine life responds to sudden shifts, and not just long-term trends, integrated monitoring systems are essential. These must combine carbonate chemistry measurements (pH, pCO_2, total alkalinity), temperature and salinity, and physical drivers like wind and upwelling, since ocean chemistry and physics are interconnected. Automated monitoring platforms are particularly valuable for collecting such data over time and space. Box 3.5 provides an explanation of the main four parameters usually monitored when tracking ocean acidification.

Box 3.4 High-frequency monitoring reveals hidden ocean carbon flux and acidification patterns

Recent research using two NOAA moorings off Southern California (CCE1 offshore and CCE2 nearshore) challenges the traditional view of the ocean as a stable carbon sink. Open ocean waters are typically a CO_2sink, while nearshore upwelling sites are usually a CO_2 source. During the 2015–2016 marine heatwave, this pattern reversed: the offshore site became a CO_2 source, while the nearshore site became a sink when warm surface waters suppressed upwelling (PMEL, 2025). This shows that regional carbon dynamics are highly sensitive to marine heatwaves and El Niño events.

High-frequency observations (every three hours) revealed short-lived events that were invisible in monthly averages. Strong winds and upwelling raised surface pCO_2– the partial pressure

of CO_2 in seawater that determines whether CO_2 moves between ocean and atmosphere – triggering rapid CO_2 outgassing. These findings suggest that conclusions based on monthly data may be misleading: the California Coastal Upwelling System may function as a net CO_2 source rather than a sink (PMEL, 2025).

This research underscores the need for sustained high-resolution monitoring. The ocean carbon sink is dynamic, and short-term variability can strongly affect carbon budgets and climate projections. Upwelling regions are particularly prone to acidification, because they bring deep, CO_2-rich water to the surface, enhancing local acidification and air–sea CO_2 release. Ocean acidification is therefore a regional and event-driven phenomenon that renders marine organisms and ecosystems especially vulnerable to rapid environmental changes.

Box 3.5 Monitoring the "big four" – why do we measure these four parameters?

pH	pCO_2	TA	DIC
When the ocean absorbs CO_2, it forms free hydrogen ions that make the water more acidic. pH measures acidity and total alkalinity, which reflects the water's ability to neutralize acids. More CO_2 means more hydrogen ions and lower pH.	The partial pressure of CO_2 (pCO_2) shows how much CO_2 there is in seawater. Higher pCO_2 means the ocean is absorbing more, which affects both water chemistry and marine productivity.	Alkalinity is the ocean's natural buffer against acidification. Total alkalinity measures how much carbonate and bicarbonate are available in seawater to neutralize excess acid.	Dissolved inorganic carbon (DIC) measures the non-living carbon in seawater, including CO_2, bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}). Tracking DIC helps us see how the ocean's carbonate balance is changing and assess the likelihood of acidification.

Source: NOAA OAP, 2026 .

Autonomous platforms can operate continuously for months or years at a time collecting physical and chemical data across a wide area without relying assistance. Examples include AUVs, profiling floats and instruments that drift through the water column or with the current. Slocum gliders, RAFOS and deep Argo floats (see Proven technology solutions) allow the monitoring of temperature, salinity, pressure, current and water mass movement, while also observing long-term changes linked to acidification and circulation.

In recent years, the development of compact sensors that directly measure carbonate chemistry in the ocean has progressed. Whereas traditional ocean acidification measurement required laboratory analysis of collected water samples, new miniature sensors enable *in situ* measurements in the ocean, and can also be placed on autonomous platforms. One such recent innovation is a total alkalinity sensor developed by the National Oceanography Centre in the United Kingdom. This autonomous sensor can measure deep-ocean total alkalinity, pH and carbonate chemistry parameters. By providing multiple co-located measurements in real time, the sensor reduces uncertainty, supports the calculation of key carbonate system variables, like saturation state and pCO_2, and enables the near-real-time integration with observation networks and ocean carbon models.

> Autonomous platforms can operate continuously for months or years at a time collecting physical and chemical data across a wide area without assistance

CTD (conductivity, temperature, depth) sensors measure the fundamental water properties determining density and circulation, which in turn influence the movement of acidified waters. These instruments are often deployed on autonomous platforms alongside chemical sensors to provide a comprehensive view of carbon system dynamics and the impact of ocean circulation on acidification (NOAA OAP, 2026).

Importantly, monitoring increasingly relies on software platforms that integrate large environmental datasets. These combine oceanographic measurements, satellite data, watershed data and ecosystem maps. GIS platforms, such as QGIS, allow researchers to map acidification hotspots and analyze interactions between runoff and coastal chemistry. Likewise, decision support platforms and portals – such as the Coastal Aquaculture Planning Portal developed by NOAA (see Proven technology solutions) – support the assessment of water quality and ecosystem risks, as well as the planning for aquaculture locations.

Marine carbon dioxide removal: emerging approaches and challenges

High-resolution monitoring reveals where and when ocean acidification is most severe, pointing to opportunities for intervention. Ocean carbon dioxide removal (mCDR) technologies are being explored, not only to lower atmospheric CO_2 and mitigate climate change, but also to reduce ocean acidity and buffer carbonate chemistry. These methods are typically grouped into three main categories: chemical, mineral and biological.

First, chemical approaches such as ocean alkalinity enhancement (OAE) aim to accelerate the ocean's natural capacity to absorb CO_2 by increasing seawater alkalinity. This involves adding alkaline materials, such as finely ground silicate rocks (e.g., olivine), limestone or manufactured hydroxide minerals, either directly into the open ocean or within coastal zones to promote carbonation reactions that convert dissolved CO_2 into stable bicarbonate ions. These ions remain in the ocean for millennia, enabling long-term carbon sequestration (>20,000 years). Although ocean alkalinity processes occur naturally over geological timescales, human-driven enhancement remains largely theoretical and at an intermediate technology readiness level (TRL ~6). Risks and uncertainties include possible ecological disruption and trace metal release, as well as the complexity of large-scale monitoring, which is technically challenging.

Mineralization approaches more broadly accelerate natural geochemical reactions, converting CO_2 into stable carbonate and bicarbonate minerals. These approaches can be applied to seawater, through enhanced weathering in coastal zones, or on land. While slower than some electrochemical methods, mineralization provides durable carbon storage and can also buffer ocean pH over time. However, it faces several technological and economic challenges. Mining, grinding, transporting and dispersing large quantities of alkaline rock, such as olivine, is both energy and cost intensive. Other challenges include establishing reliable monitoring, reporting and verification systems to confirm actual CO_2 removal (Geerts *et al.*, 2025). Given these constraints, mineralization is unlikely to scale quickly enough to offset ocean acidification on a global scale.

High-resolution monitoring reveals where and when ocean acidification is most severe, pointing to opportunities for intervention

Direct CO_2 extraction from seawater. Light-driven or electrochemical processes alter the carbonate equilibrium, resulting in the release of dissolved CO_2 as a gas that can be captured and stored. By removing CO_2 from seawater, these systems can indirectly draw additional CO_2out of the atmosphere, creating a feedback loop that reduces acidity and contributes to climate mitigation. Electrochemical carbon dioxide removal (eCDR) uses electrically-driven reactions to capture CO_2directly from seawater and stabilize it in a long-lived form. Seawater naturally contains dissolved inorganic carbon, and by locally altering pH through electrochemical processes, eCDR shifts chemical equilibria to increase CO_2 uptake from the atmosphere and convert it into stable bicarbonate, carbonate minerals or other forms suitable for long-term sequestration. Approaches range from applying voltage across electrodes to drive pH changes to extracting acid/base streams for engineered carbonation, sometimes co-producing hydrogen or mineral byproducts to improve economic feasibility. Scaling these systems would likely require large coastal or offshore facilities capable of processing large volumes of seawater using low-carbon electricity, potentially integrated with desalination plants, ports or renewable energy infrastructure. Technology readiness ranges from laboratory validation to early pilot demonstrations.

eCDR can buffer ocean acidification by raising local pH and carbonate ion concentration. However, benefits depend on using low-carbon electricity, carefully controlling local chemistry to avoid harmful pH fluctuations, and monitoring ecological impacts. Energy use, electrode durability and system integration remain key challenges, and large-scale deployment requires full environmental and lifecycle assessment.

Blue carbon, coastal restoration and seaweed cultivation: some promise, several questions

Biological and nature-based carbon dioxide removal (CDR) approaches use marine ecosystems to capture CO_2 through photosynthesis, while supporting ecosystem recovery. Examples include blue carbon restoration (mangroves, seagrasses, and salt marshes) and macro- or microalgae cultivation, which can provide habitat, improve water quality and in some cases offer localized buffering against ocean acidification.

Coastal vegetated ecosystems (mangroves, salt marshes and seagrass beds) naturally sequester carbon in plant biomass and soil, removing CO_2 from the atmosphere and contributing to localized acidification buffering. Restoration of these systems is the primary pathway for blue carbon CDR, and they can also deliver co-benefits such as coastal protection, habitat support and fisheries enhancement. Challenges include landscape changes (e.g., coastal development or erosion), climate impacts (e.g., sea level rise, storms), underinvestment in monitoring, and limited data on sequestration. To help address these challenges, carbon accounting, modeling and monitoring technologies – including sensors, remote sensing and GIS mapping – are being increasingly used to assess ecosystem growth, health and resilience.

Coastal vegetated ecosystems naturally sequester carbon in plant biomass and soil, removing CO_2 from the atmosphere and contributing to localized acidification buffering

Macroalgae (seaweed) and *microalgae* capture CO_2 through photosynthesis and can provide some localized buffering in coastal areas, aquaculture systems and farmed stands. They provide benefits, such as habitat creation, improved water quality, nutrient remediation and support for fisheries, while also producing biomass that could be stored long-term in biochar, bioproducts or ocean sinks. However, effectiveness is largely localized and context dependent. A large-scale mitigation of ocean acidification is unrealistic. Challenges include energy and nutrient requirements, scalability and potential environmental impacts such as deep-sea disturbance, altered light and nutrient dynamics, and conflict with existing ocean usage.

Experimental physical methods to mitigate ocean acidification

As discussed above under ocean warming, some CDR approaches, such as artificial upwelling (nutrient-driven), can stimulate biological carbon uptake and indirectly reduce acidification through photosynthesis. However, such methods remain highly experimental. Effects on pH are complex and regionally variable. Deep water brought to the surface is often low in pH, meaning upwelling can temporarily worsen local acidification rather than buffer it. Any potential application would require the careful monitoring of chemical, biological and ecological responses, and large-scale effectiveness remains unproven.

More broadly, some mCDR techniques are controversial. This is because they directly alter marine chemistry and/or ecosystems at scale, raising concerns about potential ecological impacts, governance and long-term effectiveness. Ocean alkalinity enhancement, artificial upwelling and large-scale algae cultivation may change local pH, nutrient dynamics or oxygen levels, and potentially affect sensitive species, food webs and sediment chemistry. While these approaches show promise for climate mitigation, most remain under active research and debate.

Innovation examples

Harnessing sailboat sensors to strengthen ocean acidification monitoring

Max Planck Institute for Meteorology, University of Hamburg, GEOMAR Helmholtz Centre for Ocean Research Kiel, and the Flanders Marine Institute



Source: Andreas Lindlahr

Researchers have shown that high-quality CO_2 measurements collected aboard sailing vessels can significantly strengthen global ocean carbon chemistry monitoring, a foundation for

understanding and responding to ocean acidification. Surface ocean partial pressure of CO_2 (pCO_2) is essential for quantifying air–sea carbon exchange and tracking changes in seawater acidity. Yet large regions of the ocean remain under-sampled. Scientists from several collaborating research centers assessed the impact of integrating sailboat-collected data, including observations gathered during global voyages by Team Malizia. When incorporated into the Surface Ocean CO_2Atlas, these additional measurements reduced uncertainties in air–sea CO_2 flux estimates and improved representation of under-monitored regions. By tapping into existing maritime activity as an observation platform, this approach provides a scalable, cost-effective way to expand acidification monitoring networks and improve regional carbonate chemistry modeling (GEOMAR, 2026).

Kelp farms turn the tide on acidification

Bangs Island Mussels; Bigelow Laboratory for Ocean Sciences



Source: Photo by Mitili Mitili on Unsplash

Bangs Island Mussels, a sea farm in Maine, produces hundreds of thousands of pounds of shellfish and seaweed each year. However, it sits within the Gulf of Maine, which is warming three times faster than the global average and particularly vulnerable to ocean acidification. This threatens shell development in clams, mussels, oysters and lobster, jeopardizing an industry generating USD 85–100 million annually. To help buffer these effects, the farm cultivates kelp, which consumes CO_2 and thrives in high-CO_2 environments. In partnership with Bigelow Laboratory for Ocean Sciences and Colby College, the team began testing water in 2015 to compare chemistry inside the kelp beds with surrounding waters, finding that mussels growing within the kelp had thicker shells. The farm now grows kelp alongside mussels using integrated multi-trophic aquaculture, which farms an ecosystem rather than a single species, and sells the seaweed to local processors for fermented foods and other products. Monitoring of seaweed farms has expanded from Alaska to Norway, and authors from Bigelow Laboratory published a 2025 article in Nature Climate Change on the potential of seaweed farming to capture carbon on the seafloor (Gezari, 2025).

Citizen science using a low cost pH sensor

Woods Hole Oceanographic Institution (WHOI); Ocean and Climate Innovation Accelerator (OCIA)



Source: Getty Images/SorinVidis

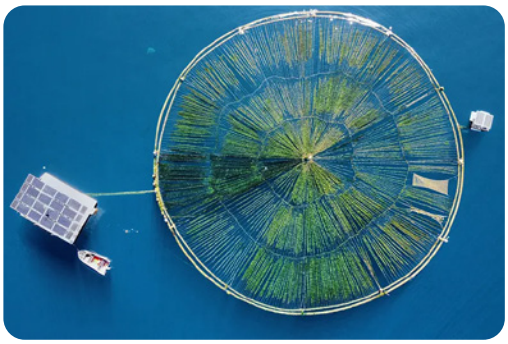
Researchers at WHOI, supported by the OCIA, are developing a low-cost, autonomous pH sensor designed for widespread use along coasts and by fishermen to improve ocean acidification monitoring. The goal is to create a pH instrument that is accurate, scalable and affordable, capable of continuous *in situ* measurements up to 300 meters deep and easy enough for fishermen or other ocean users to deploy on existing gear. Data from these sensors will be uploaded wirelessly to build high-resolution maps of coastal pH, helping scientists track acidification trends and inform mitigation strategies. Using advanced semiconductor chips and optical sensing technology, the prototype aims to be a fraction of the cost of current ocean pH instruments (potentially a tenth as much), while requiring minimal training to operate (ADI Signals, 2023).

The following collection of technologies is divided into three groups: Proven technologies have been on the market for some time and hence are well tested., Frontier technologies are available but relatively new, while Horizon technologies are close to being available but still under development.

Proven technology solutions

Marine permaculture

Climate Foundation



Source: ERIC SMITH/CLIMATE FOUNDATION

Marine Permaculture is a nature-based climate and ecosystem solution that uses renewable energy (wave, solar, wind) to drive deep water upwelling and irrigation for large-scale offshore seaweed cultivation. The system creates substrate and nutrient delivery that enables kelp and other macroalgae to grow in open ocean conditions, helping restore marine ecosystems, rebuild fish populations and sequester CO_2 by exporting carbon-rich organic matter to the deep ocean. It also supports sustainable food and feed production. The Climate Foundation is a US-headquartered nonprofit organization with activities and pilot deployments in locations such as the Philippines, Hawaii, Tasmania and other subtropical waters.

- Technological maturity: Proven
- Contracting type: For partnership or collaboration
- Technology level: Medium
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Slocum glider

Teledyne Marine



Source: Photo by Ant Rozetsky on Unsplash

The Slocum Glider is a long-endurance AUV that uses changes in buoyancy to move through the water in a sawtooth pattern, enabling efficient, months-long ocean observation missions without heavy power use. It is designed to collect high-resolution oceanographic data – such as temperature, salinity, currents and other environmental parameters – while traveling hundreds to thousands of kilometers on pre-programmed routes. Slocum Gliders operate at depths down to about 1,000 meters and regularly surface to transmit data and receive instructions via satellite, allowing remote mission control. The modular design supports a wide range of scientific sensors for physical, chemical and biological measurements. Because they are buoyancy-driven and require minimal support, the Gilders can be deployed from small vessels and withstand rough weather conditions, making them valuable for the persistent monitoring of ocean environments, climate research and large-scale circulation studies.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Deep-ocean profiling boat

MRV Systems



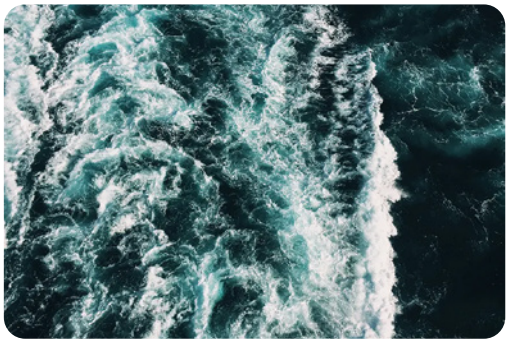
Source: Photo by Florian Delée on Unsplash

The DeepSOLO™ is a deep-ocean profiling float built by MRV Systems under license from the Scripps Institution of Oceanography specifically for the Deep Argo program. It autonomously cycles from the surface down to a depth of 6,000 meters, measuring pressure, temperature and conductivity using high-precision CTD sensors and transmitting data via Iridium satellite. A passive bottom detector helps it approach the seafloor safely before surfacing to send data. DeepSOLO is designed for long endurance – typically capable of ~250 profiles over several years – making it useful for full-depth ocean monitoring and global circulation studies.

- Technological maturity: Proven
- Contracting type: For partnership or collaboration
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

RAFOS float

Seascan Inc.



Source: Photo by Caleb George on Unsplash

The RAFOS float is an autonomous, submersible oceanographic instrument that passively drifts on water currents, while acoustically listening to fixed sound sources to determine its position over time. Deployed for months to years at a time, it provides high-resolution Lagrangian (moving with the flow) trajectories reflecting water movement below the surface. Although RAFOS itself does not measure carbonate chemistry directly, its ability to map where and how water parcels move – across space and through time – makes it a powerful platform for contextualizing alkalinity and other carbonate parameters. When fitted with sensors for temperature, salinity, pressure and optional biogeochemical variables, RAFOS floats can be integrated into observational networks able to capture the water mass dynamics affecting total alkalinity, dissolved inorganic carbon and pH. By linking physical transport pathways with the underlying chemistry, researchers are better placed to resolve the spatiotemporal patterns driving ocean acidification and ecosystem exposure.

- Technological maturity: Proven
- Contracting type: For partnership or collaboration
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Marine mapping software/hydrographic data processing system

Teledyne CARIS



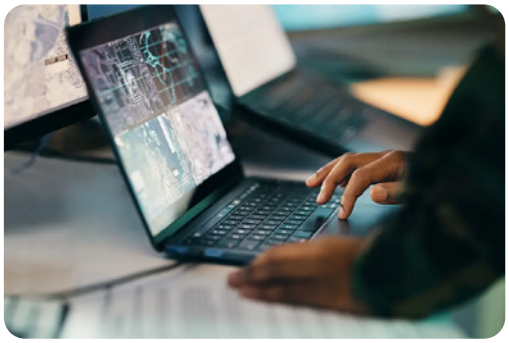
Source: Getty Images/eugenesergeev

The CARIS HIPS & SIPS is a hydrographic data processing system that converts raw sonar and survey measurements into high-resolution maps of the seafloor and the coastal environment. While it does not measure pH directly, it provides the spatial context essential for ocean acidification research. By detailing bathymetry, underwater features and upwelling zones, it helps scientists identify areas where acidification may be intensified or mitigated. Integrated with real-time survey data and cloud-based sharing, HIPS & SIPS supports habitat assessments, vulnerability modeling and strategic monitoring. Its ability to merge diverse datasets ensures that acidification studies are informed by accurate, comprehensive spatial information.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Open-source GIS platform

QGIS



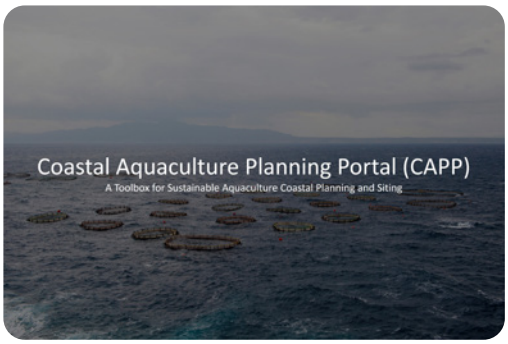
Source: Getty Images/Jacob Wackerhausen

QGIS (Quantum GIS) is an open-source geographic information system (GIS) used worldwide for spatial data analysis, mapping and visualization. It allows users to import, manipulate and analyze geospatial datasets obtained from a wide variety of sources, including satellite imagery, digital elevation models, watershed boundaries, river discharge and nutrient load data, as well as coastal water quality measurements. In the context of ocean acidification, QGIS can be used to identify and map land-based nutrient runoff hotspots (e.g., agricultural catchments, urban stormwater outfalls), visualize connections between watersheds and coastal zones, and overlay environmental layers such as pH, temperature and dissolved oxygen from monitoring networks. Its analytical tools enable the calculation of runoff pathways and contaminant flow directions, and make spatial correlations between terrestrial and coastal environmental stressors. QGIS also supports custom modeling by allowing plugins, making it a flexible platform for stakeholders wanting to integrate diverse datasets and inform adaptive strategies addressing nutrient pollution and acidification risks.

- Technological maturity: Proven
- Contracting type: Open source
- Technology level: High
- Place of origin: Switzerland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Coastal aquaculture planning portal (CAPP)

NOAA National Centers for Coastal Ocean Science (NCCOS)



Source: NOAA

The Coastal Aquaculture Planning Portal (CAPP) developed by NOAA is a web-based decision-support platform for sustainable coastal and marine aquaculture. It integrates spatial mapping tools, datasets and analytics to help planners, regulators and industry assess environmental, socioeconomic and regulatory factors relating to aquaculture siting. CAPP features interactive tools like OceanReports for customized spatial reports and National AquaMapper for the layered visualization of wave height, bathymetry, wind speed, habitats, protected species and water quality. By aggregating complex coastal data in one interface, the portal supports informed siting decisions, environmental impact assessments and permitting. Beyond aquaculture, tools within CAPP support mapping and analytical capabilities that can help track nutrient runoff, water quality trends, and ecosystem vulnerabilities, offering valuable insight for addressing ocean acidification and coastal ecosystem health.

- Technological maturity: Proven
- Contracting type: Open source
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier technology solutions

Compact conductivity–temperature–depth sensor for autonomous ocean observation and profiling

RBR



Source: Getty Images/Marta Masdeu

The RBRbrevio³ C.T.D is a compact, high-accuracy conductivity–temperature–depth sensor designed for autonomous ocean observation and profiling applications. It measures salinity indirectly by combining conductivity and temperature with pressure (depth) data, key physical properties used to calculate water density, which in turn influences ocean circulation and overturning strength. Its short, lightweight housing is ideal for integration with gliders, AUVs, floats, moorings or towed vehicles, and it supports high sampling rates (up to ~32 Hz) through real-time communication and on-board data logging. An inductive conductivity cell and fast thermistor help reduce salinity spikes and improve accuracy at varying depths, while its rugged construction supports long-term deployment at up to 6,000 meters depth, making it useful for deep ocean observing programs.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Offshore kelp forest cultivation for carbon sequestration and ecosystem enhancement

Kelp Blue



Source: Kelp Blue

Kelp Blue grows offshore forests of giant kelp (*Macrocystis pyrifera*) on submerged structures to capture CO_2 and support marine ecosystems. Giant kelp naturally absorbs carbon via photosynthesis, locking CO_2 into its tissue and releasing oxygen. Detached fragments and dissolved organic carbon drift offshore and can sink to the deep ocean floor, where carbon may remain sequestered for over 100 years, contributing to long-term carbon storage and helping counter ocean acidification by reducing dissolved CO_2 in seawater. Beyond climate mitigation, Kelp Blue's kelp forests enhance marine biodiversity, provide habitat and nursery grounds for fish and invertebrates, and improve nutrient cycling and water quality. The company sustainably harvests only the kelp canopy to produce biostimulants, bio-materials and other products.

- Technological maturity: Frontier
- Contracting type: For collaboration and partnership
- Technology level: High
- Place of origin: Kingdom of the Netherlands
- Availability: Namibia
- Contact: WIPO GREEN Database

Water-based carbon capture and stabilization system

Vycarb



Source: Vycarb

Vycarb's technology captures CO_2 using a water-based process that converts dissolved CO_2 into stable bicarbonate, enabling long-term carbon storage. The system is designed to integrate with industrial or environmental water flows, where it removes CO_2 efficiently, while producing an alkaline byproduct that can help balance water chemistry. Because it reduces dissolved CO_2 rather than simply storing compressed gas, the approach is particularly relevant to ocean acidification. An integrated hardware–software sensor system continuously measures dissolved CO_2, bicarbonate and carbonate levels, enabling fully monitored and auditable carbon storage, while ensuring the treated water chemistry remains safe for release. By storing CO_2 as bicarbonate with alkalinity in natural waters, it can help stabilize pH levels and reduce the chemical drivers of acidification harmful to corals, shellfish and other marine organisms.

- Technological maturity: Frontier
- Contracting type: For collaboration and partnership
- Technology level: High
- Place of origin: United States
- Availability: United States
- Contact: WIPO GREEN Database

Marine anoxic carbon storage (MACS) and marine sediment carbon storage (SCS)

Rewind



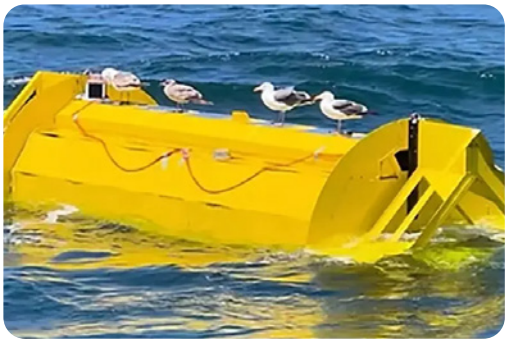
Source: Rewind

Rewind's ocean approach is focused on storing sustainably sourced plant biomass within naturally oxygen-free marine environments where low oxygen levels significantly slow microbial decomposition. In anoxic basins and sediments, organic material can remain preserved for long periods, reducing the likelihood that the carbon will return to the atmosphere as CO_2. The company has also developed sediment carbon storage (SCS), a method that involves placing biomass within low-oxygen seabed sediment, often in areas associated with dredging, where natural burial processes limit decomposition. By targeting anoxic or low-impact sediment sites, the approach aims to minimize disruption to productive oxygenated ecosystems and avoid altering nutrient balances. The method is designed to provide long-term carbon storage, while supporting broader efforts to reduce atmospheric CO_2 linked to ocean warming and acidification.

- Technological maturity: Frontier
- Contracting type: For collaboration and partnership
- Technology level: High
- Place of origin: Israel
- Availability: Georgia, Israel, Romania
- Contact: WIPO GREEN Database

Wave-powered pump for upwelling/ downwelling

Sea-Up



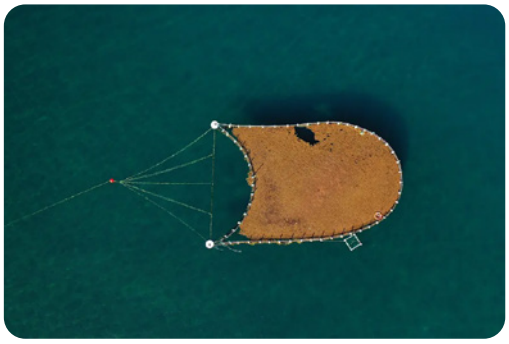
Source: Sea-Up

Sea-Up develops wave-powered upwelling systems that use the vertical motion of ocean waves to pump deeper, colder, nutrient-rich water toward the sunlit surface where natural biological productivity can be stimulated. By increasing nutrient availability in surface waters, the system aims to enhance phytoplankton growth, which may support carbon uptake through natural ocean processes. Sea-Up operates a subscription-based funding model called “Sea-Share,” through which individuals or organizations finance specific pumps and associated estimated carbon removal outcomes.

- Technological maturity: Frontier
- Contracting type: For collaboration and partnership
- Technology level: High
- Place of origin: United States
- Availability: Bermuda
- Contact: WIPO GREEN Database

Sargassum management/ seaweed valorisation

Seafields



Source: Seafields

Seafields provides a nearshore solution that intercepts Sargassum before it reaches the coast, using floating barriers and in-water paddocks to keep the seaweed alive and create a reliable, year-round biomass supply. The harvested Sargassum is processed into sustainable industrial feedstocks for products such as biostimulants, biochar and biomaterials. By managing Sargassum in nearshore waters before it washes ashore and decomposes, the system can also help avoid associated methane emissions, protect coastal and marine ecosystems, and support a circular blue economy.

- Technological maturity: Frontier
- Contracting type: For collaboration and partnership
- Technology level: High
- Place of origin: United Kingdom
- Availability: Caribbean, Mexico, United Kingdom, North Atlantic
- Contact: WIPO GREEN Database

Horizon technology solutions

Total alkalinity sensor

National Oceanography Centre



Source :Getty Images/Liudmila Chernetska

The National Oceanography Centre has developed a miniaturized total alkalinit (TA) sensor based on microfluidic lab-on-chip (LOC) technology. The system enables high resolution *in situ* measurements to be taken throughout the water column at sampling intervals of approximately 10 minutes. It operates using an open-cell design combined with spectrophotometric pH determination. The sensor features an adjustable measurement range (default 2,000–2,600 µmol kg^{-1}). First-generation units have been successfully deployed on fixed pontoons, seabed landers, shipboard underway systems, AUVs and ROVs.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: High
- Place of origin: United Kingdom
- Availability: Under development
- Contact: WIPO GREEN Database

Direct Ocean Capture (DOC) system using electrochemical CO_2 extraction

$SeaO_2$



Source: Getty Images/very good

$SeaO_2$develops DOC to remove CO_2 from seawater using an electrochemical process driven by renewable electricity and seawater alone. The system alters the carbonate equilibrium within seawater, allowing dissolved inorganic carbon to be released as gaseous CO_2, which is then captured for permanent storage in geological formations or converted into useful products like mineralized concrete, green fuels or chemicals. After treatment, decarbonized water is returned to the ocean's surface where it naturally reabsorbs CO_2 from the atmosphere, creating a continuous carbon removal cycle and helping offset ongoing emissions. Because dissolved CO_2 contributes to ocean acidification, removing it locally can buffer acidity and support marine ecosystem health as water returns with a lower carbon content. $SeaO_2$'s modular, scalable design is intended for integration with existing infrastructure, and pilot plants (e.g., in the Dutch North Sea region) are scaling from prototype to facilities with a multi-hundred tonne annual CO_2 removal capacity.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: High
- Place of origin: Kingdom of the Netherlands
- Availability: Under development
- Contact: WIPO GREEN Database

Electrochemical ocean alkalinity enhancement (OAE) carbon removal technology

Ebb Carbon



Source: Photo by Oleksandr Sushko on Unsplash

Ebb Carbon uses an electrochemical ocean alkalinity enhancement system to remove CO_2 from the atmosphere by increasing the ocean's capacity to absorb and store it. Seawater or brine flows through a modular electrochemical unit where electric current and ion-selective membranes separate it into three streams: a filtered brine stream, an acidic stream and an alkaline stream. The acidic stream can be repurposed for industrial uses, while the alkaline stream is safely returned to the ocean. Mixing with surrounding seawater, this alkaline water raises local pH and carbonate levels, promoting additional CO_2 uptake from the atmosphere and converting it into stable bicarbonate ions that remain in the ocean for thousands of years. By enhancing alkalinity, the system also helps counter ocean acidification, protecting sensitive marine organisms like corals and shellfish. The technology is modular, compatible with existing seawater or desalination infrastructure, and continuously monitored to ensure pH changes stay within natural variability.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: High
- Place of origin: United States
- Availability: Under development
- Contact: WIPO GREEN Database

Seawater electrolysis

Equatic



Source: Equatic

Equatic uses a proprietary seawater electrolysis process to accelerate the ocean's natural ability to remove and store CO_2. Seawater is pumped into an on-shore facility and electrolyzed using renewable electricity, splitting it into hydrogen, oxygen, an alkaline stream and an acid stream. The alkaline stream promotes CO_2 removal by drawing atmospheric carbon into the water where it is converted into stable bicarbonate ions and solid carbonates that can remain stored for tens of thousands of years. The acid stream is neutralized with rock before discharge to maintain safe marine chemistry, and the treated seawater is returned to the ocean without causing a harmful imbalance. This approach benefits the ocean by enabling increased carbon uptake and long-term storage, which helps mitigate ocean acidification and supports overall ocean health. Additionally, the process produces carbon-negative hydrogen, offering clean energy to reduce fossil fuel use. Equatic uniquely operates within contained plants, allowing the accurate measurement and verification of the CO_2 removed.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: High
- Place of origin: United States
- Availability: Under development
- Contact: WIPO GREEN Database

3.3 Atlantic meridional overturning circulation (AMOC) and ocean current disruption

The Atlantic meridional overturning circulation (AMOC) is a major Atlantic Ocean current that is part of a "global conveyor belt" moving warm water from the Southern Ocean to the Arctic, while returning cold, dense water to the south (MIT, 2026). The surface branch of the AMOC merges with the Gulf Stream and transports warm water from near Antarctica up to the Arctic Sea. Salinity and temperature fluctuations caused by evaporation, Mediterranean inflow and Arctic cooling drive the sinking of dense water which powers circulation. However, ocean warming makes seawater less dense, while additional freshwater from rainfall and melting ice lowers salinity. Together these processes can reduce deep-water formation and slow the AMOC.

AMOC: a potential tipping point in ocean circulation

The AMOC influences weather and climate across the Atlantic region and transports heat around the globe. It is a critical element of the climate system, having weakened or collapsed during past glacial periods and thereby contributed to abrupt climate changes. Past climate records show how disruptive such changes can be. At the end of the last ice age, large amounts of freshwater entering the North Atlantic triggered a major weakening or shutdown of circulation, leading to a sudden cooling in the Northern and a warming in the Southern Hemisphere. Evidence suggests it is once again weakening owing to a combination of ocean warming, increased rainfall and melting sea ice (Loriani *et al.*, 2025).

Direct measurement of the AMOC has been limited, but available data suggest it may have slowed by roughly 15 percent since the 1950s. Even a modest weakening can serve to cool Europe and alter precipitation patterns in South America and Africa, shift the Indian monsoon and move the tropical rain belt, potentially causing drought in the African Sahel. Some projections suggest a potential collapse could occur as early as mid-century under current emissions trajectories (Ditlevsen and Peter, 2023).

Increasing GHG emissions could raise the risk of crossing a tipping threshold. AMOC collapse would severely impact the North Atlantic climate and could have lasting effects: higher seas, stronger storms, Amazon rainfall changes and big north–south climate swings.

In situ, autonomous and satellite approaches to AMOC monitoring

Monitoring ocean currents and large-scale circulation patterns, such as the AMOC, relies on a combination of *in situ* sensors, autonomous vehicles, moored instruments and satellite observation. These systems aim to capture the velocity, direction and vertical structure of currents, as well as associated physical parameters like temperature, salinity and ocean mass. This is essential for understanding climate dynamics, heat transport and long-term variability. Some techniques are controversial. This is because they involve the active manipulation of deployment areas or rely on complex models, raising questions about accuracy, coverage gaps and interpretation in poorly observed regions.

AMOC collapse could have lasting effects: higher seas, stronger storms, Amazon rainfall changes and big north–south climate swings

A major class of instruments uses surface vehicles and AUVs. Gliders and AUVs drift or navigate through the water column, measuring temperature, salinity and currents, while transmitting data via satellite. Long-endurance gliders operate for months at a time, traversing hundreds to thousands of kilometers, while ultra-deep AUVs, capable of reaching a depth of 6,000 meters, provide high-resolution mapping of deep-ocean currents and water masses. Remotely operated vehicles complement these autonomous systems by enabling precise, localized surveys and

sensor deployment in GPS-denied or complex underwater environments. Key innovations include GNSS-aided inertial navigation systems, which improve georeferencing and motion compensation on compact platforms (correcting measurements for the movement of the platform carrying the instrument), ensuring accurate oceanographic data even when far away from a support vessel. Box 3.6 provides a brief overview of the differences between ocean monitoring platforms.

Box 3.6 Summary: How ocean platforms move

Ocean observing platforms differ in how they move through the marine environment, determining the types of measurements they are able to collect and the scale at which they operate.

Profiling floats move up and down by adjusting buoyancy and drifting with ocean currents, making them ideal for long-term climate monitoring.

Gliders likewise utilize buoyancy changes, but have added wings that allow them to glide forward, enabling slow and energy-efficient route-based surveys to be made.

Autonomous underwater vehicles (AUVs) use propellers for active navigation, allowing them to follow precise paths and conduct high-resolution seabed mapping and targeted missions.

Fixed and moored instruments remain stationary and provide continuous long-term measurements at a specific location.

Fixed and moored instruments are critical for long-term monitoring. An acoustic Doppler current profiler (ADCP) measures velocity profiles across depth cells and can be deployed on the seabed, attached to a buoy or on an autonomous platform. A passive acoustic monitoring (PAM) buoy tracks underwater sound and environmental conditions over a long duration, providing supplemental data on water mass movement and ecosystem dynamics. Deep-ocean profiling floats, such as those used in the Deep Argo program, autonomously cycle between the surface and the seabed, measuring pressure, temperature and conductivity, providing full-depth circulation information. Total alkalinity sensors now allow the high-resolution *in situ* measurement of those chemical properties influencing density-driven currents and ocean acidification.

> Ultra-deep AUVs, capable of reaching a depth of 6,000 meters, provide high-resolution mapping of deep-ocean currents and water masses

Satellite and remote-sensing technologies provide global coverage that complements *in situ* networks. Satellite altimetry missions measure sea surface height and ocean mass variations, while gravimetry missions like the Gravity Recovery and Climate Experiment (GRACE) and the Gravity field and steady-state Ocean Circulation Explorer (GOCE) track temporal and static variations in Earth's gravity field, informing estimates of large-scale current transport and ocean circulation trends. See Box 3.7 for an overview of these two missions.

Scatterometry is used to measure surface wind stress and air–sea interaction, while satellite-derived coastal bathymetry and shoreline change data support the modeling of regional circulation and coastal dynamics. High-resolution, long-term datasets obtained from these platforms are critical for ocean reanalysis systems, which integrate observations into numerical models to estimate circulation patterns and improve the understanding of large-scale ocean processes, including AMOC variability.

Box 3.7 GRACE and GOCE: Using satellite gravity to study the oceans

The Gravity Recovery and Climate Experiment (GRACE) and its successor GRACE Follow-On measure tiny variations in Earth's gravity field using twin satellites that track changes in the distance between them as they orbit the planet. These measurements reveal shifts in the distribution of mass, especially water in oceans, ice sheets and land hydrology. In oceanography, GRACE data are used to estimate ocean bottom pressure, allowing scientists to infer large-scale deep ocean currents and their variability, which improves understanding of global circulation patterns.

Meanwhile, the Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission from the European Space Agency maps the Earth's gravity field with very high precision to produce an accurate model of the geoid, the theoretical ocean surface shaped only by gravity. When combined with satellite measurements of actual sea-surface height, this geoid allows scientists to determine the speed and direction of surface ocean currents.

Together, these satellite gravity missions provide global measurements of ocean mass distribution, pressure gradients and sea-surface structure, complementing *in situ* observations and improving the monitoring of large-scale circulation systems such as the AMOC and the role they play in terms of the climate.

Source:ESA, n.d.; GFZ, 2026.

Together, these approaches represent a multi-scale, integrated monitoring network. Autonomous and moored instruments capture local and deep-water current structure, gliders and AUVs provide mobility and coverage in poorly observed regions, while satellites and reanalysis systems supply basin- and global-scale context. Innovations, such as compact GNSS-aided inertial navigation systems, ultra-deep AUVs with hovering capability and high-resolution lab-on-chip alkalinity sensors, are enhancing measurement precision and endurance, and enabling the long-term, scalable monitoring of ocean circulation.

Major monitoring systems tracking AMOC and large-scale ocean circulation

Monitoring the AMOC and ocean currents at large scale relies on a combination of observational networks and modeling systems to track large-scale ocean circulation and variability. Complementing autonomous and moored instruments, these systems provide additional precision and bring a global perspective to the understanding of this important circulation.

There are several global ocean reanalysis systems, including the HYCOM Consortium (a multinational effort to operate the Hybrid Coordinate Ocean Model (HYCOM) ocean reanalysis and prediction system supported by US institutions), Copernicus Marin (operates the Global Ocean Reanalysis System (GLORYS) based on the Nucleus for European Modelling of the Ocean (NEMO) model and incorporating *in situ* and satellite data) and the Estimating the Circulation and Climate of the Ocean (ECCO) consortium (a collaboration between Massachusetts Institute of Technology (MIT), National Oceanic and Atmospheric Administration (NOAA), Jet Propulsion Laboratory (JPL) and others) that produces estimates of ocean parameters for research. These models integrate satellites, moorings, float- and ship-based observations to produce a consistent estimate of ocean circulation inclusive of temperature, salinity and velocity. Reanalysis outputs allow researchers to quantify AMOC strength, track variability over time and project future changes under different climate scenarios.

Scatterometers – mentioned above – measure surface wind speed and direction across the ocean, the wind stress driving ocean currents, and upwelling/downwelling processes. Observations are assimilated into reanalysis and ocean circulation models to improve estimates of surface-driven AMOC variability. They are operated by NASA via its QuikSCAT SeaWinds instrument whose measurements of surface winds feed into global reanalysis research; the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), which operates an advanced scatterometer (ASCAT) on the MetOp satellite series providing marine

wind observations; and by the China National Space Administration (CNSA), which operates the HY-2A scatterometer that contributes wind observations for surface stress and circulation forcing.

Acoustic tomography uses the traveling times of sound between moorings to map ocean temperature and current distribution. Variations in sound speed provide a direct, basin-scale (overall behavior of an entire ocean basin) measure of AMOC variability over time. This is primarily a research technique pioneered by the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution. There are no large commercial providers offering basin-scale acoustic tomography systems.

Seafloor pressure and deep ocean circulation

Deep ocean circulation is monitored using precise measurements of pressure on the seafloor. Bottom pressure recorders (BPRs) measure very small changes in seafloor pressure, which reveal how deep ocean waters are moving. Often these changes amount to only a few centimeters over a single year. These measurements are critical for detecting trends, seasonal cycles and abrupt shifts in overturning circulation, which is driven by pressure gradients in the deep ocean.

> Bottom pressure recorders (BPRs) measure very small changes in seafloor pressure, which reveal how deep ocean waters are moving

The RAPID-MOC is a long-term ocean observing system jointly operated by the National Oceanography Centre (United Kingdom); the University of Miami Rosenstiel School of Marine, Atmospheric, and Earth Science; and NOAA, with support from the United Kingdom and US research funding agencies. RAPID originally stood for "Rapid Climate Change Programme," a UK research initiative launched in the early 2000s to investigate abrupt climate change risks. The observing array established under that program became known as RAPID-MOC, referring to the AMOC. It measures the strength and variability of the AMOC at 26.5°N across the Atlantic Ocean. It uses a network of moored instruments including current meters, temperature and salinity sensors, and BPRs, to track how much warm surface water flows northward and how much cold deep water returns southward.

In setups like the RAPID array at 26.5°N, BPRs provide continuous estimates. They are placed along the continental slopes on both sides of the Atlantic and help calculate the depth-independent (barotropic) transport of the ocean, which is combined with temperature and salinity measurements to determine total AMOC strength. Modern systems use very precise sensors (better than 0.01 dbar). To address the challenge of long-term sensor drift, one-year overlap periods are used between successive two-year mooring deployments and then compared with GRACE satellite data (see Box 3.7). Observations reveal that the AMOC varies significantly on a weekly-to-monthly timescale, and that it weakened measurably between 2004 and 2016 (Worthington *et al.*, 2019).

Innovation examples

Next-generation gravity mission for monitoring ocean circulation

ESA

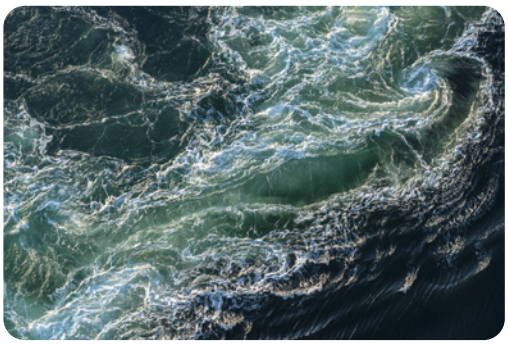


Source: Photo by NASA on Unsplash

The European Space Agency (ESA) is planning a new mission called the Next Generation Gravity Mission (NGGM). While building on the gravity measurements pioneered by GRACE and GOCE, this mission is specifically designed to improve the detection of changes in large-scale ocean circulation, including the weakening of the ocean conveyor system. It will include two satellites flying together as part of the MAGIC satellite constellation, alongside a companion pair from the GRACE-C mission developed by NASA and the German Aerospace Center. These satellites will use satellite gravimetry to measure tiny variations in Earth's gravity. Ocean circulation slightly changes gravity, because moving masses of water alter how mass is distributed across the planet. The satellites detect these changes by measuring the distance between them with extreme precision. When they pass over an area with slightly stronger gravity caused by greater water mass below, the leading satellite accelerates slightly before the trailing one. This allows scientists to map whereabouts mass is moving on Earth. The satellites can also detect pressure changes on the ocean floor. By measuring pressure differences between upper and lower continental slopes, scientists are able to estimate AMOC strength. Unlike the RAPID array, which is expensive and limited to one location, satellites can monitor the entire ocean basin continuously and potentially detect early warning signs of AMOC weakening or collapse (ESA, 2026b).

Argo meets AI: a new way to measure the AMOC

GEOMAR Helmholtz Centre for Ocean Research Kiel; Christian-Albrechts University of Kiel



Source: Getty Images/helovi

Researchers from GEOMAR Helmholtz Centre for Ocean Research Kiel and Christian-Albrechts University of Kiel have developed a machine-learning method of estimating the strength of large-scale Atlantic Ocean currents (AMOC) using data obtained from Argo floats. Because direct moored observations are expensive and require high maintenance, the study tested whether widely available Argo float data (specifically temperature and salinity profiles) could be used to estimate deep ocean currents. Using a high-resolution ocean model (VIKING20X)

and simulated Argo floats, they trained a machine learning model to convert scattered float measurements into estimates of large-scale ocean flow. The results were promising: the model explained up to 80 percent of the variation in ocean transport and had an average error of less than one Sverdrup (Sv), a unit used to measure ocean currents (equal to one million cubic meters of water per second). This is a strong result, because the AMOC itself only varies by a few Sverdrups over the course of years to decades. Finally, the researchers used explainable AI methods to understand how the model worked. They found that Argo data becomes especially useful over longer timescales, suggesting that machine learning applied to Argo float observations could help complement, or partially replace, moored estimates of the deep AMOC component in future monitoring systems (Wölker *et al.*, 2025).

The following collection of technologies is divided into three groups: Proven technologies have been on the market for some time and hence are well tested, Frontier technologies are available but relatively new, while Horizon technologies are close to being available but still under development.

Proven technology solutions

Inertial navigation system (INS) with GNSS for compact autonomous vehicles

SBG Systems



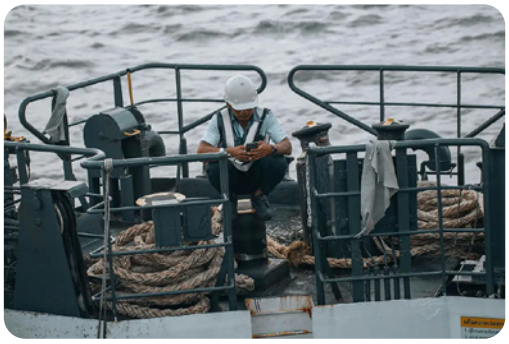
Source: Getty Images/Marta Masdeu

The Ellipse-N is a compact global navigation satellite system (GNSS)-aided inertial navigation system (measures motion using internal accelerometers and gyroscopes) optimized for smaller autonomous platforms such as gliders, medium-sized AUVs or unmanned surface vehicles (USVs). It combines a micro-electro-mechanical system (MEMS)-based inertial sensors (tiny sensors and mechanical components built on a microchip) with GNSS corrections to provide accurate orientation, position and velocity measurements, ensuring reliable motion compensation for onboard scientific instruments. Its lightweight, low-power design allows deployment on long-endurance missions, gathering temperature, salinity and current profiles critical for ocean circulation research. The Ellipse-N improves georeferencing and data quality on autonomous platforms operating far from a support vessel. When integrated into oceanographic missions, it supports climate monitoring, environmental studies and deep-ocean research. Its modular and compact form make it versatile for deployment on platforms where space and power are limited, while maintaining the accuracy required for scientific applications.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

Inertial navigation system (INS) with GNSS for high-precision navigation

SBG Systems



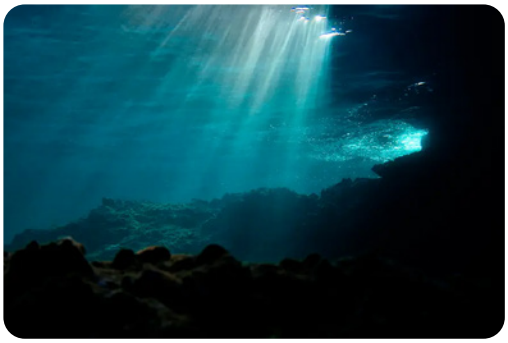
Source: Photo by Jonas Degener on Unsplash

The Ekinox-D is a high-performance inertial navigation system (INS) designed for demanding marine applications requiring precision and reliability. It integrates dual-antenna GNSS with high-grade inertial sensors to deliver accurate measurements of position, heading, pitch, roll and heave, even in rough sea conditions. Its performance ensures precise motion compensation for oceanographic sensors mounted on ships, autonomous surface vehicles or AUV support platforms. Such accuracy is essential when collecting temperature, salinity and current data for large-scale ocean circulation studies, for example, monitoring the AMOC. By improving the geospatial reliability of sensor data, Ekinox-D allows scientists to detect subtle variations in ocean currents and water mass transport, enhancing climate models, navigation accuracy and integration with satellite or other *in situ* observations.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

Autonomous underwater vehicle (AUV)

Kongsberg



Source: Getty Images/Johan Holmdahl

The HUGIN AUV is a free-swimming robotic system designed for long-range, untethered underwater survey and data collection. Operating at depths of up to 6,000 meters, HUGIN combines a hydrodynamic body with advanced navigation and a flexible array of sensors – such as synthetic aperture sonar, multibeam echo sounders, sub-bottom profilers, cameras and environmental instruments – to gather high-resolution geophysical and oceanographic data in a single mission. Since its development in the 1990s, it has become one of the most widely deployed commercial AUVs globally, used for seabed mapping, environmental monitoring and infrastructure inspection. Modern variants like the HUGIN Endurance enable long missions (up to 15 days and exceeding 2,000 km) with minimal human intervention, supported by sophisticated onboard navigation and mission planning systems.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Norway
- Availability: Worldwide
- Contact: WIPO GREEN Database

Remotely operated underwater vehicle (ROV)

Deep Trekker



Source: Deep Trekker

The Deep Trekker REVOLUTION ROV is a remotely operated underwater vehicle designed for flexible subsea operations. It offers advanced stabilization, autonomous waypoint navigation and a modular design that supports a range of modular sensor systems for environmental data collection, imaging and mapping. With flexible power options and a rotating head, the REVOLUTION can integrate high-resolution cameras, sonar systems and other survey tools needed for scientific missions. Its control software (BRIDGE Technology) allows data collection, autonomous path planning and operations in GPS-denied environments, making it adaptable for challenging water conditions. While not a dedicated scientific platform like a deep-ocean float or a mooring, the REVOLUTION ROV is effective for undertaking localized subsea surveys, habitat mapping and targeted deep-sea measurements that provide supplemental observational data in support of broader ocean circulation and climate monitoring efforts.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Solar-powered autonomous surface buoy equipped with an acoustic Doppler current profiler (ADCP)

Obscape



Source: Obscape

The Obscape ADCP Buoy is a solar-powered autonomous surface buoy equipped with an ADCP, typically supplied by manufacturers such as Nortek. It measures current speed and direction throughout the upper water column (up to ~90 meters depth depending on configuration) and transmits data in near-real-time via cellular or satellite communications. Designed for offshore and coastal deployment, the system enables the long-duration, low-maintenance monitoring of ocean currents without requiring continuous vessel support. For large-scale ocean observing systems, instruments like the ADCP Buoy provide localized, high-resolution velocity profiles that complement deep-water moorings, gliders and ship-based ADCP surveys. While not a full-basin AMOC monitoring solution on its own, it can contribute to larger networks that track ocean currents and circulation changes.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Kingdom of the Netherlands
- Availability: Worldwide
- Contact: WIPO GREEN Database

High-performance acoustic doppler current profiler (ADCP) designed for detailed water-column velocity measurements

Nortek



Source: Photo by Jakob Owens on Unsplash

The Signature1000 is a high-performance ADCP designed for detailed water-column velocity measurement. Operating at 1 MHz, it provides high-resolution current profiling suitable for coastal, shelf and upper-ocean deployment. Using broadband Doppler technology and multiple acoustic beams, the instrument measures current speed and direction across vertical depth cells, generating precise velocity profiles over time. The Signature1000 supports moored, seabed or autonomous platform installation and is engineered for long-term deployment in demanding marine environments. Its high sampling flexibility and integrated wave measurement capability allow the simultaneous monitoring of currents, turbulence and surface wave conditions. For large-scale circulation studies, instruments like the Signature1000 contribute localized, but highly detailed velocity data that can be integrated into broader observing networks, complementing deep-water ADCPs, gliders, satellite gravimetry and CTD systems used to monitor ocean transport variability and climate-relevant circulation changes.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Norway
- Availability: Worldwide
- Contact: WIPO GREEN Database

Deep sea profiling float

Tsurumi-Seiki



Source: Getty Images/Oleksandr Matsibura

Deep NINJA is a deep-ocean profiling float developed jointly by Tsurumi-Seiki Co., Ltd. and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). It is designed to autonomously sink, drift and resurface, while measuring temperature, salinity and pressure to depths of up to 4,000 meters (deeper than a standard Argo float). The float uses a buoyancy engine (a device that changes a float's density so it can move up and down in the ocean of its own accord), GPS for positioning at the surface and Iridium satellite communication to transmit data back to land. Deep NINJA has been used in scientific deployments in the Southern Ocean and Antarctic waters, contributing to Deep Argo efforts.

- Technological maturity: Proven
- Contracting type: For collaboration
- Technology level: High
- Place of origin: Japan
- Availability: Worldwide
- Contact: WIPO GREEN Database

SeaSonde

Codar Ocean Sensors



Source: Getty Images/Elias Bitar

The SeaSonde® high-frequency (HF) radar continuously maps surface ocean currents and waves over large coastal areas using shore-based antennas. It emits high-frequency radio signals that scatter off the moving sea surface. By measuring Doppler shifts and using patented direction-finding algorithms, the system derives 2D surface current velocity fields and key wave parameters in near real-time. The SeaSonde is a non-contact, low-power, remotely accessed and can support modeling, search-and-rescue and coastal management. It has been widely deployed globally, with systems providing decades of operational data and even capturing tsunami-related signatures.

- Technological maturity: Proven
- Contracting type: For collaboration
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

iSVP (Surface Velocity Program) drifting buoy

MetOcean Telematics



Source: MetOcean Telematics

The iSVP (Surface Velocity Program) drifting buoy is a Lagrangian (moving with the flow) surface current drifter that measures ocean currents by physically moving with the water. It consists of a surface float equipped with GPS and satellite telemetry, connected via a tether to a subsurface drogue (a fabric "holey-sock" sea anchor) centered at a depth of about 15 meters. This drogue ensures the buoy follows the water mass rather than being pushed by wind or waves. As the buoy drifts, it periodically records its position and transmits data via Argos or Iridium satellites, allowing scientists to calculate current velocity and direction from successive positions. The standard SVP is equipped with a sea surface temperature sensor, and buoys can also be equipped with an optional barometric pressure sensor. The standard SVP is equipped with a sea surface temperature sensor, and buoys can also be equipped with an optional barometric pressure sensor.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier technology solutions

Ultra-deep autonomous underwater vehicle

Exail



Source: Getty Images/avtk

The Exail A6K is an ultra-deep AUV designed for demanding deep-sea missions. It can operate at depths of up to 6,000 meters and supports long-endurance missions (up to about 30 hours, depending on payload), and has unique hovering capabilities for stable, low-altitude surveying. The A6K combines dual-mode survey and inspection functions and can carry a wide array of sensors – such as synthetic aperture sonar, multibeam echo sounders, high-resolution cameras, sub-bottom profilers, environmental sensors, lasers and magnetometers – tailored to mission needs. Its autonomy allows it to interrupt pre-planned routes for detailed investigation based on real-time data. It is flexible and easy to maintain, making it useful for science, ocean mapping, underwater inspections and rescue missions.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

Deep water acoustic Doppler current profiler (ADCP)

Sonardyne



Source: Sonardyne

The Origin 65 is a deep-water ADCP engineered for the long-range profiling of underwater currents, waves and turbulence. It combines advanced low-frequency acoustics with a robust “satellite-dish” transducer design and on-board Edge processing to produce high-resolution velocity profiles up to ~800 meters above the seabed, while operating at depths of between ~4,100 and 4,500 meters. An integrated acoustic modem allows remote configuration and data access without recovery, and an internal Pressure Inverted Echo Sounder (PIES) provides precise sound velocity and time-of-flight measurements that are fused with current data. These capabilities make the Origin 65 suitable for sustained deployment in challenging environments, where it can collect detailed current data for scientific missions. It has been used in long-duration ocean current programs (e.g., Loop Current studies in the Gulf of Mexico), showing its potential for deep-ocean circulation monitoring.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Coastal defense and stochastic surge model

Ocean Ledger



Source: Photo by Skyview Landscape. on Unsplash

Ocean Ledger provides insights into local coastal physical risks using satellite-derived data products and analytical methods to identify trends over time. The model uses satellite-derived bathymetry to map water depth in remote areas using multispectral satellite imagery. It generates spatially detailed shoreline positions and calculates erosion and accretion rates, as well as volume changes, at 100-meter intervals or finer along the coastline. High-resolution (15-meter) maps can then be produced detailing storm surge risk that accounts for erosion and other key factors, including estimates of surge damage frequency and severity. They can also measure historical gains and losses in ecosystem extent to support nature-based solutions and incorporate the value of natural flood defenses into catastrophe risk pricing and management. Ocean Ledger's data can be accessed directly through an application programming interface (API) for seamless integration into existing systems; or through a web-based portal, where users can request new sites and view data alongside maps and additional visualizations.

- Technological maturity: Frontier
- Contracting type: For service
- Technology level: High
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Mooring: passive acoustic monitoring (PAM) buoy

Cyprus Subsea Consulting & Services



Source: Getty Images/Philip Thurston

The PAM Smart Buoy is a moored observing platform integrating a self-powered buoy with a high-sensitivity digital hydrophone and environmental sensors. Once deployed, it sits anchored at a fixed location, continuously capturing underwater sound and environmental conditions. The system's broadband hydrophone records acoustic signals across a wide frequency with low noise, and data are transmitted in near-real-time via GSM or satellite links for analysis and event detection. Such a moored system is ideal for monitoring ambient ocean noise, marine life vocalizations or human-generated sounds over a long duration. Some oceanographic processes, such as internal waves, turbulence, deep mixing, generate sound and acoustic data can help in the studying of these processes. Acoustic data can complement physical measurements within integrated climate observing networks.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: Cyprus
- Availability: Worldwide
- Contact: WIPO GREEN Database

Bottom pressure sensor (BPR)

Sonardyne



Source: Sonardyne

The Fetch AZA is a self-calibrating bottom pressure recorder designed for long-term deep ocean monitoring. Deployed on the seafloor at depths of up to 3,000–6,000 meters, it measures the extremely small pressure changes that reveal shifts in water mass movement or vertical seabed displacement. Its key innovation is the Ambient-Zero-Ambient (AZA) calibration system, which periodically compares the main pressure sensor with a protected reference sensor to automatically correct measurement drift – one of the main limitations of conventional sensors. This allows the instrument to maintain highly accurate readings during deployments lasting up to 10 years. The system can log additional environmental data (such as temperature and sound velocity) and transmit information acoustically to vessels or uncrewed surface vehicles (USVs). These capabilities enable the long-term, high-precision monitoring of ocean circulation, seabed deformation and climate-relevant processes.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon technology solutions

Digital twin of the ocean

EDITO



Source: EDITO

The European Digital Twin of the Ocean is a high-resolution virtual replica of the ocean, integrating real-time observations and advanced models to simulate large-scale circulation patterns like the AMOC. It allows researchers to monitor shifts, forecast changes and test climate scenarios to better understand ocean dynamics and their global impact. It continuously integrates real-time data obtained from satellites and sensors, advanced ocean models, AI and high-performance computing to mirror and forecast ocean behavior. This open, interactive platform lets governments, researchers, industries and citizens monitor ocean conditions, simulate future scenarios (like climate impacts or pollution) and test “what-if” decisions to protect marine ecosystems, strengthen ocean governance and support sustainable blue economy planning. After an initial inception phase via the Horizon Europe “EDITO-Infra” and “EDITO Model Lab” projects, (2022-2025), EDITO continues developing in the framework of the Horizon Europe “EDITO 2” project (2025-2028), which is implemented by Mercator Ocean International, and the Flanders Marine Institute, with the support of Seascape Belgium on behalf of the EMODnet Secretariat. Beyond 2028, EDITO is intended to evolve into a long-term, sustained European infrastructure that extends beyond the lifetime of these projects. By 2030, EDITO envisions a fully operational European Digital Twin Ocean platform, serving as a global benchmark for digital ocean solutions and democratised access to ocean knowledge.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: France
- Availability: Under development
- Contact: WIPO GREEN Database

4 Freshwater



Freshwater ecosystems are critical for both nature and people. They cover less than 1 percent of the Earth's surface, but are home to 10 percent of animal species, including around a third of vertebrates and 40 percent of all known fish species (Schmidt-Kloiber *et al.*, 2019; Tickner *et al.*, 2020; Strayer David and Dudgeon, 2010). These fish species include around 70 species of freshwater mammals, 5,700 species of dragonfly, 250 of turtles, 700 of birds, 17,800 of fish and 1,600 of crab (Cumberlidge *et al.*, 2009; Balian *et al.*, 2008; IUCN, 2026; Fricke *et al.*, 2026). Moreover, over a half of all freshwater fish species are to be found in a single ecoregion, a high degree of endemism that makes them particularly vulnerable (Tickner *et al.*, 2020;Abell *et al.*, 2008). Numerous other animals, not least birds, are also dependent on these same ecosystems. Freshwater ecosystems have long been under pressure, with less than a fifth of pre-industrial freshwater wetlands remaining and projected to decrease to a tenth by 2050 (Albert *et al.*, 2021). This means that biodiversity in freshwater ecosystems is declining at least twice as fast compared to land and sea ecosystems, and 27 percent of the 298,500 freshwater species assessed for inclusion in the International Union for Conservation of Nature (IUCN) Red List are threatened with extinction (Tickner *et al.*, 2020;WWF, 2022). Climate change accentuates the threat through altering river flows and hydrological regimes, which exacerbates the pollution that leads to harmful algae blooms, habitat loss, invasive species and disease (Darwall *et al.*, 2018; Wang *et al.*, 2026).

4.1 Altering hydrological regime

Climate change affects freshwater ecosystems primarily by altering natural flow regimes through shifts in precipitation patterns, snowmelt timing, evaporation rates and the frequency of droughts. These hydrological changes modify the volume, timing and duration of the water flows that aquatic species depend on, resulting in habitat degradation, disrupted life cycles, reduced ecosystem connectivity and a decline in water quality. Because streamflow influences water temperature, dissolved oxygen levels and nutrient transport, changes in flow regimes can trigger cascading ecological impacts throughout freshwater systems. Technologies developed to address altered flow regimes are designed to support monitoring of river flows, forecasting of hydrological changes, optimization of water releases, and mitigation of flood and drought risks.

Responding to changing river dynamics with advanced water management technologies

Rivers respond rapidly to an increasing fluctuation in water availability, manifested through more frequent and severe droughts, floods, and shifts in seasonal flow patterns. These changes lead to greater variations in discharge, from flash flooding during heavy precipitation to prolonged low-flow conditions during dry periods. The resultant variability is propagated by connected landscapes, amplifying stress across other freshwater systems, such as the wetlands, floodplains and downstream lakes that depend on a consistent water supply and natural flow dynamics.

> Many river systems are experiencing earlier peak flows due to accelerated snowmelt and shifting precipitation patterns, followed by reduced water availability during traditionally high-demand periods

Beyond extremes, a significant transformation is occurring in the timing and seasonality of freshwater flows. Many river systems are experiencing earlier peak flows due to accelerated snowmelt and shifting precipitation patterns, followed by reduced water availability during

traditionally high-demand periods (Murodov *et al.*, 2026). These changes disrupt the ecological cues and timing regulating species migration, spawning, habitat maintenance and other freshwater ecosystem processes. Reduced baseflows during dry periods further lower river water levels, altering the sediment transport processes that help maintain river channel structure and habitat diversity. In addition, flood duration and depth is one of the primary factors determining vegetation pattern in floodplain lakes (Yao *et al.*, 2026). Increasing droughts are causing exposed shallow areas to remain dry for longer periods, potentially intensifying the effects of higher temperatures on plant growth and survival.

Technological advances are improving the ability to monitor and manage these hydrological challenges. Hydrological monitoring using stream gauges, remote sensing platforms and real-time sensors provides continuous information on river discharge, water levels and watershed conditions. Artificial intelligence (AI) and machine-learning models are increasingly being used to forecast floods and droughts, enabling more proactive water management (Matta *et al.*, 2026). Environmental flow management has emerged as a key restoration approach, using regulated water releases to mimic natural flow variability and maintain ecological processes (Yue *et al.*, 2021). Managed aquifer recharge (MAR) can complement these approaches by capturing excess water during wet periods and storing it underground in aquifers, either through infiltration basins, ponds or recharge wells. During dry periods, the stored water can be recovered for use, while the maintaining of groundwater levels can also help sustain connected rivers, wetlands and other freshwater ecosystems that depend on groundwater during periods of low flow. River restoration initiatives, including channel rehabilitation and nature-based flood management measures, further help restore hydrological function and ecosystem resilience.

Re-establishing natural river processes

Channel re-meandering is a common river restoration technique that involves either creating a new meandering channel or reconnecting cut-off meanders to restore a river to its natural course and slow water flow (Costaz-Puyou *et al.*, 2025). Reshaping the river channel improves connectivity between the river and its floodplain, and in doing so creates more diverse in-stream habitats for a wide range of aquatic and terrestrial plants and animals (OIEau ePLANETe Platform, 2026). In recent years, channel re-meandering has increasingly become a part of natural flood management (NFM) measures taken to reduce flood risk while restoring river ecosystems.

Another river restoration approach is Stage 0 floodplain reconnection, which aims to restore rivers to their natural pre-disturbance, or "Stage 0," condition. Rather than being itself a restoration technique, Stage 0 represents the historical state of a river landscape prior to any significant human modification. Achieving this state typically involves a combination of restoration measures such as raising or infilling incised riverbeds and rewetting the floodplain to restore natural hydrological and ecological processes.

In recent years, channel re-meandering has increasingly become a part of natural flood management (NFM) measures taken to reduce flood risk while restoring river ecosystems.

Unlike conventional in-channel restoration, Stage 0 adopts a landscape-scale approach that seeks to rehabilitate the entire river corridor by reconnecting the river with its floodplain and raising the water table. This is best suited to areas where there is sufficient space to allow smaller streams to reconnect with their valley bottoms and floodplains to develop naturally a diverse mosaic of wetlands, wet woodlands and multi-thread channels (The River Restoration Centre, 2026). In highly degraded valleys, active restoration techniques such as filling incised channels with sediment sourced from within the valley, adding large woody material, and

redistributing water across the valley floor help reestablish natural depositional processes in areas where natural recovery is unlikely (Revive Riverscape Solutions, 2026). By restoring these interconnected habitats, this approach increases biodiversity, improves water storage and enhances resilience to floods, droughts and climate change.

Conserving freshwater wetlands is a climate imperative

Wetlands are areas where water covers the soil or remains close to the surface for all or part of the year. They are highly dynamic ecosystems where water levels rise and fall naturally in response to the rainfall, river flooding, tides, seasonal changes, storms and droughts that strongly influences wetland ecological conditions and vegetation patterns. Wetlands provide habitats for many species and contribute nearly 40 percent of global ecosystem services, including water purification, flood control, groundwater recharge and carbon storage (Pal and Sarda, 2020).

Wetlands have been declining at an average rate of 0.52 percent a year since 1970 (Robertson *et al.*, 2025). In addition to human-induced pressures, climate change is increasingly affecting wetland hydrology by altering water balance, flood duration, water depth and water-holding capacity, particularly in dry regions whose wetlands are highly sensitive to climate variability. Prolonged flooding or excessive drying can significantly change wetland ecosystems by changing plant communities and disrupting ecological balance. Submerged vegetation may decline, while invasive or drought-tolerant species can spread rapidly. Changes in water levels and flood timing also disrupt the breeding, feeding and migratory cycles of birds, amphibians and fish, leading to habitat loss and biodiversity decline.

> Wetlands provide habitats for many species and contribute nearly 40 percent of global ecosystem services, including water purification, flood control, groundwater recharge and carbon storage

A range of technologies is being used to reduce impacts on wetlands and improve resilience. Remote sensing technologies, delivered through satellites and aerial platforms, are being widely used to track changes in wetland size, water levels, vegetation health and drying patterns in near real time. Geographic information systems (GISs) then organize, integrate and analyze the spatial datasets obtained to produce maps and track changes in wetland distribution and condition. However, accurately mapping wetlands remains difficult, with seasonal changes making it hard to differentiate between the surrounding land, vegetation and shallow water areas. Optical satellite systems provide detailed images of vegetation and surface water, while radar-based systems can detect flooding and soil moisture even under the cover or dense vegetation. Artificial intelligence and machine learning techniques are increasingly being applied in order to automate image interpretation, improve wetland classification, detect subtle ecological changes and generate predictive models of wetland loss or recovery under different climate scenarios.

Harnessing nature to restore rivers, lakes and wetlands

Nature-based solutions for rivers, lakes and wetlands, such as riparian vegetation restoration and buffer zone creation, help stabilize banks and reduce erosion. These solutions also improve water quality by filtering runoff and enhancing local biodiversity, while at the same time improving soil moisture retention. This is achieved by replanting native vegetation along the water edge to restore the plant communities previously degraded or removed. This vegetation slows surface runoff, traps sediments and nutrients, and strengthens soil structure through

its root systems, reducing pollutant flow into aquatic ecosystems. Constructed wetlands are nature-based wastewater treatment systems designed to store and treat water through natural processes, such as filtration, sedimentation and microbial activity, while also providing a habitat similar to that of a natural wetland. Beyond wastewater treatment, such wetlands can also serve as natural firebreaks between forests and other natural areas, particularly in warmer regions such as southern Europe and parts of the southern and western United States (Ecosys, 2026). Wetlands are also often used as a protection against flooding, especially in relation to urban areas, as described in the *Green Technology Book*, Adaptation edition.

Low-tech restoration using beaver dam analogues

Beaver dams are a recognized nature-based solution for river restoration. They provide many ecological benefits like reducing downstream flooding, restoring stream–riparian connectivity, trapping sediments and nutrients, and creating diverse habitats for fish, amphibians, birds, insects and aquatic plants. However, in the absence of natural beaver recolonization, today's river restoration practitioners are installing beaver dam analogues (BDAs) in thousands of degraded streams (Munir and Westbrook, 2020). These are relatively low cost, human-built structures constructed out of wooden posts, branches, mud, rock and other natural materials that function in a similar way to a beaver dam.

In degraded river systems, BDAs have emerged as a popular low-tech treatment for reducing water velocity, increasing floodplain connectivity and activating secondary side channels, and thereby enlarging the juvenile salmonid-rearing habitat (Meyer *et al.*, 2025). Consequently, it is widely recognized as an effective and practical technology for restoring degraded rivers and improving ecosystem resilience.

In degraded river systems, BDAs have emerged as a popular low-tech treatment for reducing water velocity, increasing floodplain connectivity and activating secondary side channels, and thereby enlarging the juvenile salmonid-rearing habitat

Beyond habitat restoration, beaver-related interventions also serve to strengthen climate resilience by reducing summer water temperatures, sustaining stream flow during dry periods, mitigating the impacts of floods and wildfires, and increasing watershed-scale biodiversity, which benefits species of conservation concern such as trout, salmon and amphibians. However, the magnitude of these ecological benefits depends on local climatic and hydrogeomorphic conditions (Burgher *et al.*, 2023).

Restoring hydrological connectivity to prevent freshwater habitat fragmentation

Freshwater ecosystems, for example, rivers, floodplains, wetlands and lakes, depend on dynamic connections that enable the free movement of water, nutrients and organisms. Changes in the timing, duration and volume of river flow can disrupt these connections, making seasonal flooding less predictable. As a result, freshwater habitats can become isolated and fragmented, which limits migration routes and reduces the extent and quality of the habitat available to those species reliant on seasonal flooding for reproduction and feeding. This affects a wide range of aquatic and water-dependent species such as fish, amphibians and wetland-dependent birds.

A well-known example is Cambodia's Tonle Sap Lake, which supports one of the world's most productive inland fisheries. Seasonal flooding of the Mekong River reverses the flow of water into the lake, expanding it across the surrounding floodplains and creating extensive aquatic habitats, as well as providing important fish catches for the local population. However, this natural cycle is becoming increasingly unstable as monsoon patterns shift. In some years, the lake has failed to expand to its full historical extent, reducing access to important spawning and nursery areas for migratory fish (Lovgren, 2025). Similar impacts have been observed in the floodplain lakes of the central Amazon Basin, where prolonged droughts and reduced connectivity with river channels are increasing the stress on aquatic ecosystems (Sithirith *et al.*, 2026)).

To address these challenges, satellite remote sensing and AI-based forecasting systems are improving the ability to monitor changes in flood dynamics and identify habitats at risk. Environmental flow management tools, such as eFlow-Predictor and DRIFT (see Proven technology solutions), combine hydrological monitoring with ecological modelling to help determine the timing and volume of flowing water needed to maintain river function and the seasonal flooding that supports freshwater ecosystems. Geospatial mapping, hydrodynamic modelling and floodplain restoration initiatives further help reconnect rivers with wetlands and floodplain lakes, thereby restoring critical aquatic habitats.

> Satellite remote sensing and AI-based forecasting systems are improving the ability to monitor changes in flood dynamics and identify habitats at risk

In addition, acoustic telemetry, radio tagging and GPS-based tracking systems are increasingly being used to monitor fish movement. These technologies help in understanding how changing hydrological conditions affect fish populations and where restoration efforts ought to be prioritized.

Building climate resilience for salmon through river restoration

Climate change is becoming a major threat to freshwater fish, with about 25 percent of species now at risk of extinction and at least 17 percent of threatened species affected by climate change (IUCN, 2023). For salmon, a change in river flow and rising water temperatures affect every stage of their life cycle. Warmer water, lower summer flows and more frequent droughts reduce the cool, clean water they require for migration and spawning and the growth of young fish in summer. Conversely, heavier winter rainfall and more frequent floods destroy spawning nests (redds), damage logjams and other stream habitats, wash away eggs and displace young salmon from sheltered habitats, thereby reducing survival rates. These impacts are further exacerbated by climate-driven disturbances, such as wildfires, insect outbreaks and forest loss, that continue to degrade freshwater habitats (Pacific Salmon Foundation, 2026).

> Climate change is becoming a major threat to freshwater fish, with about 25 percent of species now at risk of extinction and at least 17 percent of threatened species affected by climate change

Washington State in the United States is a case in point that illustrates these impacts clearly. Since 1949, snowfall has declined by 16 percent in the state, while snowmelt has decreased by 21 percent, resulting in lower river flows and warmer water during spring and summer when young salmon are most vulnerable (Governor's Salmon Recovery Office, 2024).

River restoration technologies is countering these impacts by playing a dual role in adapting freshwater ecosystems to climate change – restoring natural river processes, while simultaneously creating and protecting habitats for salmon and other freshwater fish. For example, floodplain reconnection and riverbank protection is helping minimize flood impacts and increase habitat availability, while riparian forest restoration along waterways is providing shade, maintaining cool and clean water, and improving habitat conditions. Another example is engineered logjams (Box 4.1). Natural logjams, also known as large woody debris, are accumulations of fallen trees, branches and roots vital to maintaining a healthy river ecosystem. Although they might be thought of as an obstruction, logjams improve river resilience and provide important habitat and ecological functions, particularly for salmon and other fish species.

Box 4.1 How logjams support river and ecosystem restoration

Where natural logjams have been lost or degraded, engineered logjams (ELJs) are increasingly being used in their place. These are large pieces of wood strategically placed in rivers to mimic natural river functions and enhance biodiversity. The key functions of ELJs are:

- to slow river flow and spreads water across multiple channels, thereby reducing erosion and protecting salmon and trout spawning nests (redds);
- to provide shelter and habitat complexity, including shade, refuge from predators and diverse habitats for fish and other wildlife;
- to create cool-water refuges by bringing groundwater to the surface, forming deep pools that support salmon during warm and low-flow periods;
- to support nutrient cycling and aquatic food webs by promoting algae and aquatic insects and recycling nutrients from spawning salmon; and
- to enhance long-term river resilience by promoting forest regeneration and sustaining the natural cycle of large woody debris.

Source: The Seattle Times, 2025

Floodplain reconnection for ecosystem restoration and flood management

Floodplain reconnection helps rivers become more resilient to a change in the flow regimes. It is a nature-based river restoration approach that reconnects rivers with the surrounding floodplain by removing or relocating barriers, such as levees and dikes, raising the riverbed or expanding the river bank. This gives the river more space to spread during high flow and store water during wet periods, allowing natural flow dynamics to recover over time. By restoring the connection between a river and its floodplain, this approach helps to reestablish natural flood patterns, improve water storage, recharge groundwater and create a diverse habitat for plants and wildlife.

Floodplain reconnection through earthworks involves physically reshaping the river and surrounding landscape to restore the natural connection between a river and its floodplain. Restoration practitioners excavate new channels, reconnect abandoned river pathways, lower riverbanks or create wetland areas so as to allow water to move more naturally across the landscape. Another approach is to raise a deeply engraved riverbed through the addition of sediment or other natural materials and bring the river closer to its floodplain, thus restoring more frequent connections during moderate flows. Interventions such as these accelerate natural recovery by recreating the physical conditions needed for rivers, wetlands and floodplains to function as an interconnected system.

Other common techniques include removing or relocating barriers such as levees and dikes, which allows floodwaters to spread into adjacent areas during high-flow events. Although floodwalls and levees have traditionally been built to mitigate flooding, they can work to

disconnect a river from its floodplain by confining water to narrow channels and in doing so increasing flow velocity, erosion and sediment accumulation (CTCN, 2026).

> Restoring the connection between a river and its floodplain helps to reestablish natural flood patterns, improve water storage, recharge groundwater and create a diverse habitat for plants and wildlife

While many floodplain reconnection projects involve large-scale engineering interventions, connectivity can also be restored through locally-managed, nature-based approaches. For example, community fish refuges (CFRs) in Cambodia's Tonle Sap Lake are locally-governed, low-cost interventions that contribute to restoring functional river–floodplain connectivity and sustaining resilient aquatic ecosystems under climate change and hydrological alteration. They function as dry-season refuges for fish, supporting survival and later recolonization when the floodwaters return. By maintaining water in key areas, CFRs help sustain a connection between a lake and its surrounding floodplain, extending floodwater coverage and supporting productivity driven by seasonal flood pulses during the inundation period. This lateral connectivity also links the Tonle Sap Lake with thousands of hectares of surrounding rice fields through a dynamic change in water levels, integrating permanent water bodies, floodplains and agricultural areas into a connected socio-ecological system (Sithirith *et al.*, 2026)

Floodplain reconnection has benefits for both ecosystem recovery and flood resilience. For example, the expansion of the original floodplain of the Danube River in Europe has supported the recovery of fish populations, including endangered species, and promoted the natural regeneration of floodplain ecosystems. Similarly, modelling studies on the Tisza River has shown that floodplain reconstruction and reconnection has restored estuaries and riparian wetlands, reduced flood peaks and improved the river's capacity to buffer extreme flows (Li *et al.*, 2022).

Technologies enabling coexistence of energy generation and aquatic biodiversity protection

Dams, culverts and other human-made structures on rivers and streams provide important services, including flood mitigation, water for drinking and irrigation, and clean, renewable power. Hydropower, for example, accounts for more than a half of global renewable energy production (IHA, 2026). However, hydropower projects can also have significant impacts on river systems by altering natural flow regimes, fragmenting rivers and disrupting the migration and habitats of fish and other aquatic species. American eel is one prime example, with populations in the Lake Ontario and Ottawa river systems having declined by around 99 percent, dams and other barriers among the contributing factors (Sra, 2024).

Dam removal can help restore river connectivity and ecological processes, and thousands of small and old dams have been removed in Northern America and Europe to this end (Nyqvist *et al.*, 2025). However, removing dams is not always feasible from a societal perspective, and a range of measures are therefore being adopted to reduce the impacts of existing dams, while also maintaining the services they provide. These include maintaining environmental flows and improving fish passage through dams and other barriers. Fish passage is an active area of research, with scientists and partners developing new approaches and technologies to support the passage of more fish and other aquatic species through dams (Pacific Northwest National Laboratory, 2026). Fish ladders, bypass channels, fish lifts and eelways help different species pass these structures. Fish ladders allow migratory species, such as salmon, to travel upstream, while fish lifts collect fish in a water-filled tank and mechanically carry them over the dam. Eelways are narrow, textured ramps that allow young eels to climb or wriggle around dams and

other barriers. Improved sensors and receiver technologies, including autonomous receivers, can also track fish movement and environmental conditions in near-real time, helping to improve the effectiveness of these measures.

> Innovation in turbine design is emerging as a promising solution to making hydropower more fish-friendly

Innovation in turbine design is emerging as a promising solution to making hydropower more fish-friendly, reducing the risk to fish when they pass through dams (Sra, 2024). Fish-friendly turbines, including modified conventional and low-head turbines, are designed to reduce injury by changing blade design, spacing and water flow through the turbine. Physical screens and behavioral deterrents, including acoustic or ultrasound systems, can help keep fish away from turbine intakes and guide them toward safer routes. Together, these measures can help reduce the effects of hydropower infrastructure on fish and aquatic biodiversity, while allowing dams to continue providing energy and other essential services.

From carbon sink to source: monitoring peatland response to groundwater change

In addition to supporting biodiversity, freshwater wetlands – particularly peatlands – play a critical role in climate regulation by storing large amounts of carbon. Peatlands are a type of wetland characterized by waterlogged soils whose low oxygen content slows the decomposition of dead plant matter. Over thousands of years, this process has led to the accumulation of carbon-rich organic material known as peat. Peatlands cover only between 3–4 percent of the Earth's land surface, but they store nearly a third of the world's soil carbon, making them among the most important long-term carbon sinks on the plane (UNEP, 2022).

However, drainage for agriculture, forestry and peat extraction, together with climate-driven droughts and rising temperatures, serve to lower the water table and expose peat to oxygen. This change in hydrological conditions accelerates decomposition, transforming peatlands from major carbon sinks into significant sources of greenhouse gas (GHG) emissions, accounting for an estimated 5 percent of the global anthropogenic carbon emitted annually (IUCN, 2017). Partially drained peatlands can also increase the emission of nitrous oxide (N_2O), a GHG with a global warming potential approximately 273 times greater than that of CO_2.

To mitigate such environmental impacts, rewetting (typically achieved by blocking drainage ditches, raising water tables and restoring natural water flows) is widely regarded as a key nature-based solution for reversing hydrological degradation in peatlands. Although restoration may temporarily increase methane emissions, especially at the early stages through the decomposition of newly submerged vegetation, this effect is generally outweighed by the long-term prevention of CO_2 emissions arising from peat oxidation and continued carbon loss. The long-term development of northern peatlands over the past 10,000–14,000 years, for example, is considered to have had an overall cooling effect on the global climate (International Peatland Society, 2019). Restoring natural hydrological conditions may also improve water retention, reduce flood peaks and enhance water quality at the catchment scale.

> Peatlands cover only between 3–4 percent of the Earth's land surface, but they store nearly a third of the world's soil carbon, making them among the most important long-term carbon sinks on the planet

Peatland restoration is increasingly being supported by advanced remote sensing technologies enabling the early detection, monitoring and assessment of degradation. Interferometric synthetic aperture radar (InSAR) helps identify areas undergoing peat subsidence by measuring millimeter-scale vertical ground movements over time. Healthy peatlands naturally expand and contract according to seasonal changes in water content, whereas degraded peatlands experience persistent sinking as the drained peat decomposes and loses its structure. By locating these subsidence hotspots, InSAR helps prioritize areas for rewetting and restoration. Optical satellite imagery, such as Sentinel-2 and Landsat satellites are being used to monitor hydrological stress in peatlands, such as the loss of moisture-dependent sphagnum moss and the expansion of bare peat or woody vegetation, both of which indicate drying and degradation.

LiDAR produces high-resolution elevation maps that reveal drainage ditches, peat domes, slopes and areas where water is escaping from peatlands. These data are integrated into GIS-based hydrological models in order to simulate water movement and identify the most effective locations for restoration. Ditch blocks are small barriers built across drainage ditches to slow water flow and raise the water table and may be suitable for some locations, while peat bunds are low embankments constructed from peat to retain water within the landscape and prevent it from draining away.

Innovation examples

The River Lea restoration and wetland creation project in the United Kingdom



Source: Getty Images/John Leckey

R. J. Bull Environmental Contractors carried out habitat enhancement and floodplain restoration along the River Lea at Water Hall, Bayford. The project was focused on improving ecological function, reducing flood risk and creating a more resilient river and floodplain system through targeted channel restoration, wetland creation and hydrological reconnection. Approximately 200 m of river channel was restored through bed and bank reprofiling, with berms, timber flow deflectors and large woody material installed to restore natural flow processes and increase habitat diversity. Around 3,000 m^3 of material was excavated to create two floodplain wetlands and reconnect the river with its floodplain. The restoration has improved river flow dynamics by reducing erosion, enhancing low-flow habitats, increasing channel complexity and providing temporary flood storage. These measures have improved habitats for fish, water voles, birds and invertebrates, demonstrating how integrated river restoration can strengthen biodiversity, ecosystem resilience and natural flood management (R J Bull Ltd, 2026).

Constructed wetland in China for water quality improvement and biodiversity restoration



Source: Photo by Shane Monarc on Unsplash

China Power Construction Ecological Environment Group Co., Ltd. has developed an integrated constructed wetland technology to improve water quality, while at the same time restoring freshwater ecosystems. The technology combines pre-sedimentation ecological ponds, subsurface-flow wetlands and aquatic plant ponds in a near-natural cascade treatment design, supported by technologies for preventing wetland clogging and restoring aquatic vegetation. This approach enhances pollutant removal efficiency, while improving the long-term ecological functioning of large-scale constructed wetlands. Applied in projects such as the Fuhe River Estuary Wetland, the technology reduced chemical oxygen demand by 41 percent, ammonia nitrogen by 76 percent and total phosphorus by 54 percent, with 99 percent of treated water meeting surface water standards. Beyond water purification, the project has improved regional ecological conditions, with more stable plant and bird communities, enhanced wetland habitat quality, and recovery of wetland biomass as a resource. The system also provides climate benefits by fixing approximately 12,540 tonnes of CO_2 annually (CEETT, 2025).

Floodplain reconnection: "The Room for the River" program in the Kingdom of the Netherlands



Source: Getty Images/hansenn

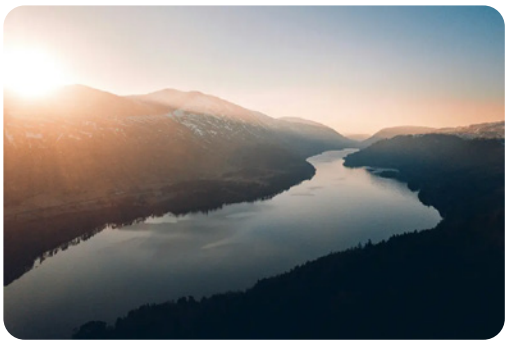
An example of floodplain reconnection technology is the "Room for the River" program in the Kingdom of the Netherlands, in which Royal HaskoningDHV contributed to the design, environmental assessment and implementation of multiple projects. The technologies applied in the program combined hydraulic modelling, landscape engineering and controlled water flow systems in the strategic reconnection of rivers with their floodplains, while managing safety risks. Notable measures included the reconnection of the 4,450-hectare Noordwaard polder in the Rhine–Meuse delta, so that it is able to convey up to 25 percent of the Waal river's flow during a high-water event, and the development of water retention capacity in the 8,300-hectare Lake Volkerak-Zoom, providing storage for up to 200 million m^3 of water. These interventions function as multi-purpose landscape systems, where engineered floodplain reconnection is used to combine flood protection with groundwater recharge and wetland habitat restoration, as well as enhance ecological diversity through the re-establishment of natural wet–dry cycles (Haskoning, 2026).

The following collection of technologies is divided into three groups: Proven technologies have been on the market for some time and hence are well tested, Frontier technologies are available but relatively new, while Horizon technologies are close to being available but still under development.

Proven technology solutions

Spatialized rainfall-runoff simulator

Tenevia



Source: Photo by Jack Anstey on Unsplash

HydroCore® is a spatialized rainfall-runoff simulator that models flow across a catchment, forecasting stream conditions and supporting flood prediction, water resource management and hydropower planning. It integrates spatial rainfall-runoff modelling with observed hydrology to forecast water availability and stream behavior across a landscape. This allows practitioners to anticipate dry versus wet periods and plan interventions, evaluate how changes (restoration works, beaver dams, reforestation) affect flow regimes, and support water resource planning for vegetation, aquatic habitat and sediment transport.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

Contactless radar-based river and channel monitoring

Geolux



Source: Photo by Michael Krahn on Unsplash

Geolux radar technology combines surface velocity and water level measurements to calculate total discharge (flow rate) internally. It enables the continuous, accurate, contactless monitoring of open-channel flow above the water surface, offering easy installation, low maintenance, compact design and low power consumption. As a result, it is widely used in river and channel monitoring, flood early-warning systems, irrigation networks, hydropower management and urban drainage, with its non-contact approach improving safety, durability and reliability even in harsh conditions.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Croatia
- Availability: Worldwide
- Contact: WIPO GREEN Database

Constructed wetland as wastewater solution

Suez



Source: Lilian Marchand

The Dragonfly® Wetland is a nature-based solution for wastewater treatment that utilizes the self-purification capacity of specially designed wetland ecosystems to improve water quality before discharge into the natural environment. Typically located downstream of wastewater treatment plants or stormwater networks, the system consists of a series of vegetated basins where water flows through the plants, microorganisms and sediments that naturally remove suspended solids, nutrients, pathogens and certain micropollutants. In addition to enhancing water quality, the system can support biodiversity by creating wetland habitats and help regulate water flow, contributing to the protection of downstream aquatic ecosystems. The system can be adapted to different sites and scales.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

EcoLog 1000, all-in-one cellular water level station

Ott



Source: Ott

The Ott ecoLog 1000 is an all-in-one water level logging and telemetry system designed for remote hydrological monitoring. It continuously measures water level changes and transmits real-time data via an integrated cellular modem, enabling the long-term observation of hydrological dynamics such as saltwater intrusion and its effects on surrounding wetland vegetation. Built for challenging environments with limited accessibility, the system is designed to operate in harsh conditions, including at high humidity and variable temperatures. Its integrated lithium battery can operate for years without the need for external solar panels or battery banks, while automatic cellular data transmission and remote diagnostics minimize on-site maintenance requirements.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

River restoration and ecosystem scenario modelling

Southern Waters Ecological Research and Consulting



Source: Photo by Pro on Unsplash

DRIFT is a decision-support modelling platform used to assess the ecological, hydrological and socioeconomic impacts of river management and development scenarios. The software simulates river ecosystems and the interactions among the hydrological, geomorphological, ecological and social factors influencing ecosystem services. It can evaluate the effects of altered flow and sediment regimes, barriers to river connectivity and management interventions on individual ecosystem components and overall river health. By comparing multiple scenarios, DRIFT supports environmental flow assessments, river restoration planning and water resource management, providing a structured framework for assessing potential outcomes and informing stakeholder decision-making.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: South Africa
- Availability: Africa, Asia, South America
- Contact: WIPO GREEN Database

Environmental flow allocation and water management operations

eWater



Source: Getty Images/nazar_ab

eFlow-Predictor is a decision-support tool that assists in the design and evaluation of environmental flow regimes for rivers. The software enables users to develop flow scenarios that meet ecological objectives such as maintaining seasonal base flows and supporting flow events required for ecosystem processes and species life cycles. It can assess multiple environmental flow requirements simultaneously, estimate the additional water needed to achieve target conditions and evaluate the environmental outcomes of alternative flow management strategies. The tool supports river restoration and water resource planning by helping practitioners balance ecological flow needs with water availability and management constraints.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Australia
- Availability: Worldwide
- Contact: WIPO GREEN Database

Riparian vegetation restoration

Biohabitats



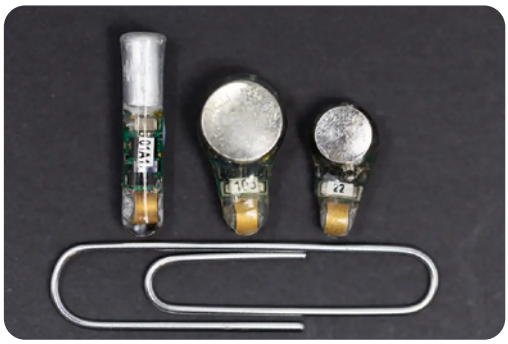
Source: Getty Images/nazar_ab

Biohabitats designs and implements riparian restoration projects that re-establish native vegetation along riverbanks, streams, and wetland margins. These vegetated buffer zones help stabilize soils, reduce erosion, filter sediments and pollutants from runoff, improve water quality and support soil moisture retention, contributing to the protection and restoration of wetland ecosystems.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Juvenile Salmon Acoustic Telemetry System (JSATS) Acoustic Micro Transmitter (AMT)

Lotek



Source: Lotek

The Acoustic Micro Transmitter (AMT) is a miniature acoustic tagging technology developed to support research on juvenile salmon migration, survival, behavior and fish passage in river systems. Weighing just 0.31 g, the Transmitter minimizes impacts on fish, while having a long operational life. It uses binary phase-shift keying (BPSK) technology to transmit more than 65,000 unique IDs on a single acoustic frequency, enabling accurate, real-time monitoring with minimal signal interference. Compatible with JSATS receiver networks, the system supports the autonomous detection of fish presence and two-dimensional positioning, providing high-resolution data to evaluate river restoration, habitat connectivity and the effectiveness of conservation measures such as fish passages and engineered logjams.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier technology solutions

Wetland Identification Model (WIM)

University of Virginia and Esri



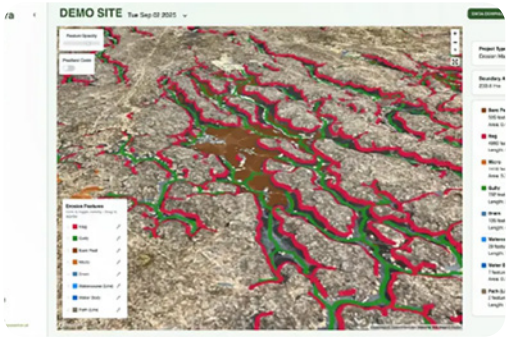
Source: Photo by Jevgeņijs Grigorjevs on Unsplash

The Wetland Identification Model (WIM) was originally created at the University of Virginia as a python workflow using various open-source libraries such as scikit-learn and GDAL. It was then implemented as a series of Arc Hydro Python Script Tools for ArcGIS Pro, a geographic information system (GIS) desktop application developed by Esri. The WIM derives topographic and hydrological indices from a high-resolution digital elevation model and uses them in a Random Forest classifier to predict the areal extent of wetlands. The model can be used to support wetland field surveying by identifying likely wetland areas.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

AI-based platform for peatland monitoring and restoration

Calterra



Source: Calterra

Calterra provides an AI-based platform for peatland restoration planning, monitoring and project management. The platform uses aerial and drone imagery, as well as machine learning, to provide high precision mapping of peatland conditions and assess erosion. The tools include AI-generated restoration plans based on vegetation, hydrological flow, gully metrics and site accessibility data. It can track the real-time monitoring of restoration progress and ecological health. Also it offers data-sharing and visualization, and has collaboration features such as 3D-mapping and monitoring dashboards.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Geospatial software for watershed analysis and nature-based planning

Scalgo



Source: Photo by Pix Tresa on Unsplash

SCALGO develops geospatial analysis software that supports watershed management, peatland restoration and nature-based water management planning. Its platform – SCALGO Live – combines high-resolution terrain data, hydrological modelling, land-use information and soil datasets to help users assess water flow pathways, identify suitable restoration sites and evaluate the impact of interventions such as peat dams, wetland creation, woodland planting and stream re-meandering. The platform also enables terrain modification and scenario analysis, allowing practitioners to estimate water retention, rewetting potential and earthwork requirements during project design.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: Denmark
- Availability: Europe, Northern America
- Contact: WIPO GREEN Database

Radar technology to detect peatland movement

Terra Motion Ltd



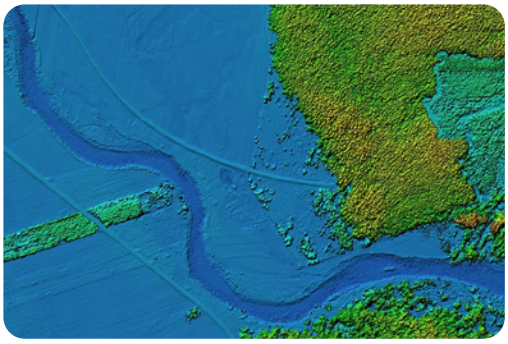
Source: Photo by Matt Benson on Unsplash

APSIS™ (Advanced Pixel System using Intermittent SBAS) technology, developed in collaboration with the University of Nottingham in the United Kingdom, processes large volumes of satellite radar data using InSAR techniques to detect land surface movement with millimetric precision. The system enables consistent measurement across vegetated and complex terrains without requiring ground control points or reflectors. APSIS™ captures ground deformation ranging from millimeters to several centimeters per year across land types such as agricultural areas, forests, peatlands as well as infrastructure, while its associated applications convert these outputs into environmental and engineering insights for land management and infrastructure monitoring.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: United Kingdom
- Availability: United Kingdom
- Contact: WIPO GREEN Database

Real-time river monitoring platform for low flow management

vorteX-io



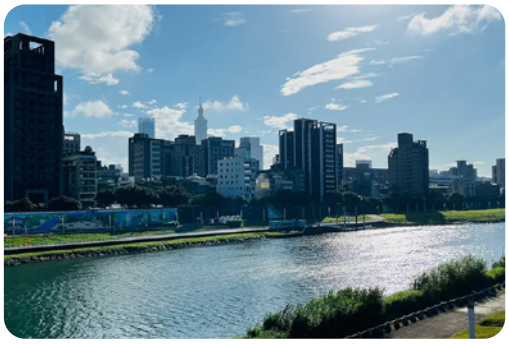
Source: Getty Images/Ungrim

vorteX-io has developed a real-time river monitoring system designed to support water resource management, particularly during low-flow periods. The platform combines LiDAR-based water level measurements, automated river image analysis and hydrological modelling to continuously monitor water levels, surface velocity and flow rates. Data are transmitted in real time to provide a continuous view of hydrological conditions, while historical records help identify seasonal and long-term trends. By coupling measured parameters with calibration curves, the system generates real-time flow estimates, supporting proactive management of water availability and water shortages.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

AI-powered video monitoring to support river restoration

Vivotek



Source: Photo by XinYing Lin on Unsplash

This solution combines a network of high-resolution PTZ (pan-tilt-zoom) cameras with the VORTEX cloud surveillance platform to enable continuous, remote monitoring of the river ecosystem, centralized video management and cloud-based data access in order to improve ecological research and environmental management efficiency. The system allows researchers to observe wildlife around the clock without disturbing natural behavior, replacing field inspections, manual observations and conventional infrared cameras with limited coverage and fixed viewing angles. It also provides real-time information on water levels and environmental conditions, helping authorities detect pollution incidents, monitor environmental change and flood risks during extreme weather. In addition, time-lapse footage and recorded videos are used as educational materials for schools and local communities, helping raise awareness of biodiversity and ecological restoration.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: Taiwan Province of China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon technology solutions

Peatland restoration: biomass-storage-in-peatlands for carbon removal

Restore Carbon



Source: Getty Images/Andrii Chagovets

Restore Carbon™ has developed a patented peatland carbon removal approach that involves placing plant biomass below the groundwater table in peat soils where low-oxygen conditions can limit decomposition and support long-term carbon storage. The method aims to enhance carbon sequestration beyond natural peat formation, while contributing to peatland restoration. The company also states that the approach may help reduce soil subsidence and improve soil stability, potentially supporting continued land use in affected areas.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: High
- Place of origin: Kingdom of the Netherlands
- Availability: Under development
- Contact: WIPO GREEN Database

Next generation autonomous water monitoring systems

Fluvio



Source: Fluvio

Fluvio is developing a computer vision-based stream gauging system that uses camera imagery, machine learning and cloud-based analytics to estimate water flow and velocity in rivers and streams. The company is currently refining its prototype to develop a commercially available technology for hydrological monitoring. The system is designed to support the remote, continuous monitoring of waterways, providing a cost-effective alternative to conventional gauging methods and reducing the need for field-based measurements. Planned enhancements include validation across a range of waterway conditions, integration of real-time water quality load monitoring, and a cloud-based platform for data storage, visualization and analytics to support water resource management, catchment monitoring and flood risk management.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: High
- Place of origin: Australia
- Availability: Under development
- Contact: WIPO GREEN Database

4.2 Heat stress and water quality

Freshwater ecosystems are heavily affected by activities both within the surrounding area and upstream. Urban areas generate large amounts of wastewater; agriculture generates nutrient rich run-off; industry and power plants dispense heated water; and hydropower dams change the character of water bodies. Climate change increases run-off by giving rise to more frequent extreme weather events and warming waters and this affects biological processes within freshwater systems. Together, these factors place freshwater ecosystems under growing stress, making innovation and technology increasingly important for monitoring, mitigating and adapting to these changes.

Nutrient pollution and eutrophication

When run-off to rivers and lakes increases through a change to rainfall patterns and extreme weather events, sediment and nutrients carried by the water often concentrates in the recipient areas. Such an influx of nutrients can lead to a sudden rapid increase in the growth of algae and phytoplankton, producing what is known as an algae bloom (Sharabian *et al.*, 2018). The immediate environmental impact is to block sunlight from reaching the aquatic vegetation deep under water, which may then die off as a consequence. Moreover, after having used the nutrients, the algae will also die off and sink to the bottom where it decays, leading to a depletion of oxygen and potential creating a dead zone where fish and other aquatic life are unable to survive. This process is referred to as eutrophication. When an algae bloom is caused by cyanobacteria – also known as blue-green algae though technically a photosynthesis-performing bacteria – the water environment may become toxic, as many strains of the bacteria produce toxins such as, for instance, microcystins (Chorus and Welker, 2021). This can adversely affect not only the aquatic environment, but also birds and other animals that feed on aquatic species. For birds in particular, warming waters may give rise to avian botulism, the bacteria *Clostridium botulinum* thriving in warm, oxygen poor environments and producing a neurotoxin that kills birds once it has entered the food chain (Espelund and Klaveness, 2014).

The source of the nutrients that produce algae blooms is often surplus fertilizer and manure originating from agricultural land, but it can also be urban runoff and the wastewater and sewage system (IPCC, 2022). However, increased run-off is not the only climate change related driver of eutrophication. Warmer waters serve to accelerate algae growth, especially cyanobacteria, which thrives at temperatures above 25°Celsius, creating the ideal conditions for algae to bloom (Jöhnk *et al.*, 2008; Paerl and Huisman, 2008). The decay of the algae in anaerobic conditions also leads to production of methane and nitrous oxide, both highly potent greenhouse gasses. Eutrophic freshwaters can emit up to 48% more methane than non-eutrophic ones, and taken together eutrophic emissions are estimated to have a climate impact equivalent to 31% of annual CO_2 emissions from fossil fuel combustion (Li *et al.*, 2021). Warmer waters also boost the internal release of phosphorous by accelerating microbial activity within sediments, while the reduced water viscosity associated with warming can increase nutrient mobility and further promote algae growth (Cano-Barbacil *et al.*, 2022; Sharabian *et al.*, 2018). A positive-feedback warming mechanism has also been demonstrated to result from the absorption of sunlight by algae. This has led to a rise in water temperature within algae blooms in the Baltic Sea of at least 1.5°Celsius (Paerl and Huisman, 2008).

Warmer waters serve to accelerate algae growth, especially cyanobacteria, which thrives at temperatures above 25°Celsius, creating the ideal conditions for algae to bloom

Detecting algae blooms and toxic algae

Detecting eutrophication and the presence of cyanobacteria typically relies on a chain of large scale technologies, ranging from satellite images down to microscopic-scale laboratory analyses. Satellite images can detect algae blooms in lakes and to some degree in rivers, and may even be able to identify cyanobacteria by detecting the optical signature of the unique blue pigment found in cyanobacteria called phycocyanin (Schaeffer *et al.*, 2024; US EPA, 2026). Drones can perform a similar task for narrower rivers where satellites may be less effective (Choi *et al.*, 2023). Remote sensing is followed up by *in situ* verification, especially to determine the presence of cyanobacteria. Technologies for verification range from highly advanced laser and automated, solar-powered stationary fluorometers to simple dipsticks and handheld fluorometers. Fluorometers operate by exposing algae to a specific wavelength of light, causing them to emit fluorescence from which phycocyanin can be detected. To determine whether cyanobacteria are capable of producing toxins or are actively doing so, DNA analyses are able to identify the genes responsible for toxin production, while ELISA (Enzyme-Linked ImmunoSorbent Assay) is able to detect toxins in water samples using antibodies that bind to them (Redden *et al.*, 2026; Zaffiro *et al.*, 2016).

Mitigating eutrophication

Eutrophication can be mitigated by either reducing the nutrient content in the wastewater or run-off released into the environment or by altering conditions within the environment itself. In this chapter, we have focused on the rivers and lakes themselves and the technologies to remedy eutrophication, while in general excluding the many technologies available for upstream wastewater treatment. Some of the technologies applied in wastewater treatment plants may, however, also be used in, for example, open lakes and for that reason have been included where relevant.

As mentioned, most of the nutrients causing eutrophication originate from agriculture. Therefore, reducing surplus nutrient run-off, primarily nitrogen and phosphorous, is an obvious starting point for prevention. Simple measures are already implemented by law in many countries; for example, vegetated buffer zones between fertilized fields and waterways, and limits on the quantity and timing of manure application. Constructed or enhanced wetlands where vegetation can slowly absorb nutrient-rich water can be effective measures if the land is available. The application of fertilizer onto fields can be controlled and optimized, making precision agriculture technologies important. GPS-controlled agricultural machines, satellite and drone-derived crop and field images, and soil sensors can all help farmers ensure that fertilizers are applied optimally and that they benefit crops, rather than algae. Some of these solutions have been discussed in the *Green Technology Book*, Mitigation edition.

Most of the nutrients causing eutrophication originate from agriculture. Therefore, reducing surplus nutrient run-off, primarily nitrogen and phosphorous, is an obvious starting point for prevention

Treating algae bloom

Treatments for algae bloom typically include oxygenation of the deeper layers of water or the application of safe chemicals that bind phosphorus, letting it precipitate to the bottom of a lake where it will form part of the lakebed sediment (Pereira and Mulligan, 2023). Injecting air into the deep bottom layers of a lake is a far more efficient alternative to surface aeration using paddles and so on. So-called hypolimnetic aeration and oxygenation uses various methods of injecting fine air bubbles into deep cold waters, thereby avoiding disruption to the lake's thermal stratification, which is vital to some fish and other aquatic organisms. Methods include injecting

nano-bubbles that remain buoyant in the water, pumping water up then oxygenating and pumping back and finally direct contact bubble diffusers. Several of these solutions are systems, rather than standalone technologies, and can be quite expensive to operate due to sourcing, handling and storing of oxygen required (Preece *et al.*, 2019).

Another way of destroying algae is through ultrasound. A number of companies have developed small devices that emit ultrasound which adversely affects the algae, either by breaking down its cell walls or causing it to sink and die through lack of sunlight. Such solutions offer an alternative to chemical treatment and can also be used to reduce biofilm buildup.

Toxic algae can also be removed using Dissolved Air Flotation (DAF). Enhancing its natural buoyancy forces algae to float to the water surface where it be collected and processed. Lakeside processing units use a flocculation treatment to clump the algae together. Micro-bubbles are then injected into the algae clumps forcing them to the surface where they are skimmed off. This method prevents dead algae from sinking to the bottom and releasing toxins. Due to high costs, DAF is most often applied to choke points with a higher concentration of algae or used in polluted tributaries. The algae can be processed into bio crude oil or agricultural fertilizer, thereby reducing costs (USACE, 2026).

> Chemical treatment can be effective in reducing nutrient pollution and the resultant eutrophication. But it is only a temporary solution – it will not prevent future algae blooms if nutrients continue to pollute the environment

The more traditional method for controlling algae blooms is to deprive algae of its main nutrient source, namely, phosphorous. This is typically achieved by applying substances to the water that bind to and immobilize phosphorus in the lake sediment. Aluminum sulfate (alum) and lanthanum-modified clay are the most common substances used for this purpose (Gargiulo, 2017). Alum is highly effective in clearing the water column, but is acidic and tends to lower the pH, and may become toxic to aquatic life at pH levels below 6. It must therefore be carefully administered and monitored during ecosystem applications.

A more modern alternative to alum is engineered Polyaluminum Chloride (PAC). It works similarly to alum, but does not lower pH, posing less risk to aquatic life while being more efficient. It works by introducing positively charged particles that bind with particles, including phosphorus, suspended in the water column (Bratby, 2016). PAC is currently one of the most widely used water treatment chemicals. Lanthanum-modified clay is considered more environmentally safe than PAC, as it creates a very strong bond with phosphorus in the resulting mineral rhabdophane, which remains stable even if environmental parameters change (Spears *et al.*, 2016). However, lanthanum is a rare earth mineral, which makes it a relatively expensive solution. Chemical treatment solutions can be effective in reducing nutrient pollution and the resultant eutrophication; but it may also create a layer of flocculants on the lakebed and is only a temporary solution – it will not prevent future algae blooms if nutrients continue to pollute the environment (ITRC, 2022).

Phosphorus removal from eutrophicated lakes has been the focus of several research projects. It is a complex challenge. This is because open freshwater ecosystems contain a large volume of water, have ultra-low phosphorus concentrations and sensitive flora and fauna. Any solution must therefore be non-toxic, operate under ambient flow conditions, and extract the phosphorus by physical means, rather than allowing it to sink to the sediment bed. Although removing phosphorous at source, for example, at wastewater treatment plants, is more efficient and likely to be cheaper, it does not address run-off and other non-point sources of pollution. However, several new solutions have emerged from research into phosphorus removal.

Iron nano particles are effective in absorbing phosphorous when they oxidize but may have adverse impacts on aquatic life ingesting the particles. Using magnetized micro or nano particles such as magnetic chitosan (a biopolymer sourced from recycled crustacean shells) allows for recuperation of the particles by applying a magnet after phosphorous absorption. Like this, the particles are removed from the ecosystem and may even be reused, thus lowering operation costs (Funes *et al.*, 2017). This technology is also being tested in wastewater treatment plants for efficient phosphorous removal (Kemira, 2026; Fraunhofer, 2026).

Sediment microbial fuel cell (sMFC) technology has been tested in Denmark as a highly efficient method for immobilizing and reducing phosphate concentrations in the water column by up to 94 percent. A durable steel mesh containing anodes is deposited on the sediment with a cathode mesh suspended in the overlying water layers. Through the action of naturally occurring electroactive bacteria (exoelectrogen) growing on the anode mesh, the structure creates a low-voltage steady electric current that draws electrons out of the sediment and creates the chemical condition for the oxidization of iron ions, enabling them to bind dissolved phosphates (Haxthausen *et al.*, 2021).

In smaller water bodies, algae and weed (which also thrives at higher phosphorus levels) can be removed mechanically using specialized boats and autonomous drones. The collected biomass can then be converted into useful products such as foam and rubber for shoes.

Sediment run-off also affects freshwater ecosystems

With increased run-off from land into aquatic systems the result of more extreme weather events, large amounts of suspended solids, such as soil, silt, sand and clay particles, are brought into the ecosystem. While this is a natural phenomenon, larger and more sudden events may have a detrimental effect on aquatic systems. The sediment is likely to block out sunlight, at least temporarily, affecting the aquatic life that depends upon it and thereby depleting oxygen. When the sediment settles on the bottom, it may over lay and alter the habitat. Insects may suffocate and fish suffer gill damage. Water birds preying on freshwater species may no longer be able to see and catch prey, and the sediment may introduce various pollutants and toxic substances, such as heavy metals, motor oil and pesticides, into the food chain. The high sediment content of turbid waters can also have a warming effect by absorbing the sun's infrared heat and releasing it into the water (Bilotta and Brazier, 2008; Wood and Armitage, 1997).

Figure 4.1 Sediment-rich water mixing at the confluence of the Arve and Rhône rivers at Junction, Geneva 2026



Source: Photograph by Peter Oksen

Warming freshwater and impacts on animals and plants

Freshwater warming due to climate change represents a fundamental threat to many aquatic species for several reasons. Warmer water holds less dissolved oxygen and since all freshwater fish, amphibians and insects are cold-blooded their body temperature, and hence their metabolism increases. It has been found that, in general, the metabolism of cold-blooded animals doubles for every 10°Celsius rise in temperature (Clarke and Johnston, 1999). This in turn increases the need for oxygen resulting in a so-called "oxygen squeeze," which threatens the aquatic habitat. It also increases the demand for food, sources of which may have been negatively affected by warming. This can result in stunted and undernourished fish populations (Pörtner, 2010; Kraemer *et al.*, 2021). A higher metabolism also means that pollutants, such as pesticides and microplastics, are absorbed faster, affecting other parts of the local food chain, as well as humans (Noyes *et al.*, 2009).

> The high sediment content of turbid waters can produce a warming effect by absorbing the sun's infrared heat and releasing it into the water

Some fish species are especially vulnerable to warming, because they depend on cool, oxygen-rich surface water. When this becomes scarce, fish have to move to deeper, cooler water, which is often low in oxygen during summer. This can make otherwise suitable habitats unhospitable for species such as trout, salmon and char. Prolonged oxygen depletion in deeper water can also convert naturally occurring mercury into the neurotoxin methylmercury, which then accumulates in the food chain (Stern *et al.*, 2012).

Warming water may also disrupt the reproductive cycle of aquatic life, as abnormally warmer temperatures can trigger mating, causing the season to begin too early. This may in turn affect the timing of other species that depend on a particular food source at a specific stage of their life cycle. Of particular concern are long-distance migratory waterbirds (e.g., ducks, geese, wading birds) whose seasonal migratory patterns are determined by length of day, whereas the reproductive cycles of their freshwater prey, which are cold-blooded, are controlled by changes in temperature. Migratory birds may therefore arrive too late to benefit fully from this critical feed source on their journey to summer breeding grounds, potentially adversely affecting their own reproductive success (Clausen and Clausen, 2013; Kwon *et al.*, 2019; Both *et al.*, 2009).

Temperature may also impact egg development in female fish, especially in cold water, where warm water can result in sterile or mutated eggs. For some fish species, such as tilapia and catfish, sex determination is impacted by temperature, with changes in temperature potentially leading to sex imbalances. During summer when river water levels are lower, stretches of shallow water may warm up and effectively create a migration barrier for cold-water fish, preventing them from reaching their spawning grounds upstream. Warmer water in rivers and lakes can hence produce a fundamental change in ecosystem dynamics (Pankhurst and Munday, 2011; Baroiller *et al.*, 2009; Murdoch *et al.*, 2015).

Aquatic plants are also affected by warming waters. Rooted plants may find warmer waters beneficial for growth, but be hampered by algae bloom limiting the available light. Reduced winter ice cover that allows more light to penetrate the water, in combination with the water being warmer, may also serve to disrupt the seasonal life cycles of plants.

Several technology solutions to the temperature issues described are the same as those for eutrophication, in the sense that they feed oxygen to the deeper areas of lakes and monitor environmental parameters in real-time using buoys or remote sensing. There is also the option to cool the waters, for example, through the planned release of cold water drawn from the bottom of hydropower dams or by reducing the amount of hot water released into the environment from power plants and industrial cooling systems. For more localized problems, one solution is to pump

up and release cold groundwater into important fish refuge areas during a heatwave. Planting trees that shade the riverbank is a simple nature-based solution. An interesting technology rapidly gaining popularity to help lakes and reservoirs stay cool are photovoltaic panels that float, so-called floatovoltaics. By blocking sunlight, they lower the water temperature and limit evaporation, and may also reduce algae growth. The resultant cooler environment also has the effect of increasing the efficiency of the panels. In order to reduce any negative effects on the ecosystem, it is recommended that the panels should cover no more than between 10–30 percent of the water's surface.

> Warmer water in rivers and lakes can represent a fundamental change in ecosystem dynamics

Another approach is to increase fish tolerance to warmer water. Selective breeding, supported by genomic sequencing to identify those fish possessing the desired inheritable traits, such as heat tolerance and resistance to disease and lice, is being used in aquaculture and hatchery breeding programs. Genetic editing of genes related to cellular stress and metabolism is also being explored, but faces significant regulatory constraints intended to protect ecosystems and wildlife. Aquaculture genetics is a growing technology field driven by fish farmers confronted by warming waters and the potential for substantial financial losses. In respect to conservation, technologies such as these may become a last resort for protecting endangered species from the effects of climate change.

Invading threats to warming freshwater ecosystems

When native aquatic species become heat stressed and weaker they may be displaced by invading species better adapted to warmer conditions. Examples of the latter group include carb and zebra mussels, which are able to tolerate warmer water of a poorer quality. Some invasive species are introduced into the environment after having escaped from aquaculture and water gardens during flooding, while the reservoirs for hydropower dams are a hotspot for others (Rahel and Olden, 2008).

The water hyacinth is an example of an invasive species that is causing major environmental problems in freshwater ecosystems. Originally imported from the Amazon basin as an ornamental plant, it soon escaped into the wild where it spread rapidly due to its ability to grow extremely fast. These floating plants form a massive and dense mat over the surface of waters, blocking out sunlight and preventing wind from mixing the water, resulting in oxygen depletion and dead zones for aquatic life. It also dramatically increases evapotranspiration, leading to water loss and creating ideal an breeding ground for mosquitoes. The spread of the water hyacinth is exacerbated by warming waters and the availability of nutrients, and climate change is enabling it to extend into climate zones previously too cold in winter for it to survive. Physical removal of the plants is the most environmentally sound way of combatting this species (Villamagna and Murphy, 2010; Brendonck *et al.*, 2003).

Fungi and some diseases spread faster and become more virulent in warmer waters, accelerating the life cycles of pathogens and parasites. Examples include the Chytrid fungus, which has caused mass extinctions of frogs in the highlands of the American tropics; the flesh-eating bacteria Aeromonas which attacks fish; and the parasite *Myxobolus cerebralis*, which attacks the spine of trout, causing whirling disease (Marcogliese, 2008; Alan Pounds *et al.*, 2006; Karvonen *et al.*, 2010).

Innovation examples

Floating solar panels in the Hapcheon Reservoir in the Republic of Korea helps mitigate eutrophication

Hapcheon Dam reservoir, Hanwha



Source: Energy Matters.

Hanwha Qcells deployed a massive 41.5-megawatt floating solar power plant on the Republic of Korea's Hapcheon Dam reservoir. Arranged in the shape of plum blossom, the project highlights the advanced technological and ecological capabilities of floating solar panels. Technologically, the project utilizes specialized Qcells solar modules engineered strictly for an aquatic environment. The panels are constructed using lead-free, eco-friendly alloys and highly moisture-resistant components to guarantee that they do not leach heavy metals into the reservoir's water supply over their operational lifespan. Crucially, the Hapcheon Dam project functions as an active ecological management tool. The sprawling floating array acts as a targeted shade canopy across the water. By blocking intense ultraviolet sunlight, the technology helps inhibit the explosive growth of harmful algae that historically plagued the reservoir during the summer. This suppression of toxic algal blooms prevents eutrophication and helps maintain healthy dissolved oxygen levels. Furthermore, the buoyant structures below the surface provide a safe, shaded habitat that encourages native fish to spawn. Ultimately, the project demonstrates how advanced floating technology can generate high-efficiency renewable energy, while simultaneously protecting and restoring the ecosystem of a major freshwater reservoir. Contact: WIPO GREEN Database.

Pulse release of cold water from deep hydropower reservoir breaks down thermal blockades preventing salmon migration

U.S. Army Corps of Engineers, Northwest Power and Conservation Council, Nez Perce Tribe DFRM



Source: Getty Images/ChrisBoswell

Summer heatwaves frequently create lethal "thermal blockades" in Idaho's Snake and Clearwater rivers, pushing water temperatures above the 20°Celsius threshold. At these temperatures, migrating endangered sockeye and chinook salmon face extreme physiological stress and mass mortality. To prevent this, the US Army Corps of Engineers utilizes Dworshak Dam as a massive climate-adaptation tool for artificially chilling the river system. As detailed by

the Northwest Power and Conservation Council, Dworshak Dam is equipped with specialized, multi-level “selector gates.” These unique mechanical gates allow engineers to bypass the sun-heated surface water and instead draw frigid, 6°Celsius water from deep within the reservoir's bottom layer. By analyzing data from real-time river temperature sensors and weather forecasts, engineers precisely time the release of this deep-water. The targeted cold-water releases – or “pulses” – augment the rivers’ natural flow and drastically lower downstream temperatures for dozens of miles. By breaking the thermal barrier exactly when the river is at its hottest, this technological intervention creates a vital cold-water corridor, ensuring that migrating salmon survive the extreme heat and successfully complete their upstream journey to spawn.

The following collection of technologies is divided into three groups: Proven technologies have been on the market for some time and hence are well tested., Frontier technologies are available but relatively new, while Horizon technologies are close to being available but still under development.

Proven technology solutions

Ultrasound clicks for algae control

ClickSonic



Source: Photo by Gennady Zakharin on Unsplash

Instead of broad-spectrum waves, the G-Sonic emits targeted, high-frequency “click” sound signals underwater. These precise vibrations cause the gas vacuoles inside the algae cells to resonate and tear, causing them to lose buoyancy and sink to the bottom and die naturally. Operating at low voltage (12–24V DC or 230V AC), the energy-efficient G-Sonic line is designed for eco-compliance. It effectively treats biofilms and blooms, while remaining completely safe for fish, amphibians, water plants and aquatic wildlife.

- Technological maturity: Proven
- Contracting type: Sale
- Technology level: Medium
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Precise, targeted ultrasound waves for algae bloom control

Lake Aid



Source: Photo by Gennady Zakharin on Unsplash

The Cell Buster series, engineered by the UK-based A.G.A. Group, is a chemical-free, ecologically conscious ultrasonic solution designed to combat severe blue-green and filamentous algal blooms. The technology focuses on structural disruption, rather than cellular destruction. By broadcasting precise, low-power ultrasound waves through the water column, it targets the internal gas vacuoles of the algae. This specific vibration causes the vacuoles to collapse, stripping the organisms of their buoyancy. As a result, the algae sink to the dark bottom of the water body, where they are safely starved of sunlight and die naturally. Crucially, by keeping the outer cell walls intact, the system prevents the sudden, dangerous release of toxic cyanotoxins into the water.

- Technological maturity: Proven
- Contracting type: Sale
- Technology level: Medium
- Place of origin: United Kingdom
- Availability: United Kingdom
- Contact: WIPO GREEN Database

Ultrasonic algae removal device

Beijing OKSUltrasonic Group



Source: Getty Images/Svetlana Vatolina

The company's ultrasonic algae removal device is a specialized industrial tool designed for swimming pools, fish ponds, lakes and wastewater treatment plants. It utilizes high-frequency pulse waves (28–42kHz) to create cavitation, which disrupts algal cell walls, enzymes and gas vesicles. The resonance effect produced forces algae to sink and die naturally without secondary pollution. The system features automatic frequency tracking and a bending vibration mode, achieving over 85 percent algae removal within 15 days. Available in 60W and 100W models with effective radiation ranges up to 50 meters, the device is marketed as a cost-effective, low-maintenance solution – reportedly costing only 8 percent of traditional chemical methods – and remains safe for human and aquatic life.

- Technological maturity: Proven
- Contracting type: Sale
- Technology level: Medium
- Place of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Deepwater lake oxygenation

Polycon GmbH



Source: Polycon GmbH

The TIBEAN (TiefenwasserBElüftungsANlage) system, developed by Polycon GmbH, is a specialized solution for deep-water aeration in stratified lakes, dams and ponds. With over 25 years of global success, the system oxygenates deep water layers without disrupting a lake's thermal stratification. By maintaining oxygen concentrations around 4 mg/L, it supports the oxidation of iron and manganese, prevents the formation of toxic hydrogen sulphide, and aids in fixing phosphorus within the sediment. This process effectively reduces nutrient levels and improves overall water quality. Polycon provides end-to-end support, including bespoke planning, construction and maintenance, offering both custom-engineered systems and standardized versions such as those adapted for cold-climate ice prevention.

- Technological maturity: Proven
- Contracting type: Service
- Technology level: Medium
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Lake bottom oxygen saturation solution

Clarity Research Group



Source: Clarity Research Group

The Clarity Research Group's Oxygen Saturation Technology (OST®) is a patented, industrial-grade aeration system designed to resolve critical water quality issues – such as harmful algal blooms, muck and odors – without disrupting thermal stratification. Unlike traditional mixing or bubble systems, OST® pumps deep water through an oxygen contact chamber assembly positioned on the bottom and injecting oxygen from an onshore oxygen generator, hyper-oxygenating it up to 25 mg/L before distributing it back along the lakebed. This creates a targeted "oxygen blanket" over the sediment, preventing nutrient release and suppressing anaerobic processes. Fully automated and driven by real-time monitoring, the system runs only when needed. This targeted operation reduces runtimes to a third of conventional aerators, delivering substantial electricity savings, while maintaining optimal ecosystem health.

- Technological maturity: Proven
- Contracting type: Service
- Technology level: Medium
- Place of origin: United States
- Availability: United States
- Contact: WIPO GREEN Database

Lake and river oxygenation systems

ECO_2 Technology



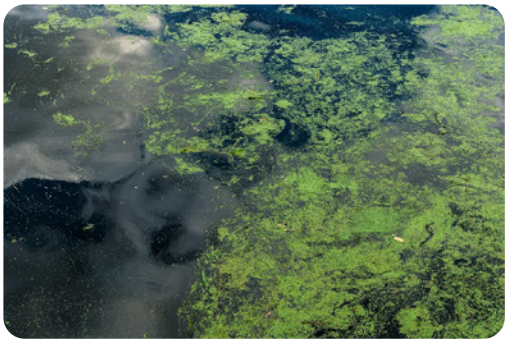
Source: Getty Images/borchee

ECO_2 specializes in advanced gas transfer systems, centered on the patented Speece Cone®, a stainless steel, maintenance-free device with no moving parts designed for high-efficiency oxygen dissolution. To ensure precise performance, the system integrates proprietary, fully automated oxygen flow controls that adjust in real time to water conditions. A side-stream pump serves as the system's only moving part, ensuring straightforward maintenance and consistent circulation. Oxygen is supplied either through on-site generation for long-term savings or via liquid oxygen (LOX) deliveries for operational simplicity. By replacing hazardous chemicals with pure oxygenation, ECO_2 reduces operating costs, minimizes environmental risk and provides a sustainable, scalable and highly reliable solution for water and wastewater treatment applications worldwide.

- Technological maturity: Proven
- Contracting type: Sale/Service
- Technology level: Medium
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Flourometer for algae and cyanobacteria detection

Xylem



Source: Getty Images/CHUNYIP WONG

The YSI ProDSS Total Algae-Phycocyanin (TAL-PC) sensor is an advanced, dual-channel optical fluorometer designed for the real-time monitoring of freshwater ecosystems. Built for the rugged, handheld ProDSS multiparameter system, this titanium-housed smart sensor allows environmental professionals to simultaneously detect chlorophyll and phycocyanin. By measuring chlorophyll, it tracks overall algal biomass, while the phycocyanin channel specifically isolates the presence of potentially toxic cyanobacteria (blue-green algae). Operating via*in vivo*fluorescence, the sensor emits specific wavelengths of light to excite cellular pigments and measure the resultant glow. Immediate,*in situ*data collection eliminates the wait time for lab results, providing water managers with a crucial early warning system for harmful algal blooms (HABs) in lakes, rivers and drinking water reservoirs.

- Technological maturity: Proven
- Contracting type: Sale
- Technology level: Medium
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Algaetorch for quick screening of algae and cyanobacteria

bbe Moldaenke



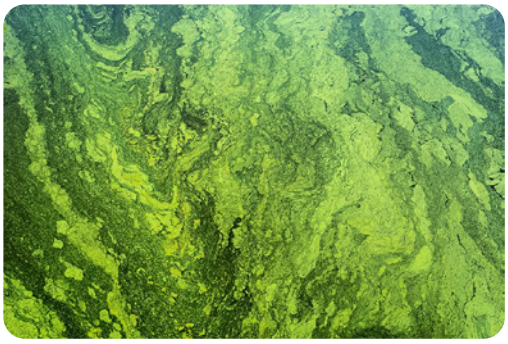
Source: Getty Images/Andrey Rykov

The AlgaeTorch is a lightweight, handheld fluorometer engineered for the rapid,*in situ*detection of cyanobacteria and total microalgae. Eliminating the need for laboratory sample preparation, this portable instrument utilizes multi-wavelength*in vivo*fluorescence. It emits specific LED light frequencies into the water to excite cellular pigments, simultaneously measuring chlorophyll-a (for total algal biomass) and phycocyanin (specifically isolating toxic blue-green algae). The device calculates and displays real-time cell concentrations directly on its built-in screen. Fully submersible and equipped with an automatic cleaning wiper, the AlgaeTorch ensures accurate readings in harsh environments. Integrated GPS and data logging allow users to instantly map harmful algal blooms (HABs) across lakes, providing a crucial, immediate environmental diagnostic tool.

- Technological maturity: Proven
- Contracting type: Sale
- Technology level: High
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Test strips for detecting cyanobacteria toxins

Gold Standard Diagnostics



Source: Getty Images/mycola

The Abraxis Microcystins Test Strip Kit is a rapid, on-site screening tool engineered to detect toxic cyanobacteria in recreational waters. Utilizing advanced lateral flow immunoassay technology, these dipsticks rely on specific antibodies that bind directly to microcystin toxins, producing a visible color change to indicate toxin concentrations at 0, 10 or 20 parts per billion. A crucial technological advantage is the integrated QuikLyse™ system. This chemical lysis process ruptures intact cyanobacteria cells directly in the field, releasing trapped intracellular toxins to ensure the test measures total microcystins, not just free-floating toxins. Environmental Protection Agency (EPA)-verified and requiring no heavy laboratory equipment, this kit provides a highly accurate, 45-minute diagnostic tool.

- Technological maturity: Proven
- Contracting type: Sale
- Technology level: Low
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Detecting algae bloom and toxins through environmental DNA testing

Diagnostic Technology



Source: Photo by Ela108 Garwacka-Goralik on Unsplash

The Phytoxigene™ CyanoDTec is an advanced molecular diagnostic technology designed to monitor algae blooms in freshwater ecosystems. Utilizing multiplex quantitative Polymerase Chain Reaction (qPCR) technology, this laboratory assay analyzes environmental DNA (eDNA) extracted directly from water samples. Unlike optical sensors or chemical toxin strips, CyanoDTec goes to the genetic level. It simultaneously quantifies total cyanobacteria biomass and detects the specific genes responsible for producing deadly cyanotoxins such as microcystins, saxitoxins and cylindrospermopsin. By identifying these toxin-producing genes before the algal cells actually rupture and release toxins, the technology serves as a highly accurate early warning system.

- Technological maturity: Proven
- Contracting type: Sale
- Technology level: Medium
- Place of origin: Australia
- Availability: Worldwide
- Contact: WIPO GREEN Database

Lanthanum-based phosphorus removal from lakes

Phoslock Environmental Technologies (PET)



Source: Getty Images/SawitreeLyaon

Phoslock is an advanced remediation technology designed to prevent Harmful Algal Blooms (HABs) by permanently locking away their primary nutrient: phosphorus. Technologically, it is a lanthanum-modified bentonite clay. When applied to lakes, the clay sinks, chemically binding with dissolved phosphorus in the water column to form an insoluble, stable mineral called rhabdophane. Upon reaching the lakebed, Phoslock forms an active capping layer over the sediment, effectively neutralizing the internal release of legacy phosphorus. Unlike traditional aluminum-based treatments, Phoslock is non-toxic, safe for aquatic ecosystems, and remains highly effective even under anoxic (oxygen-depleted) conditions or across wide pH fluctuations. It provides water managers with a long-lasting, ecologically safe solution to combating severe eutrophication.

- Technological maturity: Proven
- Contracting type: Sale
- Technology level: Low
- Place of origin: Australia
- Availability: Worldwide
- Contact: WIPO GREEN Database

Polyaluminum Chloride for safe phosphorus flocculation in lakes

Taki Chemical Co.



Source: Getty Images/Chadchai Krisadapong

Taki Chemical Co., based in Japan, is the historic pioneer of Polyaluminum Chloride (PAC), having commercialized the technology globally in the 1960s. Taki-PAC is an advanced, pre-polymerized coagulant engineered for superior water treatment. By introducing strongly positively charged aluminum molecules, it rapidly neutralizes negatively charged suspended solids – such as toxic algae and sediment – while chemically binding with dissolved phosphorus. This process forms large, heavy flocs that settle quickly to clear the water column. Compared to traditional aluminum sulfate, Taki's high-purity PAC is significantly more efficient, performs better in cold water, and produces less residual sludge. Crucially, because it is partially pre-neutralized, it does not cause dangerous drops in water pH, making it a safe solution for restoring fragile freshwater ecosystems.

- Technological maturity: Proven
- Contracting type: Sale
- Technology level: Low
- Place of origin: Japan
- Availability: Worldwide
- Contact: WIPO GREEN Database

Weed and algae boat harvesters

Aquarius Systems



Source: Aquarius Systems

The Aquatic Weed Harvester is a heavy-duty surface boat designed to manage overgrown aquatic environments. While built primarily to be “underwater lawnmowers” for rooted weeds, these machines are also crucial for battling the thick, filamentous algae mats fueled by warming waters. The harvester features a front-mounted cutting system and a porous conveyor belt that scoops up heavy surface algae, allowing clean water to drain back into the lake. By physically removing massive quantities of algae and plant matter from the water and storing it onboard for onshore disposal, the machines extract trapped nutrients like phosphorus. This mechanical removal prevents the algae from rotting in the lake, which would otherwise deplete dissolved oxygen, create toxic dead zones and suffocate native fish.

- Technological maturity: Proven
- Contracting type: Sale
- Technology level: Low
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Breeding fish for higher resistance in warmer waters

Benchmark Genetics



Source: Thomas Morel

The company is a major player in aquaculture biotechnology, and runs two breeding programmes for Atlantic salmon in Norway and Iceland. As sea temperatures rise, farmed salmon face heavier disease and parasite pressure and less oxygen dissolved in the water. The company meets these challenges by combining traditional family breeding strategies with modern genetic technologies. Priority traits include resistance to diseases and parasites that have become more common in warmer seas; gill and heart health, which determine how well a fish breathes when oxygen is scarce; and general robustness, so fish handle stressful events, including temperature variation, with less strain. The same expertise is offered as a service to breeders of more than 30 aquatic species worldwide, helping them adapt their own stocks to local conditions. The result is farmed animals better equipped for a changing climate, with better welfare, fewer farm losses, and more sustainable production for producers.

- Technological maturity: Proven
- Contracting type: Sale and service
- Technology level: High
- Place of origin: Norway
- Availability: Worldwide
- Contact: WIPO GREEN Database

High-density floating photovoltaic panels

Isigenere



Source: Getty Images/Tsvetan Ivanov

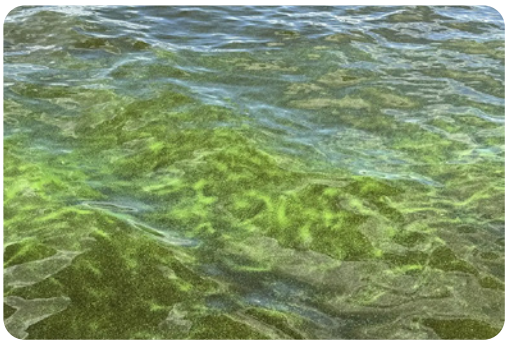
Isifloating, developed by the Spanish engineering company Isigenere, is a patented floating solar system designed to mount photovoltaic panels on water bodies such as reservoirs, ponds and lakes. The company's webpage highlights the system's high-density design, which maximizes the electrical capacity installed per surface area, while significantly reducing water evaporation by up to 80 percent. The surface shading effect produced directly improves local water quality by inhibiting the growth of harmful algae blooms. The system utilizes unique floats manufactured from durable, UV-resistant high-density polyethylene (HDPE), engineered to withstand extreme wind, wave and temperature variations. The Isifloating design prioritizes logistical and structural efficiency, utilizing stackable components that minimize shipping costs and allow for rapid, tool-free assembly on-site without the need for heavy machinery.

- Technological maturity: Proven
- Contracting type: Sale
- Technology level: Medium
- Place of origin: Spain
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier technology solutions

Laser and fluorometer-based measurement of algae blooms

Sequoia Scientific



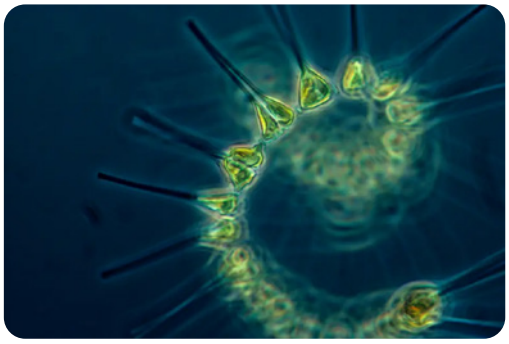
Source: Getty Images/Olena Lialina

The LISST-HAB is an advanced,*in situ*optical instrument engineered to detect and monitor Harmful Algal Blooms (HABs). Unlike traditional sensors that measure only bulk fluorescence, the LISST-HAB utilizes a powerful combination of laser diffraction and fluorescence technologies. By emitting a laser into the water, it calculates the exact size distribution and concentration of suspended particles. Simultaneously, an integrated fluorometer measures the fluorescence of these particles. This technological synergy allows the instrument to differentiate cyanobacteria and algal cells from non-biological particles like sediment, based on both physical size and pigment signature. Designed for continuous, real-time deployment, the LISST-HAB provides water managers with highly accurate, localized data for rapidly tracking bloom dynamics without having to wait for laboratory results.

- Technological maturity: Frontier
- Contracting type: Sale
- Technology level: Medium
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

In-field algae class detection using multiple light emitters

JFE Advantech



Source: Photo by NOAA on Unsplash

Multi Exciter is an advanced,*in situ*multi-wavelength fluorometer engineered to classify phytoplankton communities in real-time. Unlike standard sensors that use a single light source, this instrument utilizes nine separate LED excitation wavelengths to generate a highly detailed fluorescence spectrum of the water. This sophisticated optical technology allows researchers to differentiate between various algal classes – such as green algae, diatoms and potentially toxic cyanobacteria – based on their unique pigment signatures. Designed for autonomous deployment in marine and freshwater ecosystems, it provides continuous, high-resolution data on algal biomass and species composition. By analyzing complex optical responses in the field, the instrument allows precise, immediate measurements to be taken for the detection and tracking of algae blooms.

- Technological maturity: Frontier
- Contracting type: Sale
- Technology level: Medium
- Place of origin: Japan
- Availability: Worldwide
- Contact: WIPO GREEN Database

Oase Algae Management

Oase



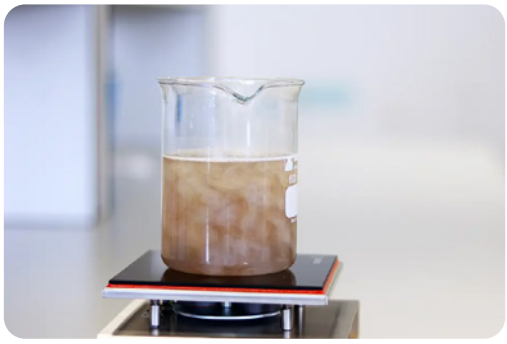
Source: Photo by engin akyurt on Unsplash

The Oase Algae Management is a science-led, system-wide technology approach focused on addressing the root causes of algae growth – specifically excess nutrients, low oxygen and biological instability – rather than simply reacting to symptoms. The technology stack relies on three main components: phosphorus binders (SeDox Max®), which chemically immobilize free orthophosphates into insoluble apatite minerals to starve algae at the source; sediment remediation matrixes (SchlixX Plus®), which combine active oxygen with targeted microorganisms to degrade organic sludge and prevent internal nutrient recycling; and aeration systems, which use artificial circulation and oxygenation to break thermal stratification, increase dissolved oxygen, and maintain optimal ecological balance across lakes, ponds and industrial water bodies.

- Technological maturity: Frontier
- Contracting type: Service
- Technology level: Medum
- Place of origin: United States
- Availability: United States and Europe
- Contact: WIPO GREEN Database

Chitosan-based flocculants for water remediation

Dober



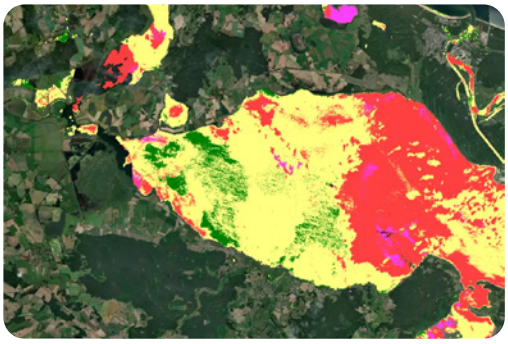
Source: Getty Images/Arpon Pongkasetkam

The HaloKlear water treatment line by Dober focuses on all-natural, chitosan-based flocculation technologies engineered for environmental remediation, construction dewatering and stormwater management without making the environment toxic. Its core technological innovation is centered on Chitosan Chemistries (sourced from recycled crustacean shells) and a proprietary Dual Polymer System (DPS), which pairs cationic chitosan coagulants (LiquiFloc) with natural anionic biopolymers (DBP-2100) to rapidly bind fine suspended solids, heavy metals and phosphorus into dense, high-shear flocs that settle rapidly. Offered in liquid, dry concentrate and passive semi-solid formats (GelFloc Socks), the technology provides an acrylamide-free, 100 percent biodegradable alternative to synthetic polyacrylamides (PAMs), delivering 30 percent lower dosing requirements, field-verifiable zero aquatic toxicity and full compliance with strict US National Pollutant Discharge Elimination System (NPDES) discharge standards for natural water bodies.

- Technological maturity: Frontier
- Contracting type: sale
- Technology level: Medium
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Detecting algae bloom and cyanobacteria from space

EOMAP



Source: EOMAP

The Harmful Algal Bloom (HAB) Indicator is a remote-sensing technology designed to detect cyanobacteria from space. It is also an ecological indicator for assessing climate-change impacts, a key measure of bathing-water safety, and essential for monitoring drinking-water sources. It operates by analyzing satellite imagery to identify the unique optical signatures of specific cyanobacterial pigments, namely Phycocyanin and Phycoerythrin. Technologically, the algorithm calculates the reflectance and absorption discrepancies specifically between the 550nm and 650nm wavelength bands. Rather than providing exact cell counts, the system currently generates a qualitative classification, categorizing the likelihood of a bloom into four tiers—from "no HAB" to "very likely." While its accuracy is validated against in-situ data for early warning surveillance, the optical sensors face limitations in highly turbid, humic, or sediment-heavy waters. The technology relies on the European Space Agency's Sentinel-2 and Sentinel-3 satellites.

- Technological maturity: Frontier
- Contracting type: Service
- Technology level: Medium
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Autonomous aquatic biomass and waste collector

RanMarine Technology



Source: RanMarine Technology

The WasteShark is an innovative electric aquatic drone designed to clean calm water environments like marinas, ports and lakes. Operating autonomously or via remote control, this unmanned surface vessel acts like a robotic vacuum for water. It glides quietly across the surface, skimming up to 500 kg of plastic trash, debris and invasive biomass – such as duckweed and algae mats – per day. Beyond physical cleaning, the WasteShark serves as a mobile data hub. It comes equipped with advanced sensors to monitor real-time water quality, measuring critical data like temperature, pH and dissolved oxygen levels. With zero emissions and a wildlife-safe design, the WasteShark offers a smart, modern solution for combating aquatic pollution and preventing ecological dead zones.

- Technological maturity: Frontier
- Contracting type: Sale
- Technology level: Medium
- Place of origin: Kingdom of the Netherlands
- Availability: Worldwide
- Contact: WIPO GREEN Database

Fighting invasive plants and algae with autonomous boats

Clearbot



Source: Clearbot

Clearbot is a marine technology company that designs AI-driven autonomous electric boats for aquatic cleanup and data collection. Clearbot fleets act as robotic skimmers, identifying and collecting marine plastics, invasive weeds and heavy surface algae. Utilizing AI and onboard cameras, the drones are able to distinguish between trash, biomass and aquatic wildlife, ensuring safe and efficient removal. They are fully electric, emission-free and can self-dock to recharge. By physically removing algae and pollutants from marinas, ports and lakes, Clearbot helps prevent oxygen depletion and toxic dead zones. Operating globally, this technology provides scalable, cost-effective solutions for municipalities and private waterfronts struggling with the ecological impacts of warming, polluted waters.

- Technological maturity: Frontier
- Contracting type: Sale & lease
- Technology level: Medium
- Place of origin: China
- Availability: Asia
- Contact: WIPO GREEN Database

Turning algae and seaweed into foam and rubber

BLOOM Sustainable Materials



Source: Getty Images/-lvinst-

BLOOM Materials is an innovative biomaterials company transforming toxic algae into high-performance materials. As warming waters trigger harmful algal blooms that suffocate aquatic ecosystems, BLOOM partners with water management facilities to harvest this excess algae. Physically removing the algae in this way helps restore clean water and oxygen to lakes and rivers. The harvested algae is dried and processed into eco-friendly pellets used in the manufacture sustainable EVA foam. This foam is utilized by major global footwear and consumer brands to create shoes, insoles and sports goods. BLOOM's circular economy model effectively cleans polluted waterways, sequesters carbon and reduces the manufacturing industry's reliance on fossil fuel-based plastics.

- Technological maturity: Frontier
- Contracting type: Sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Full floating photovoltaic systems with advanced anchoring

Quant Solar



Source: Photo by Maximus Beaumont on Unsplash

Incubated at the Indian Institute of Technology (IIT) Guwahati, the company designs, engineers and manufactures its own patented floating pontoons tailored for inland water bodies like reservoirs, dams and industrial ponds. The company emphasizes its comprehensive EPC (engineering, procurement and construction) services, highlighting an in-house expertise in complex mooring and anchoring systems required to withstand drastic water-level fluctuations and severe weather. The technology is presented as a dual-purpose solution that generates high-yield renewable energy through the water's cooling effect on the panels, while simultaneously conserving critical water resources by significantly reducing surface evaporation and limiting harmful algae growth.

- Technological maturity: Frontier
- Contracting type: Sale and service
- Technology level: Medium
- Place of origin: India
- Availability: India
- Contact: WIPO GREEN Database

Floating photovoltaic panels in reservoirs

Sunlution



Source: Photo by Soren H on Unsplash

Sunlution engineers modular floating solar systems utilizing durable, UV-resistant high-density polyethylene (HDPE) floats using the French company Ciel et Terre's Hydrelio float and solar panel attachment technology. These interlocking platforms securely mount photovoltaic panels across deep-water bodies such as hydroelectric reservoirs. The patented core technology relies on a highly specialized mooring and anchoring architecture designed to dynamically adjust to the extreme wind loads and drastic water-level fluctuations inherent to large dam basins. By hybridizing directly with existing hydroelectric infrastructure, the system leverages pre-built grid connections for efficient energy transmission. The physical floating structure acts as a barrier, shielding the water so as to drastically reduce evaporation and suppress algae growth. Simultaneously, the water beneath the structure functions as a natural thermal heat sink, actively cooling the solar semiconductors and thereby significantly increasing electrical generation efficiency.

- Technological maturity: Frontier
- Contracting type: Sale and service
- Technology level: Medium
- Place of origin: Brazil
- Availability: Brazil, Latin America
- Contact: WIPO GREEN Database

Turning Africa's reservoirs into photovoltaic power sources

Floating Solar Kenya Ltd.



Source: Photo by Soren H on Unsplash

The floating solar technology utilizes modular, UV-stabilized high-density polyethylene (HDPE) membranes engineered specifically to withstand extreme solar radiation. The system integrates standard photovoltaic panels onto interlocking buoyant structures designed for deployment on agricultural irrigation dams, mining ponds and municipal reservoirs. The core technology features a localized, highly scalable mooring system that accommodates significant water drawdown, ensuring structural stability during severe dry seasons. By physically covering the water surface, the floating array drastically reduces evaporation rates – a critical technological advantage in water-scarce climates. Additionally, the close proximity to the water surface creates a microclimate that provides natural conductive and convective cooling to the solar modules, preventing thermal degradation and maximizing the system's overall electrical energy yield.

- Technological maturity: Frontier
- Contracting type: Sale and service
- Technology level: Medium
- Place of origin: Kenya
- Availability: Africa
- Contact: WIPO GREEN Database

Horizon technology solutions

Immobilization of phosphate in lakes using sediment microbial fuel cells

Aarhus University, Danish Technical University (DTU)



Source: Karl Haxthausen

The sediment microbial fuel cell (sMFC) technology tested in Denmark's Lake Søllerød – developed by DTU researchers in collaboration with Aarhus University – offers a chemical-free, circular method for lake restoration. The system places low-cost, durable stainless steel mesh anodes directly into the anoxic lake sediment and suspends cathodes in the overlying oxygenated water. Naturally occurring electroactive bacteria in the sediment feed on organic matter, transferring electrons to the anode to generate a mild electrical current. This process raises the sediment's surface redox potential, prompting natural iron oxides to bind and immobilize up to 98 percent of free water-column phosphates. Beyond trapping phosphorus to starve algal blooms, the system degrades organic pollutants and suppresses harmful methane and hydrogen sulfide emissions (Haxthausen *et al.*, 2021).

- Technological maturity: Horizon
- Contracting type: Not applicable
- Technology level: High
- Place of origin: Denmark
- Availability: Under development
- Contact: WIPO GREEN Database

River water quality treatment using high-throughput flat-plate plasma

Shanghai Qiyuan Energy Technology Co., Ltd.



Source: Shanghai Qiyuan Energy Technology Co., Ltd.

The Plasma Nano-Bubble (PNNB) system is an advanced water treatment technology designed to restore polluted rivers and degraded aquatic ecosystems on a smaller scale. It combines a high-throughput plasma generator with a micro-nano bubble generator. This process subjects water to intense mechanical shear forces and pressure, creating highly soluble micro-nano bubbles, while breaking down molecular clusters. Inside these bubbles, the system generates powerful free radicals, particularly highly oxidative hydroxyl radicals. These free radicals aggressively attack and decompose the stubborn organic pollutants and pesticide residues that natural purification processes are unable to effect. Through this water–gas fusion, contaminants are chemically broken down and safely released as harmless gases like nitrogen, carbon dioxide and oxygen. This highly efficient approach purifies odorous water and replenishes oxygen without creating secondary chemical pollution.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: Medium
- Place of origin: China
- Availability: Under development
- Contact: WIPO GREEN Database

DNA sequencing for facilitated adaptation of animal species

Revive & Restore



Source: Getty Images/M-Production

Revive & Restore is a pioneering conservation organization dedicated to genetic rescue, utilizing biotechnology to save endangered species from extinction. While renowned for cloning mammals and researching gene-editing to help marine corals survive warming oceans, its current work with freshwater fish is focused on foundational genomic research. Through its "Wild Genomes" initiative, the organization funds the complete DNA sequencing of threatened aquatic species. Mapping genomes is the crucial first step toward what it terms "facilitated adaptation." By building comprehensive databases of genetic markers linked to thermal tolerance, disease resistance and environmental adaptability, Revive & Restore provides researchers with the biological blueprints required to eventually help vulnerable freshwater populations survive rapidly warming rivers, oxygen depletion and climate-driven habitat loss.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: High
- Place of origin: United States
- Availability: Under development
- Contact: WIPO GREEN Database

Engineering climate-resilient freshwater fish

Institute of Hydrobiology (IHB) of the Chinese Academy of Sciences



Source: Getty Images/jonathanfilskov-photography

The Institute is a major research institution focused on freshwater ecology, fish genetics and aquatic biotechnology. A significant portion of its research addresses severe ecological challenges in freshwater habitats, specifically analyzing the toxic cyanobacterial blooms that rapidly expand in warming waters. Through its State Key Laboratory of Freshwater Ecology and Biotechnology, researchers utilize advanced genomics and CRISPR gene-editing to study freshwater fish developmental biology and environmental adaptation. Studies investigate how specific fish genomes respond to physiological stressors, including hypoxia and metabolic strain, which are greatly exacerbated by warming aquatic environments. The Institute applies this genetic data to bio-breeding programs, engineering robust, disease-resistant fish strains optimized for commercial freshwater aquaculture operations.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: High
- Place of origin: China
- Availability: Under development
- Contact: WIPO GREEN Database

Innovative floating structure for photovoltaic systems

PROvendis GmbH



Source: Photo by Markus Spiske on Unsplash

Scientists at the Aachen University of Applied Sciences have developed an innovative floating structure technology for mounting photovoltaic systems on water bodies. Unlike conventional bulky plastic pontoons, this patented invention utilizes a unique “twisted tubing” design to provide buoyancy. By constructing the float out of coiled or spiraled tubes, the system significantly reduces material usage, overall weight, as well as transportation costs due to its highly stackable nature. This specialized twisted tube architecture is engineered to be highly ecologically friendly. Gaps within the twisted tubing allow sufficient sunlight and ambient air to penetrate the water surface, protecting the underlying aquatic ecosystem from severe shading and oxygen depletion. Furthermore, this open structure maximizes water’s natural cooling effect on the solar panels, increasing electrical efficiency.

- Technological maturity: Horizon
- Contracting type: N/A
- Technology level: Medium
- Place of origin: Germany
- Availability: Under development
- Contact: WIPO GREEN Database

5 The cryosphere





The cryosphere is Earth's frozen water, including glaciers, ice sheets, snow, permafrost, seasonally frozen ground, lake and river ice, ice shelves, icebergs and sea ice. It plays a vital role in regulating climate, storing freshwater, impacting sea level and shaping landscapes. Mountain and polar regions are among the most climate-sensitive components of the Earth system. They are especially delicate: even small changes in temperature can trigger rapid melting, permafrost thaw and shifts in snow cover.

These changes ripple through ecosystems and human societies, altering river flows, water availability and the risk of hazards such as floods, landslides and glacial lake outburst events. Because glaciers and the wider cryosphere are closely linked to the hydrological system, understanding their dynamics is critical for predicting climate impacts, managing water resources and protecting the ecosystems that depend upon them (IPCC, 2019b).

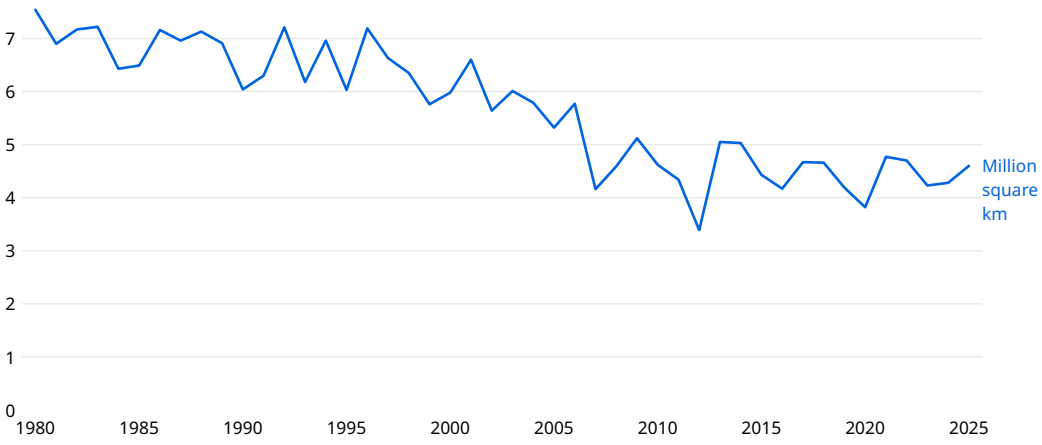
5.1 Sea ice and glacial melting

Glaciers and sea ice are among Earth's most ancient and dynamic reservoirs of frozen water, yet today they are retreating at unprecedented rates, reshaping landscapes, ecosystems and the global water cycle. Sea ice forms in the ocean, while glaciers are formed on land. Roughly 10 percent of Earth's land area is covered by ice, of which almost 90 percent is in Antarctica with the remaining 10 percent in the Greenland ice sheet (WWF, 2026).

> Glaciers and sea ice are among Earth's most ancient and dynamic reservoirs of frozen water, yet today they are retreating at unprecedented rates

Arctic sea ice is also declining rapidly as rising air and ocean temperatures accelerate summer melt and reduce winter recovery. Unlike glaciers, sea ice already floats on the ocean and therefore does not directly contribute to sea-level rise when it melts. However, its loss has major implications for the global climate system. Sea ice has a high albedo, which is the ability of a surface to reflect incoming solar radiation back into space. Bright ice reflects much of the sun's energy, helping to keep the Arctic cool. As sea ice disappears, darker ocean waters absorb more solar heat, creating a self-reinforcing ice–albedo feedback that accelerates regional warming (WWF, 2026). Satellite observations show a long-term decline in both the extent and thickness of Arctic sea ice. Since 1979, summer sea ice extent has decreased by approximately 12.2 percent per decade, contributing to ecosystem disruption, altered ocean–atmosphere interactions and amplified warming across the Arctic (NASA, 2025). Figure 5.1 illustrates annual Arctic sea ice minimum extent from 1979 to 2024, revealing a long-term reduction in sea ice cover despite annual fluctuations.

Figure 5.1 Annual September sea ice minimum extent, 1980–2025



Source:(NASA, 2025).

Both glaciers and sea ice are critical components of the cryosphere. Glaciers can range from several hundred to several thousand years of age. The majority of the world's glaciers are melting at an accelerated rate due to climate change, which is reducing snow accumulation as well as snow cover duration. Glacial retreat has been rapid since the 20th century with precipitous acceleration in recent decades. According to the Intergovernmental Panel on Climate Change (IPCC) in its Working Group I contribution to the Sixth Assessment Report, the widespread retreat of glaciers since 1950 is unmatched in at least the past 2,000 years (Hock *et al.*, 2019). The IPCC's Cross-Chapter Paper 5: Mountains (Adler et al., 2023)reports that glacial retreat is accelerating faster than previously indicated in the 2019 Ocean and Cryosphere Special Report (IPCC, 2019b). Many small, low-elevation glaciers are projected to lose over half their mass even at 1.5°Celsius of warming, while several glaciers are slated to disappear entirely by 2100 (UNESCO, 2025a).

Recent research shows that glaciers are losing their natural self-cooling ability, which has historically acted like an "environmental air conditioner" in mountain regions. Katabatic winds that bring cold air down glacier slopes have previously slowed warming near glacier surfaces by roughly 0.83°C for every 1°C increase in ambient air temperature(Ever Blue Life Foundation, 2025). However, as glaciers melt and become debris-covered, this cooling effect is weakening, meaning glacier surfaces are beginning to warm at nearly the same rate as the surrounding air. This loss of natural cooling accelerates melt, increases slope instability, creates a higher risk of avalanches, landslides and glacial floods. Over time, accelerated glacier loss also reduces the long-term water storage function of glaciers, threatening freshwater availability for downstream populations that rely on seasonal meltwater during dry seasons.

Some alarming examples illustrate these points. Extreme melting events on the Greenland ice sheet are becoming more frequent, intense and widespread. Since the 1990s, these events have driven 30–40 percent of Greenland's total ice melt and contributed about 3.5 mm to sea-level rise between 2005 and 2017. This is roughly comparable to the contribution from all glaciers worldwide (Bonsoms *et al.*, 2026). These episodes also trigger cascade effects, including faster ice flow into the ocean and potential disruption of major systems like the Atlantic Meridional Overturning Circulation (AMOC), which influences climate in Europe and the North Atlantic (see Chapter 3 for an in-depth look at the AMOC). The study shows that warming is a key driver, increasing melt during extreme events by about 25 percent compared to mid-20th century conditions, and up to 63 percent when unprecedented events are included. Notably, seven of the 10 most extreme melt events have occurred since 2000. Looking ahead, under high emissions scenarios, extreme melt intensity could rise by up to 372 percent by 2100, especially in northern Greenland – significantly accelerating sea-level rise (Bonsoms *et al.*, 2026).

> Extreme melting events on the Greenland ice sheet are becoming more frequent, intense and widespread

The Antarctic ice sheet shows similarly alarming trends, though its dynamics and tipping points differ from those in Greenland. Even in the absence of additional warming, West Antarctica could lose up to 40 percent of its ice, leading globally to a 2.1 meter sea-level rise (Winkelmann *et al.*, 2026). While scientists often try to predict total future ice loss, outcomes are still uncertain due to complex feedback loops. New research has revealed that the Antarctic ice sheet contains different regions or basins that have their own tipping points (or thresholds) beyond which ice loss accelerates or becomes abrupt. Some areas melt gradually, while others can move rapidly with small temperature rises. Crossing these tipping points will not cause immediate collapse, but it can lock in long-term and irreversible ice loss over centuries. For example, the Thwaites and Pine Island glaciers could lose roughly 70 percent of their ice under less than 1°C of warming, and contribute 0.9 meters of sea-level rise. At higher levels of warming, much larger ice systems that could raise sea levels by 5 meters will become vulnerable (Winkelmann *et al.*, 2026).

To add another layer of complexity, mountain regions are increasingly exposed to emissions from wildfires and dust storms. These, alongside other human activities, deposit black carbon and particulate matter on glaciers and snowpack, darkening surfaces and lowering the albedo, which accelerates melt rates (UNESCO, 2025a).

And in other regions, such as Asia, the picture is no less dire. The Asia-Pacific region contains the world's highest mountains and largest glacier systems. The Third Pole, including the Tibetan Plateau and surrounding ranges, spans about 5 million km^2 with 100,000 km^2 of glaciers. Known as the "Water Tower of Asia," it feeds over 10 major rivers and sustains nearly 2 billion people across the region (ESCAP, 2025). Key mountain ranges within the Third Pole supply critical freshwater to billions, making accelerated melt a major socio-environmental concern:

- The Hindu Kush Himalayan region, shared by eight countries, holds the largest volume of ice outside the poles and supplies 10 major rivers, supporting water, agriculture, energy and industry for 1.3 billion people.
- In Central Asia, the Pamir, Tien Shan and Karakoram ranges provide critical freshwater for hydropower, agriculture and domestic use.
- The Mekong River, sourced from Tibetan glaciers, currently supports regional water supplies, but accelerated melt threatens long-term water availability and ecosystem stability.

Not a silver bullet: the role and limits of technology in glacier loss

Given these trends and the critical role of glaciers for human and ecological systems, a range of technological approaches has been developed to monitor, slow or adapt to ice loss. Current technological approaches largely fall into three interconnected categories. First, high-precision monitoring through satellites, unmanned aerial vehicles (UAVs), synthetic aperture radar (SAR), light detection and ranging (LiDAR) and sensor networks provides near-real-time data on ice mass, melt rates and surface dynamics, supporting climate research and early-warning systems. Second, localized anti-melt interventions, including reflective geotextiles, radiative cooling films and other passive materials, aim to decrease surface ice loss in more targeted areas. Third, adaptation-focused strategies preserve downstream water availability and the ecosystem services formerly provided by glaciers. While these technologies cannot restore glaciers at scale, they improve understanding, enable localized mitigation and support ecosystem resilience in high-alpine and cryosphere regions.

Accepting glacier loss as an inevitable outcome of global warming is necessary in some regions, with a shift away from saving glaciers and instead preserving the ecosystem services they provide. Therefore, the focus in these places has shifted to maintenance of downstream water availability using technologies such as artificial ice reservoirs (for example ice stupas) and seasonal water storage that mimics glacier function.

> Effective cryosphere monitoring requires an international framework to coordinate observations, measurement standards, best practices, metadata and data exchange

In the end, it would be unrealistic to expect any current technology to truly reverse glacier loss at scale. However, technology can improve our understanding at higher resolutions and provide additional local protection and adaptation strategies. In addition to advances in technology, effective cryosphere monitoring requires an international framework to coordinate observations, measurement standards, best practices, metadata and data exchange across all cryosphere components. The World Meteorological Organization (WMO) Global Cryosphere Watch (GCW) provides this framework and plays a central role in improving our understanding of the cryosphere and monitoring its changes. Through the WMO Integrated Global Observing

System, WMO Information System and WMO Integrated Processing and Prediction System, the GCW supports interoperable observations and operational services for weather, water, climate and hazard applications.

Hyper-precision monitoring and risk intelligence

Continuous and automated sensing through the fusion of UAVs, satellites, LiDAR, Global Navigation Satellite System (GNSS), SAR and internet of things (IoT) sensors is replacing manual fieldwork. Autonomous and extreme-environment robotics are facilitating autonomous data collection in remote landscapes. Multi-sensor drones are becoming the standard link between field sensors and satellites, due to their ability to conduct high-resolution mapping, thermal sensing and detect meltwater and temperature gradients as well as, of course, their capacity for rapid deployment.

This integrated monitoring approach is already being deployed operationally. In Qinghai Province, China, glacier monitoring combines GF-7 stereo satellite imagery, UAV photogrammetry, field validation and long-term remote sensing observations to generate high-resolution three-dimensional glacier models. The resulting digital surface models (DSMs) and digital orthophoto maps (DOMs) support continuous monitoring of glacier dynamics and hazard-prone areas, providing scientific evidence for glacier disaster prevention and water resource management(Kang and Li, 2025).

Artificial intelligence (AI), as seen in other sectors, is being increasingly used to process massive data sets, therefore improving change detection. Thus, real-time glacier mass balance and movement tracking is rapidly improving, as is the detection of micro-scale changes (ablations and more subtle deformations). As a consequence, monitoring of secondary risks, such as glacier lakes, meltwater flows and avalanches, is also quickly improving. As seen in other chapters of this edition and in the *Green Technology Book* Climate disaster edition, this has enabled a shift from more siloed data sets to interoperable global monitoring networks. The growth of coordinated global monitoring systems, like the World Glacier Monitoring Service, alongside the integration of regional systems in the Arctic and major mountain ranges is enabling a transition toward standardized measurement protocols. Through its GCW, the WMO provides the international framework for coordinating cryosphere observations, developing measurement standards and best practices (Jarraud, 2008), and promoting interoperable metadata and data exchange across observing systems. This has resulted in more robust long-term climate baselines that support intervention technologies in being validated and more effectively and efficiently scaled.

> Real-time glacier mass balance and movement tracking is rapidly improving, as is the detection of micro-scale changes

Specifically, the integration of AI with satellite monitoring of glacier-fed lakes is improving early warning systems for glacial lake outburst floods (GLOFs) and ice collapse events. This enables the development of more robust disaster risk management systems as well. Overall, the combination of more precise and continuous monitoring via sensors, trackers and cameras, combined with satellite and drone use and topped off with AI analytics, has driven a powerful combination that is enhancing predictive intelligence.

From blankets to gravity-powered snow: localized cooling and snow experiments

Localized cooling experiments and glacier protection techniques do not stop glacier retreat but can help delay melting and preserve ice in targeted areas. These use reflective fabrics or geotextiles to cover glacier surfaces and reduce absorbed solar energy (the albedo effect). Passive cooling and reflective surface technologies follow two main pathways. The first uses reflective covers for glaciers, such as geotextiles and synthetic sheets to increase albedo and reduce surface heating. Nanomaterials and radiative cooling films may offer advantages over

traditional blankets by reflecting solar radiation while emitting heat into space, although their large-scale effectiveness remains unproven.

Switzerland has used reflective geotextile blankets composed of plastic and fleece since the 1990s (Box 5.1). Studies have demonstrated that covered areas can reduce melting by 30–70 percent in localized trials, such as on the Morteratsch and Rhone glaciers (Ruggeri, 2023). On the Rhone Glacier, 35 meters of ice thickness was preserved over seven years.

The challenge is that it is only economically feasible to cover small areas. Large-scale application on entire glaciers or ice sheets is impractical and expensive. Covering several glaciers would cost roughly USD1.5 billion per year in Switzerland alone (Ruggeri, 2023). Thus, logistics and cost remain major constraints. The need for biodegradable and low-impact materials that have minimal ecological impacts in fragile alpine environments is potentially also becoming a hurdle and design constraint. Thus, potential innovations in nanomaterials, high-albedo surfaces or engineered reflective coatings are promising but experimental and limited.

> Localized cooling experiments and glacier protection techniques do not stop glacier retreat, but can help delay melting and preserve ice in targeted areas

Artificial snow and snow management are commonly utilized in ski resorts. Snowmaking can increase snow cover and bolster surface reflectivity, and potentially delay melt locally by 10–20 percent, but cannot completely counter warming trends (Wang *et al.*, 2026). It is highly energy-intensive and reliant upon water, which is scarce in some areas. Traditional snowmaking equipment is not designed specifically for glacier protection, but the technology has been repurposed in experiments to test its potential benefits for this application.

Box 5.1 Blanketing the ice: can geotextiles slow glacier melt?

To slow glacial melt, some researchers and ski resorts are experimenting with reflective geotextile blankets. In the Swiss Alps and on Italy's Presena Glacier, more than 300 sheets covering 110,000 cubic metres of ice are deployed each summer. The operation is logistically complex: a small team of workers with snowcats may take six weeks or more to place the tarps. Studies show that these white geotextiles can boost ice reflectivity by over 50 percent. Despite local success, scaling the approach is economically and practically unfeasible. Covering the world's 250,000 km^2 of glaciers would be prohibitively expensive, and the benefits are perceived as limited to areas with financial or touristic value. Still, local interventions provide mitigation in key locations, helping to preserve glaciers that act as critical freshwater reservoirs (Sacyr, 2023).

A new approach – gravity-powered snowmaking – uses water from higher elevations and leverages the elevation drop as water is fed from a point 200 meters or more above the target area. Thus, no electricity is needed – the water's potential energy is converted into pressure naturally, generating about 20 bars (290 psi), which is sufficient to spray snow. Towers are spaced across the glacier area with cables strung between them. Snow guns are mounted on the cables and the pressurized water is sprayed as fine droplets that freeze into snow on the glacier surface. A pilot project operated by GlaciersAlive from ETH Zurich at Diavolezza pass in Switzerland (which overlooks and connects to the Morteratsch Glacier) has proven feasibility and can slow glacier retreat at a cost of USD2.15 million. Models indicate that covering about 1 km^2 of the Morteratsch Glacier consistently for 30 years could slow or reverse the glacier's retreat, preserving roughly 0.5 km of glacier length by 2100. However, at a larger scale, it would require major infrastructure, including a concrete dam and reservoir alongside tunnels and

cables across the glacier. The Diavolezza project estimates the cost at USD163 million, which critics argue could be better spent on reducing CO_2 emissions globally (Ruggeri, 2023).

Large-scale engineering involving space-based sunshades (orbital shades) designed to reduce incoming solar radiation and massive structures to shade ice shelves or redirect warm water are considered to be potential geoengineering methods. These concepts remain largely theoretical, very expensive and are the subject of scientific, political and ethical debate.

When glacial lakes break: monitoring and managing glacial lake outburst floods

GLOFs can be catastrophic to human lives and infrastructure. These occur when water suddenly escapes from a glacial lake, often due to natural dam failure, ice collapse or overflow. They can destroy villages and roads, hydropower plants and farmland. Historically, human safety and infrastructure protection have dominated the focus for the monitoring and mitigation of GLOFs. However, there are growing ecological concerns to address as well. Sudden floods can wash out riverbeds, alter sediment flows, strip vegetation and destroy aquatic habitats. They can influence the biodiversity of fish populations and modify nutrient distribution. Controlled mitigation, such as gradual lake drainage, can limit sediment deposition and maintain ecological function.

Reliably detecting high-mountain glacial lakes remains challenging due to complex terrain and harsh conditions. Key technologies include satellite-based remote sensing, machine learning, sensors and engineering interventions, such as artificial drainage channels. Satellite-based sensors – both optical and SAR – are used to monitor lake levels and map lake boundaries. SAR is discussed in detail in the *Green Technology Book* Climate disaster edition. Increasingly, AI-based image analysis tools are being used to automatically identify glacial lakes in satellite imagery and track changes in their size over time, improving flood risk assessment and reducing the need for manual interpretation. Two deep learning models commonly used for this purpose are U-Net and DeepLab, which process multi-spectral Lansat-8 satellite imagery to detect and extract glacial lake boundaries (Sharma *et al.*, 2024). These methods help overcome challenges such as mountain shadows, glacial lake turbidity and seasonal snow cover that can obscure lakes in satellite images (Tang *et al.*, 2024). A specialized version of the U-Net architecture incorporates the Normalized Difference Water Index (NDWI) to improve detection of lakes that are small or difficult to identify and has been used for automated mapping in the Karakoram and Hindi Kush regions (Ali et al., 2025; Sharma et al., 2024). DeepLab architectures are often favored for larger-scale and more complex mapping tasks and have demonstrated better performance than U-Net in some studies (Tang et al., 2024).

GLOF early warning systems (EWS) combine real-time sensors, data integration and predictive modeling to detect instability in glacial lakes. They collect data on weather, lake levels, snow conditions and ground stability using water level sensors, weather stations and deformation monitors. The Glacier Lake Outburst Floods in Central Asia project (GLOFCA) has developed EWS tailored to the unique conditions of each area. Unlike conventional hydro-meteorological forecasting systems, which provide warnings days in advance, GLOFCA's systems must detect and respond to hazards within minutes. They integrate advanced technologies with public awareness, institutional coordination and community drills (GLOFCA, n.d.). The main challenge remains the high logistical complexity of operating in remote, high-altitude locations and the cost of engineering interventions. Combining high-resolution commercial satellite imagery with community-based, local monitoring (e.g. in the Himalayas) is considered the most effective hybrid approach (Zhang *et al.*, 2025).

Beyond supporting national and regional early warning systems, the WMO is strengthening global coordination of GLOF monitoring and forecasting through the Early Warnings for All (EW4All) initiative. The WMO is promoting the integration of cryosphere observations, hydrometeorological forecasting and impact-based warning services, while facilitating the transition of research capabilities into operations through the WMO Integrated Processing and Prediction System (WIPPS). Current WIPPS pilot activities are exploring standardized approaches for integrating global flood prediction products and advancing multi-hazard forecasting capabilities that can support GLOF early warning services and improve the delivery of timely warnings to vulnerable communities.

GLOF early warning systems (EWS) combine real-time sensors, data integration and predictive modeling to detect instability in glacial lakes

Artificial drainage channels for GLOF mitigation are not standardized technologies but are typically designed and implemented on a site-specific basis by specialized engineering consultancies and public–private project consortia.

Mirroring the mountains: moving beyond EWS with digital twins for glaciers

Existing EWS have been limited by delayed data integration, low levels of automation and inadequate real-time modeling. Digital twin platforms address some of these limitations by creating virtual replicas of cryosphere systems that are continuously updated with incoming data. These systems can use remote sensing, real-time observations, seismo-acoustic data and numerical simulations. Importantly, they enable multi-source data integration and automated updates using machine learning, physics-based modeling and interactive visualization (Cui *et al.*, 2024). Glacier Digital Twins are emerging tools that create dynamic, interactive simulations of glaciers and mountain environments by combining satellite imagery, in-situ measurements, sensor networks, advanced modeling and AI. Various projects globally are producing live digital twins of mountain glaciers, continuously updating data on mass balance, volume, runoff and future melt scenarios. The DTC Glaciers project (see Horizon technology solutions) provides dashboards and cloud-based access for scientists, hydrologists and policymakers to forecast glacier behavior and manage water and climate risks. Similarly, EnvironTwin (see Horizon technology solutions) expands digital twins to entire alpine landscapes, while integrating LiDAR, cloud computing and sensor networks to model complex systems influenced by climate change and human activity. Interdisciplinary collaboration and cross-border data sharing are extremely important for future development, which will be focused on modular software frameworks, robust algorithms, rapid numerical simulations and sensor networks(Cui *et al.*, 2024). Box 5.2 describes the Svalbard Digital Twin, which is being developed under ESA's Digital Twin Earth programme.

Box 5.2 Svalbard Digital Twin: using open-source satellite data and a state-of-the art physics-based model to describe snow cover, glacier mass balance and sea ice dynamics in Svalbard

The SvalbardDT digital twin is one of many Earth Observation Digital Twin Components (EO DTCs) being developed under the European Space Agency's (ESA) Digital Twin Earth program, which itself feeds into the larger Destination Earth (DestinE) initiative led by the European Commission. These digital twin projects are intended to become pre-operational components that could be integrated into DestinE in the future. The SvalbardDT digital twin aims to create a digital twin of Svalbard's cryosphere using satellite Earth Observation data and physics-based models. It will capture snow cover, glacier mass balance and sea ice dynamics in 3D across the 21st century, feeding into a self-learning spatio-temporal AI model. The system will integrate Svalbard's extensive observational record for validation and improved environmental modeling. Two main use cases are planned:

- analyzing extreme weather impacts on glaciers, snow and sea ice, including Rain on Snow and Ice (ROSI) events; and
- supporting terrestrial and marine navigation by providing stakeholders, such as local authorities, logistics and tourism operators, with precise snow and ice condition forecasts.

ESA issued a Call for Expressions of Interest in 2023 to gather proposals for EO DTCs, and nearly 80 submissions nationwide demonstrate strong community support (ESA, 2026a;2026d).

Democratizing glacier monitoring with citizen science and low-cost technologies

Citizen science and low-cost ground-based sensing are rapidly transforming glacier monitoring by bridging spatial and temporal gaps left by satellites and high-tech UAVs. These grassroots approaches, which often use open-source technology, provide continuous, real-time data in remote environments. They lower barriers to participation so that local observers, smaller institutions and communities can contribute to global glacier monitoring efforts, complementing global data sets like the World Glacier Monitoring Service.

> Glacier Digital Twins are emerging tools that create dynamic, interactive simulations of glaciers and mountain environments

Crowdsourced mountain observations are collected using platforms like MountaiNow, which let visitors use smartphones to upload geo-tagged observations of glaciers and permafrost. These observations create a living map that helps scientific groups like GLAMOS and OMERIS in the Alps to fill in gaps(MountaiNow, 2024). Open-source hardware is also being explored for remote meteorological and environmental monitoring in glacier regions. These systems can collect in-situ data to support glacial analysis (Filhol *et al.*, 2023).

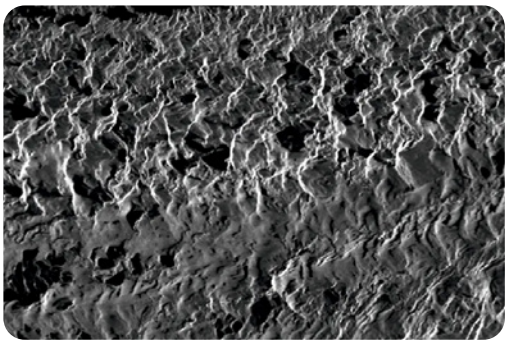
Raspberry Pi is a small computing platform that can run a full operating system and conduct general computing tasks. Research groups have tested inexpensive Raspberry Pi-based camera arrays for structure-from-motion monitoring of glacial fronts. These systems produce 3D models of glacier movement and calving events (the process where chunks of ice break off from the edge of a glacier – typically where it meets a body of water) at a lower cost than professional photogrammetry. This provides a way for community groups or smaller research teams to contribute observational data (Taylor *et al.*, 2023).

Whereas ice-penetrating radar is specialized, high-performance and research-grade – often expensive and requiring training for operation and data interpretation – emerging technologies are being designed for wider accessibility and collaboration. For example, Stanford researchers have developed an open source modular radar ecosystem for studying glaciers. They started with ORCA, a flexible framework for building inexpensive software-defined ice-penetrating radar systems. Using ORCA as a foundation, they created platforms such as Peregrine (a UAV-based system) and MAPPERR (a ground-based system). Together, these innovations expand access to glacier monitoring by providing researchers with flexible tools, enabling them to collect and share glacier data. This approach democratizes the study of ice sheets, which previously relied on highly specialized radar systems accessible to only a small number of expert teams. However, ensuring the quality of the data remains an essential factor. Standardized observation protocols, calibration against reference instruments, metadata documentation and quality-control procedures are needed to ensure that citizen science and low-cost observations can be integrated confidently with established monitoring networks.

Innovation examples

SAR satellites track Himalayan glaciers in real time

University of Leeds and Capella Space



Source: Image provided by Professor Duncan Quincey from the University of Leeds

The University of Leeds is collaborating with Capella Space to monitor Himalayan glaciers using high-resolution SAR imagery. This technology allows researchers to see through persistent cloud cover and snow and capture year-round changes in glacier surfaces that optical imagery cannot. By tracking features like seasonal pond filling, glacier flow rates and debris covers, researchers can assess meltwater dynamics, surface melt rates and unusual glacier behaviors. This SAR-based monitoring is particularly important for the Karakoram and Himalayan glaciers, which supply critical water to rivers like the Indus and support hydropower, agriculture and drinking water. Capella's sensors detect fine-scale surface streams and pond dynamics, helping to create data sets that inform numerical models and predict climate-driven changes. This collaboration enables a rapid analysis of glacial response to warming and provides a baseline for comparisons and improved understanding of glacier-induced flooding risks (Capella Space, 2022).

Mapping Arctic ice with satellites and drones

UiT The Arctic University of Norway, Norwegian Polar Institute and FRAM – High North Research Center for Climate and Environment



Source: Sebastian Gerland, Norwegian Polar Institute

In April and May 2022, Norway launched its first Arctic expedition focused on validating satellite-based observations of sea ice and icebergs. Aboard the research vessel*Kronprins Haakon*, scientists from UiT The Arctic University of Norway and the Norwegian Polar Institute collected ground-truth data in the western Fram Strait and East Greenland waters to improve the accuracy of satellite remote sensing products. The team combined traditional fieldwork with innovative tools. Drones equipped with optical, infrared, thermal and radar sensors captured high-resolution images of sea ice, icebergs and open water, while tomographic (image processing by sections or slices) ground-based radar provided calibration data at the same frequencies as those used by satellites. Snow pits and ice cores measured thickness, density, temperature and salinity, while red laser profilers mapped ice surface roughness, which is critical for interpreting radar backscatter in satellite imagery. These observations were cross-

referenced with data from SAR satellites such as ESA Sentinel-1 and RADARSAT2. Together, the collected data feed into an “innovative toolbox” that integrates satellite products, models and in-situ measurements (Fram Forum, 2023).

China tests nanomaterials to slow glacier melt

Chinese Academy of Sciences (CAS)



Source: Photo by Richard Young on Unsplash

China is experimenting with innovative technologies to slow glacial melt. Researchers at the Key Laboratory of Cryospheric Science and Frozen Soil Engineering have deployed thermal blankets, nanomaterial “glacier covers” and artificial snow systems on glaciers including Ürümqi Glacier No. 1 and Dagu Glacier. Standard geotextile blankets increase surface reflectivity, reducing heat absorption and lowering melt rates. On Dagu Glacier, a 500-square-metre blanket reduced melting by roughly 34 percent between August 2020 and October 2021. More advanced nanofiber materials on Ürümqi Glacier No. 1 showed even greater promise, lowering summer melt rates by up to 70 percent through enhanced optical and thermal properties. Artificial snowmaking supplements glacier mass and increases albedo. Operations on the Bailanghe Glacier basin using smoke generators, rockets and aircraft contributed to a 5.9 percent gain in glacier mass over a few days, while helping to clean away heat-absorbing dust and black carbon. Despite local successes, these techniques are limited in scale, costly and carry environmental risks. Researchers emphasize that large-scale glacier preservation also requires global greenhouse gas (GHG) reduction. Nonetheless, combining high-tech glacier coverings, artificial snow, drones and real-time monitoring offers a multifaceted approach to slow melting (UNESCO, 2025b).

The following collection of technologies is divided into three groups: Proven technologies have been on the market for some time and hence are well tested, Frontier technologies are available but relatively new, while Horizon technologies are close to being available but still under development.

Proven technology solutions

Ice motion trackers

Greenland Guidance



Source: Greenland Guidance

Greenland Guidance designs and builds customized, rugged instruments for polar and glaciated environments. Its ice motion tracker is a solar-powered GNSS unit that monitors surface movement on sea ice or glaciers and transmits location data in near real time. The draw wire ice ablation tracker measures up to 14 meters of ice melt and can include additional sensors, while the surface mass balance tracker combines ablation measurements with snow height and air temperature monitoring. A glacier weather station records key meteorological variables and can be configured to measure accumulation and melt. The polar time-lapse camera captures long-term visual changes such as calving or meltwater flow in extreme conditions. Thermistor strings measure subsurface temperatures in ice, snow or soil. In partnership, robotic platforms are available for autonomous data collection in hazardous or inaccessible terrain.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Kingdom of the Netherlands
- Availability: Worldwide
- Contact: WIPO GREEN Database

Timelapse camera stations for glacier and ice-melt observation

Enlaps



Source: Enlaps

Enlaps' Tikee systems are autonomous, solar-powered timelapse camera stations designed for long-term outdoor environmental monitoring, including glacier and ice-melt observation. The Tikee 4X and Tikee Mini+ capture high-resolution wide-angle images (up to 6K panoramic) at programmable intervals, allowing continuous visual tracking of glacier terminus retreat, surface lowering, seasonal snow cover change and proglacial lake development. Built for remote deployment, the units feature integrated solar panels, long-life batteries, 4G/LTE or Wi-Fi connectivity, Global Positioning System (GPS) tagging and weather-resistant enclosures suitable for harsh alpine conditions. Images are automatically transmitted to the myTikee cloud platform, which enables remote configuration, data storage, timelapse generation and project dashboards for longitudinal analysis and reporting. While not direct mass-balance sensors, Tikee systems provide high-frequency visual data sets that support glacier change documentation, communication and complementary scientific monitoring efforts in remote cryosphere environments.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

Ablation stake system

A2 Photonic Sensors



Source: A2 Photonic Sensors

The SmartStake station is an automated instrument designed to monitor glacier ice ablation over extended periods. It serves as an alternative to traditional ablation stakes, providing more frequent and precise measurements. The system records up to four measurements per hour, with a resolution of 1 mm, and can track cumulative ablation of up to 7 meters. Data are stored on an internal SD card and can be transmitted wirelessly via satellite. The station also integrates additional sensors, including GPS, a snowfall detector, and a temperature sensor, to support broad environmental monitoring. The instrument has been developed in collaboration with the Institut des Géosciences de l'Environnement (IGE, France) and is supported by the World Glacier Monitoring Service (WGMS) as part of glacier observation initiatives.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

Collaborative monitoring network

World Glacier Monitoring Service (WGMS)



Source: Photo by Erol Ahmed on Unsplash

WGMS operates within the Global Terrestrial Network for Glaciers (GTN-G), contributing to standardized global glacier observation. Its work combines in-situ measurements (e.g., mass balance stakes, GPS surveying and photogrammetry) with remote sensing technologies, including satellite imagery from the Landsat program and Sentinel satellites. WGMS curates and harmonizes these data sets using geospatial databases and interoperable standards for long-term climate analysis. GTN-G is jointly managed by WGMS, the US National Snow and Ice Data Center (NSIDC) and the Global Land Ice Measurements from Space (GLIMS) initiative, with a steering committee established in 2009 to coordinate activities. WGMS is based in Zurich, Switzerland, while NSIDC and GLIMS are coordinated from Boulder, Colorado, USA.

- Technological maturity: Proven
- Contracting type: Open access
- Technology level: High
- Place of origin: Switzerland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Integrated global cryosphere monitoring platform

World Meteorological Organization (WMO) Global Cryosphere Watch (GCW)



Source: Photo by Sam Ferrara on Unsplash

The WMO, through its GCW, provides the international framework for coordinating cryosphere observations, developing measurement standards and best practices and promoting interoperable metadata and data exchange. WMO's Unified Data Policy supports the free and unrestricted international exchange of Earth system data, including cryosphere observations where available, to improve weather, climate, water and related environmental services. At present, snow depth observations, which are critical for glacier monitoring, are exchanged operationally through the WMO Information System 2.0 (WIS2), while work is underway to extend to other cryosphere components. The WMO also supports the operational use of cryosphere information through its Integrated Processing and Prediction System (WIPPS) and the development of regional service capabilities, including Regional Climate Centers (RCCs) for the Arctic, Antarctic and the Third Pole, to improve the delivery of cryosphere information for climate monitoring, prediction and early warning services.

- Technological maturity: Proven
- Contracting type: Open access
- Technology level: High
- Place of origin: Switzerland
- Availability: Worldwide
- Contact: WMO Global Cryosphere Watch

Ice stupas

Nilus



Source: Nilus

Ice stupas, or artificial ice reservoirs, are conical structures designed to store meltwater in cold, high-altitude regions and release it gradually during warmer months. Inspired by Himalayan techniques, they are built by channeling water from nearby glaciers or streams through elevated pipes, then spraying it into sub-zero air where it freezes almost instantly into layered ice cones. The conical shape minimizes sun exposure, slowing melting and maximizing water retention. In Chile's Andes, Nilus has deployed ice stupas up to 33 feet high, capturing thousands of cubic meters of water, which can provide irrigation and drinking water well into dry seasons. While they do not increase the total glacier mass, they serve as seasonal water reservoirs, helping communities manage shortages caused by glacial retreat and drought. Ice stupas are relatively low-tech, sustainable and scalable, offering a practical adaptation strategy for water security in alpine regions facing climate-driven glacier loss.

- Technological maturity: Proven
- Contracting type: Project-based
- Technology level: Low
- Place of origin: Chile
- Availability: Worldwide
- Contact: WIPO GREEN Database

GLOF early warning system

MicroStep-MIS



Source: Photo by Connie de Vries on Unsplash

The MicroStep-MIS GLOF Monitoring and Early Warning System is an integrated platform designed to detect and manage the risk of GLOFs. It combines real-time data collection from weather stations, water level sensors and ground stability instruments with remote sensing and forecasting models. These inputs are processed in a centralized system that analyzes lake conditions, predicts inflows and potential flood scenarios, and assesses overall stability. A built-in decision support system provides operators with actionable insights, while automated alerts are triggered when risk thresholds are exceeded. Warnings can then be rapidly communicated to authorities and downstream communities via multiple channels, such as SMS, sirens and radio. Rather than preventing GLOFs, the system focuses on early detection, forecasting and coordinated response, helping reduce loss of life, infrastructure damage and environmental impacts in vulnerable mountain regions.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Slovakia
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier technology solutions

UAV-based glacier mapping-monitoring

FlyPix AI



Source: Photo by Xavier Balderas Cejudo on Unsplash

FlyPix AI uses AI-powered analysis of UAV, satellite and LiDAR data to transform glacier monitoring and environmental assessment. Its platform provides fast, precise insights on ice mass, glacier retreat, surface deformation and seasonal changes, supporting climate research and conservation efforts. The intuitive, no-code interface allows users to conduct complex geospatial analyses without technical expertise, automating tasks like ice classification, surface movement tracking and environmental risk assessment. FlyPix AI integrates with geographic information systems (GIS) and environmental management systems, enabling scalable and customizable monitoring workflows for both small- and large-scale projects.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Advanced geosynthetics to slow ice melt

Naue



Source: Photo by Raimond Klavins on Unsplash

GlacierProtect is a biodegradable geotextile designed to slow glacier melt. Made from eco-friendly fibers, it reflects sunlight to reduce surface temperatures, stabilizes glacier surfaces and helps prevent erosion. Lightweight and durable, the material can be easily transported and deployed in remote, extreme environments, withstanding harsh weather conditions. By lowering ice melt rates, GlacierProtect contributes to preserving water reserves and stabilizing ecosystems. Its fully biodegradable composition ensures no harmful residues are left in sensitive glacier environments. Combining practicality, high reflectivity and long-term durability, GlacierProtect provides a scalable and sustainable approach to mitigating glacier loss and its associated climate impacts.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Compact and intelligent multi-sensor flagship drone series for enterprise industries

DJI



Source: Getty Images/Vladyslav Horoshevych

The DJI Matrice 4 Series consists of advanced enterprise drones (Matrice 4T and 4E) built for intelligent aerial operations with multi-sensor imaging, AI-assisted detection and precise measurement tools, such as a long-range laser rangefinder and high-resolution cameras. The 4E model excels at rapid, high-accuracy mapping and surveying with orthophoto and oblique capture, fast frame intervals and Smart 3D Capture for detailed terrain models, while the 4T adds thermal and near-infrared (NIR) imaging, useful for detecting temperature contrasts (e.g., meltwater flows or crevasse boundaries). Both models benefit from robust low-light capability and GNSS/real-time kinematic (RTK) positioning for reliable data capture in challenging environments. These features make the series applicable for ice and glacier monitoring, as they enable detailed topographic surveys, change detection and environmental assessment over dynamic cryospheric landscapes.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Anti-ice propeller for drone

DJI



Source: Getty Images/Travel Wild

The anti-ice propellers (made for the DJI Matrice 4D Series) are specialized rotor blades designed to improve flight reliability and stability in cold, wet and challenging weather conditions. They feature an anti-ice coating that helps reduce the build-up of ice on the propeller surfaces, maintaining aerodynamic performance and consistent lift even in freezing rain or high humidity environments. The blades are aerodynamically optimized and dynamically balanced, which not only enhances flight stability but also reduces noise and vibration during operation. These qualities make them especially useful for professional aerial tasks, such as mapping, monitoring or search and rescue, where cold-weather performance and quiet, stable flight are critical.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon technology solutions

Nano-thin radiative cooling material to stop glacial melt

Nanjing University



Source: Photo by XXWW on Unsplash

Professor Zhu Bin and his team at Nanjing University have developed a nano-thin, eco-friendly radiative cooling material made from cellulose acetate (CA) to reduce glacier melting. The material reflects over 92 percent of sunlight while radiating heat from the glacier into space, significantly lowering ice temperatures under direct sunlight. Pilot tests on Dagu Glacier (5,000 m above sea level) showed up to an 80 percent reduction in melting, suggesting potential for net glacier volume growth over three to five years. The porous, roll-to-roll electrospun film promotes passive cooling without external energy and is biodegradable. The internet company Tencent sponsored the project and provided support through its Carbon Neutrality Laboratory under a sustainability initiative. The technology is still in field-testing phases with controlled experiments and scaled deployments underway, representing a promising approach to passive glacier conservation and climate mitigation in high-altitude environments.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: China
- Availability: Under development
- Contact: WIPO GREEN Database

Glacier digital twin

University of Bristol, European Space Agency, University of Zurich, University of Innsbruck, enveo, Earthwave, University of Edinburgh



Source: University of Bristol

The Digital Twin Component for Glaciers (DTC Glaciers) project, developed under ESA's Digital Twin Earth initiative, creates a dynamic "digital twin" of mountain glaciers. It integrates satellite (Earth observation) data, in-situ measurements and advanced models (including AI) into a single, interactive platform that continuously updates as new data comes in. This system allows users to monitor glacier changes, such as mass balance, volume and runoff, on a near-real-time basis and to simulate future scenarios, like melt rates or water availability. Accessible through dashboards and cloud-based tools, the platform supports scientists, hydrologists and policymakers in analyzing glacier behavior, predicting impacts and managing water and climate risks. It functions as a live data-driven simulation of glaciers, enabling better forecasting and decision-making in rapidly changing cryosphere environments. Its first phase (prototype stage) was completed in January 2026.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: United Kingdom
- Availability: Under development
- Contact: WIPO GREEN Database

Digital twin for complex mountain environments

Eurac Research



Source: Eurac Research

The EnvironTwin technology uses advanced digital twins to replicate complex mountain environments including forests, pastures, rocky glaciers, and agrivoltaic systems, providing detailed computer representations of these landscapes. Unlike traditional digital twins that track single objects, EnvironTwin models entire environmental systems influenced by climate change and human activity. The models integrate sensor networks, LiDAR, cloud computing, and sophisticated data modeling to monitor and predict landscape evolution, risks, and management strategies. Four alpine case studies, supported by Eurac Research's Sensor System Technology Lab and Environmental Data Platform (EDP), will enhance research infrastructure and provide practical tools. Funded by the ERDF 2021–2027, the project aims to improve understanding and management of complex mountain systems by combining high-resolution monitoring with predictive modeling.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: Italy
- Availability: Under development
- Contact: WIPO GREEN Database

Open source software to support the development of ice-penetrating radar

Stanford University



Source: Stanford University

Open Radar Code Architecture (ORCA) is an open-source, modular architecture for building ice-penetrating radar systems used to study glaciers and ice sheets. It combines software-defined radio with standardized hardware components, allowing researchers to construct low-cost, customizable radar instruments capable of mapping ice thickness, internal layering and subglacial terrain. By dramatically reducing cost and complexity compared to traditional radar systems, ORCA enables wider access to cryosphere monitoring tools and promotes data standardization across research groups. Its flexible design supports integration with multiple platforms, including ground-based systems, aircraft and drones. ORCA represents a shift toward collaborative sensing infrastructure for understanding glacier dynamics and improving projections of sea-level rise.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: United States
- Availability: Under development
- Contact: WIPO GREEN Database

UAV-based radar platform

Stanford University



Source: Stanford University

Peregrine is a lightweight UAV system designed to carry miniaturized ice-penetrating radar instruments built using the ORCA architecture. As a field-portable fixed-wing UAV equipped with a miniaturized ice-penetrating radar, it enables high-resolution mapping of glaciers and ice sheets in remote or hazardous regions where traditional survey methods are difficult or expensive. By combining drone mobility with compact radar payloads, Peregrine allows researchers to collect detailed subsurface data with greater flexibility and lower operational cost. The platform is particularly valuable for targeted surveys, repeat measurements and accessing previously unreachable terrain. Peregrine demonstrates how modular sensing technologies like ORCA can be deployed in field systems to expand the scale and frequency of cryosphere observations.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: United States
- Availability: Under development
- Contact: WIPO GREEN Database

5.2 Permafrost

Permafrost underlies much of the Northern Hemisphere, storing vast amounts of carbon accumulated over millennia. It is ground (rock, soil or sediment) that remains continuously frozen for at least two years, formed under persistently low surface temperatures and often lasting for thousands to hundreds of thousands of years(Froese *et al.*, 2008). Permafrost occupies roughly 11 percent of global landmass and about 15 percent of the Northern Hemisphere, mainly in northern Eurasia (especially the Russian Federation), North America (Canada and Alaska), Greenland, Nordic regions and some high-mountain areas (Obu, 2021).

Permafrost distribution is commonly classified into four types: continuous, discontinuous, sporadic and isolated. Continuous permafrost underlies more than 90 percent of the land area and occurs in the coldest regions, such as parts of Siberia. Discontinuous permafrost underlies 50–90 percent of the surface area and is found in Canada. Sporadic permafrost extends beneath 10–50 percent of the ground, while isolated permafrost occurs where it underlies less than 10 percent of the surface (Earth.org, 2022).

> The Arctic is warming four times faster than the global average and permafrost regions now emit more carbon than they absorb

Permafrost is overlain by the active layer, a near-surface layer of soil and sediment that thaws and refreezes seasonally, regulating the exchange of heat between the atmosphere and the underlying frozen ground. This layer acts as an interface, transferring heat to and from the underlying permafrost. Within the frozen organic matter of permafrost lies roughly twice the amount of carbon found in the atmosphere(Schuur, 2019).

Older IPCC models assumed that permafrost thaw would be a small contributor to climate change this century, but new research suggests this is an underestimation. Long-term observations show that permafrost is warming at a global scale, with particularly strong warming documented in European mountain regions during the early 21stcentury (Biskaborn *et al.*, 2019; Noetzli *et al.*, 2024).The Arctic is warming four times faster than the global average and permafrost regions now emit more carbon than they absorb – shifting from a carbon sink to a source. As climate warming raises surface temperatures, permafrost thaws either gradually, releasing primarily CO_2 through aerobic decomposition, or abruptly through nonlinear processes such as thermokarst – the uneven sinking and collapse of ground that happens when permafrost thaws and the melted ice leaves empty spaces – which can rapidly release large quantities of CO_2 and methane (Walter Anthony *et al.*, 2018). Once thaw begins, emissions can continue for centuries, creating a self-reinforcing cycle that may persist even if anthropogenic emissions cease. Current climate models and mitigation pathways may underestimate the long-term contribution of permafrost carbon emissions, suggesting that carbon budgets associated with targets such as 1.5°C could be smaller than currently estimated (Natali *et al.*, 2021).

Indicators and proxies track permafrost conditions

There are several direct and indirect metrics used to track permafrost conditions and health. No single metric suffices; instead, measurement relies on combining direct observations with indirect proxies to capture permafrost dynamics.

*Snow and surface conditions*are the most obvious indicators. Snow has a complex influence on permafrost. During winter, a thicker snowpack insulates the ground, reducing heat loss to the atmosphere and often resulting in warmer ground temperatures. However, if snow persists into spring and summer, it can delay ground warming and thaw, thereby helping to preserve permafrost (Hrbáček *et al.*, 2021). Land surface temperature measurements via remote sensing provide satellite-derived data that can be used as indirect indicators.

Ground temperature metrics are critical. Borehole ground temperature (BGT) is used extensively to measure temperature at depth. Active layer thickness (ALT), the depth of seasonal thaw above the permafrost, is also used as a proxy for ground temperature. Borehole temperature monitoring systems are specialized systems that measure subsurface temperatures with thermistor strings installed along the length of boreholes that are typically 20–100 meters deep to provide high-accuracy data (±0.1°C) on the thermal state of permafrost and ALT, typically recording automatically over time (Biskaborn *et al.*, 2019). These systems support climate research by tracking permafrost degradation, determining annual thaw depths and validating temperature models, though challenges can include sensor drift, data gaps and post-installation stabilization (Smith *et al.*, 2022).

*Surface movement and deformation*are assessed through the measurements of surface subsidence (where the ground sinks due to ice melt – also called thermokarst). Interferometric synthetic aperture radar (InSAR) and high-precision GPS measurements can detect millimeter-scale ground movement over time (Liu *et al.*, 2010). Slope instability and increased landslide frequency often indicate thawing permafrost (Stoffel and Huggel, 2012; Wei *et al.*, 2024).

*Hydrological proxies*include river discharge and timing; runoff that is early or greater than usual in volume can indicate thaw. Changes in groundwater flow, as well as the release of ions, carbon and heavy metals from thawing soils, are also used as indicators.

*Carbon and ecosystem signals*include changes in vegetation type and productivity, GHG fluxes indicating decomposition of frozen organic matter and shifts in soil microbial activity as frozen ground becomes active.

Geophysical methods, including electrical resistivity tomography (ERT) and seismic surveys, are also employed. ERT is a method that sends small electrical currents through the ground to measure how easily the subsurface conducts electricity. Since ice and frozen soil conduct electricity poorly compared with water or thawed soil, ERT can create a 3D image showing which areas are frozen or contain liquid (Hauck and Kneisel, 2008). Seismic methods differentiate between frozen and unfrozen ground based on wave velocity.

*Rock glaciers*also serve as indicators. They are downslope-moving landforms composed of rock debris and interstitial ice, whose flows have a distinct tongue shape that can be as big as a kilometer wide and several kilometers long. Their movement, ranging from centimeters to meters per year, responds to thermal conditions; increasing velocity is often associated with warming permafrost. They can also contribute to landscape instability and natural hazards, such as debris flows (Bartsch *et al.*, 2023; Hu *et al.*, 2025).

Technologies for monitoring, managing and protecting permafrost

Building on these indicators, monitoring systems have become increasingly integrated and technologically advanced. Permafrost monitoring has evolved into a well-established field driven by the need to maintain infrastructure in cold regions. Unlike in the “Sea ice and glacial melting” section above, on sea ice and glacial melting, for which technologies are mostly geared toward observation and experimental intervention, the permafrost is already a mature engineering problem, because infrastructure is reliant upon it.

Multi-layer monitoring systems both above and below ground are the new normal as a shift is underway from single-variable monitoring to multi-physics sensing that combines thermal, hydrological and mechanical stability data.

IoT-enabled monitoring and real-time alerting systems are increasingly deployed, using low-power sensors with data transmission via satellite and cellular technology and integration into decision-making platforms. These systems improve early warning capabilities for thaw and ground instability. In parallel, machine learning is being used to analyze complex data sets, with tools increasingly designed for use by non-experts.

Multi-layer monitoring systems both above and below ground are the new normal

Advancements in subsurface imaging are also critical. Techniques such as electrical resistivity and induced polarization, which detects how subsurface materials temporarily store and release electrical charge, now enable 2D, 3D and time-lapse (4D) mapping of frozen and thawed ground, allowing researchers to track thaw progression over time. This marks a shift from point-based measurements toward full 3D visualization of permafrost systems.

At the same time, advanced simulation tools can model heat transfer, groundwater movement and freeze–thaw cycles. Climate-driven advanced simulations integrate soil properties, infrastructure characteristics and future climate scenarios to support research and engineering decision-making.

Unlike glacier-focused interventions, permafrost technologies have been widely implemented in practice. Passive and active cooling systems are used to stabilize ground conditions in vulnerable areas. Thermosyphons – passive heat-transfer devices that require no external power – have been used since the 1970s to maintain frozen ground beneath infrastructure such as buildings and pipelines. They consist of sealed pipes filled with a refrigerant that evaporates underground as it absorbs heat and condenses above ground in colder air, passively transferring heat out of the soil and helping to preserve permafrost. For example, the Trans-Alaska Pipeline incorporates approximately 120,000 thermosyphons to stabilize its length and delay thaw.

Active cooling methods, including refrigeration systems and buried cooling pipes, are also used in industrial settings, such as tailings ponds. These systems could theoretically be extended across wild and remote permafrost regions, combined with vertical boreholes or vertical heat exchangers to extend cooling deeper into the ground, or enhanced with active refrigeration systems that circulate chilled fluids to maintain sub-zero temperatures However, there is limited research on their long-term effectiveness, costs, scalability and environmental impacts, and it is likely that large-scale deployment would be expensive and disruptive.

Thermosyphons – passive heat-transfer devices that require no external power – have been used since the 1970s to maintain frozen ground beneath infrastructure

While thermosyphons remain the dominant solution, hybrid systems that combine passive and active cooling are becoming more common (Loktionov *et al.*, 2022; Sharaborova et al., 2025). Building on these, dynamically controlled ground-cooling systems, which can be considered similar to heating, ventilation and air-conditioning (HVAC) systems for soil, can adjust to changing thermal conditions. Although more costly, they provide greater reliability under increasingly variable climate extremes.

Infrastructure needs are driving engineering advances in permafrost areas

Infrastructure needs and requirements in Arctic and high-altitude areas have driven the development of engineering solutions such as specialized pile foundations, load-distributing structures and reduced ground disturbance construction. These advances are helping infrastructure to tolerate thaw and minimize heat input into the ground, and adapt to instability.

Hydrology has become critical to understand internal water movement and to monitor pore-water pressure inside the permafrost (Pellet *et al.*, 2016). Thaw results in melting, which leads to more water, weakening and risk of collapse. Thus, permafrost is increasingly viewed and treated as a hydro-thermal system and not just frozen soil. A much better understanding of internal water movement is needed in order to tailor interventions correctly.

While many of these engineering solutions are technologically mature, it is worth noting that the goal is to stabilize critical areas where failure is unacceptable, rather than endeavoring to save the global permafrost.

Interventions and stabilization technologies

Nanorefrigerants are being researched to significantly improve the cooling efficiency of thermosyphons, which are passive heat-transfer devices used to keep permafrost frozen and stabilize infrastructure such as roads, railways and pipelines. Adding nanoparticles to conventional refrigerants creates "nanorefrigerants," which improve how the fluid conducts and transfers heat (particles such as aluminum oxide, copper oxide or carbon nanotubes carry heat more efficiently, speeding up heat movement by 50–60 percent). This also boosts system efficiency (meaning that more heat is removed from permafrost with the same energy input) (Qin *et al.*, 2025; Kumar *et al.*, 2022). Many nanorefrigerant technologies for permafrost are still experimental, facing challenges such as particle clumping (nanoparticles sticking together), increased fluid viscosity (thicker fluid that is harder to pump) and uncertain long-term durability. Extensive field testing is needed before they can be widely deployed for long periods in extreme Arctic conditions.

Artificial ground freezing (AGF) is a geotechnical technique used for ground stabilization, seepage control and infrastructure development, and is used in tunneling, mining, urban metro construction and permafrost preservation. It was first patented in the mid-19thcentury in Germany for sinking shafts in waterlogged soils and gained traction in Europe and North America by the early 20thcentury, including in the Paris Métro. AGF was introduced in China in the 1950s for mining and used in urban metro trials in Beijing and Shanghai in the 1970s–1980s. The dawn of computational modeling in the 1970s enabled precise thermal and mechanical predictions. Since the 2000s, China has pioneered local horizontal freezing and energy-efficient systems, applying AGF at a larger scale for urban expansion and permafrost engineering.

While AGF is a mature engineering method, most traditional applications to date have been for short-term soil stabilization in construction and tunneling (Zhou *et al.*, 2025). Its use explicitly for long-term permafrost preservation is mostly at the experimental research and pilot concept stage. Research efforts have demonstrated that engineered permafrost cooling systems are beginning to be studied beyond their traditional uses. These include wind-powered cooling setups (Qin *et al.*, 2023) and solar-driven refrigeration arrays (Sharaborova, 2025)(see Horizon technology solutions).

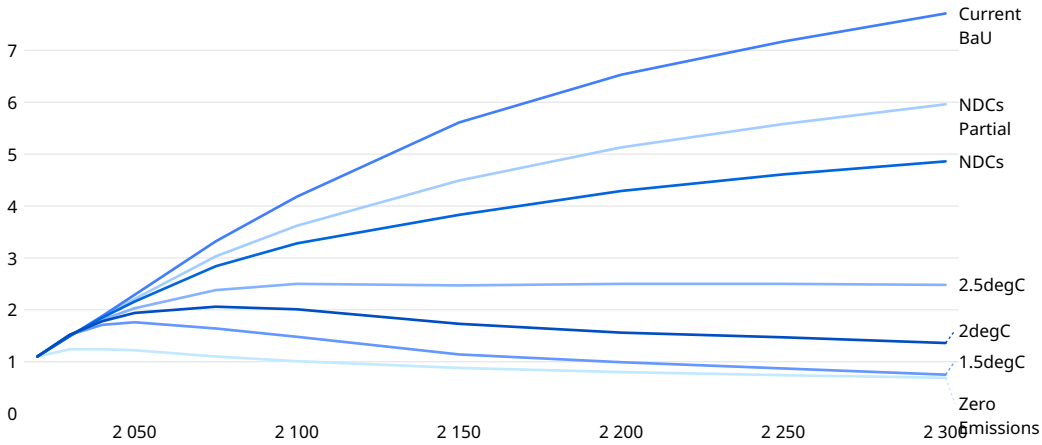
Snow compaction. Fresh snow is light and full of air pockets, making it a good insulator that can trap heat in the ground during winter. Compaction increases snow density, reduces air pockets and raises thermal conductivity, allowing heat to escape more easily and lowering ground temperatures. Small-scale experiments suggest that compaction can reduce permafrost thaw, but scaling up requires personnel, equipment, suitable terrain and sufficient snowfall. Repeated compaction may harm ecosystems, damage soil and produce carbon emissions; it is also potentially costly and environmentally disruptive. Therefore, its effectiveness in remote areas and for timely mitigation of thaw remains uncertain.

Thawing permafrost – a methane time bomb

Methane (CH_4) is the second most significant anthropogenic greenhouse gas after CO_2, accounting for approximately one-third of current global warming. Due to its relatively short atmospheric lifetime of about a decade, it represents a critical target for near-term climate mitigation. In recognition of this, more than 155 countries have committed to the Global Methane Pledge, aiming to reduce global methane emissions by 30 percent by 2030 compared to 2020 levels (CCAC, 2025).

As warming thaws permafrost, CO_2 and methane are released, which further speeds warming. Arctic methane emissions have increased rapidly. Polar and high-altitude regions are warming at least three times faster than the global average, and permafrost temperatures increased roughly 0.3°C between 2007 and 2016 (Earth.org, 2022). Permafrost thaw could release up to nearly 1 gigatonne of methane globally by 2100 (Earth.org, 2022). Figure 5.2 depicts projected methane emissions from thawing permafrost.

Figure 5.2 Methane emissions from thawing permafrost: global mean temperature simulations under a range of climate scenarios (gigatonnes)



Source: Yumashev*et al.*, 2019

Methane monitoring technologies

Monitoring platforms and networks for permafrost are maturing, integrating long-term data sets with standardized methods for climate research and infrastructure planning. Within this broader monitoring landscape, high-frequency methane flux measurements are becoming more standard, using both airborne and ground-based systems. This shift reflects the growing recognition of permafrost as a significant risk, making robust methane monitoring essential for both climate modeling and emissions accounting.

Eddy covariance flux systems with methane analyzers. Eddy covariance measures vertical turbulent transport of gases between the surface and the atmosphere. A 3D sonic anemometer measures wind velocity fluctuations at high frequency (10–20+ Hz) and a methane analyzer (open-path or closed-path) measures CH_4concentration simultaneously at the same frequency. The covariance between vertical wind speed and methane concentration gives a direct landscape-scale flux, expressed as mass per area per time. It is currently the standard for ecosystem emissions research (Burba and Anderson, 2026).

Open-path methane analyzers measure methane concentrations in the atmosphere using infrared laser absorption across an open air path. When combined with high-frequency wind measurements from a sonic anemometer, these systems can estimate landscape-scale methane fluxes using the eddy covariance method. They are commonly used at permafrost and wetland sites to monitor real-time methane emissions from thawing soils, thermokarst features and other landscape sources (McDermitt *et al.*, 2011).

Closed-path cavity ring-down spectroscopy (CRDS) analyzers. Closed-path CRDS systems draw a continuous stream of air through a sampling tube into a temperature- and pressure-controlled optical cavity. A laser pulse enters the cavity and the system measures how quickly the light decays (“ring-down”) due to absorption by methane molecules. Because the path length effectively becomes extremely long inside the cavity, even tiny methane concentration changes (parts-per-billion level) are detectable with high stability (Crosson, 2008).

> High-frequency methane flux measurements are becoming more standard, using both airborne and ground-based systems

UAV-mounted compact CRDS and laser sensors. UAVs equipped with lightweight CRDS or laser absorption sensors can fly predetermined grid patterns or transects over thaw features. These sensors measure methane concentration in the air below the UAV and, when combined with precise GPS data, they can map where methane emissions are occurring and how large they are. This approach is ideal for inaccessible terrain and captures the spatial heterogeneity of methane emissions (UK Environment Agency, 2014).

Portable chamber flux systems with integrated gas analyzers. A closed chamber is placed over soil, water or vegetation surfaces. As gases accumulate inside the chamber headspace, a portable methane analyzer (infrared or CRDS) measures the concentration increase over time, allowing calculation of methane flux from the surface (Hollenbeck *et al.*, 2021).

Long-term fixed sensor arrays (point observations). Stationary instruments installed near or within permafrost landscapes continuously log methane concentrations at fixed heights and locations. These may be single-channel infrared analyzers or multi-gas CRDS sensors. They are useful for baseline monitoring and long-term trends, and are often integrated into research stations or meteorological towers (Campbell Scientific, 2026).

Satellite-based methane and atmospheric trace gas monitoring systems

Monitoring methane and other atmospheric pollutants from space is critical for tracking emissions and guiding mitigation efforts. There is a growing suite of satellite missions, ranging from global instruments to platforms that detect large-scale trends and localized emission sources.

> Monitoring methane and other atmospheric pollutants from space is critical for tracking emissions and guiding mitigation efforts

Global satellite systems

- *TROPOMI (Sentinel-5P, 2017).* European satellite providing daily global coverage of methane and other trace gases at ~5.5 × 3.5 km resolution. Operates in the shortwave infrared to detect point sources and regional hotspots. Supports Copernicus Atmosphere Monitoring Service (CAMS) and research communities (ESA, 2026e).
- *Sentinel-4 and Sentinel-5 (Copernicus)* are follow-up missions to Sentinel-5P/TROPOMI. Sentinel-4 is geostationary, monitoring Europe's air quality. Sentinel-5 provides broader global trace gas coverage, similar to TROPOMI (ESA, 2026c).
- *MethaneSAT (2024).* American–New Zealand mission designed for high-resolution monitoring of methane from oil and gas and major sources (~130 × 400 meters, oversampled to ~45 meters). Contact was lost in early 2025, probably rendering the satellite unrecoverable (EDF, 2025).
- *GHGSat.* Private Canadian satellites with high-resolution monitoring (~50 meters) of methane emissions from individual facilities worldwide. It is focused on oil and gas, mining and other industrial sources (GHGSat, 2024).

- *Atmospheric Infrared Sounder (AIRS) on NASA's Aqua satellite.* Global monitoring of GHGs including methane, CO_2 and water vapor. It has coarser resolution and is used more for climate trend analysis than for pinpointing point sources (NASA JPL, 2026).
- *Greenhouse Gases Observing Satellite, Japan (GOSAT).* Since 2009, it has recorded global CO_2 and methane observations with a focus on regional and global fluxes rather than facility-level detection (NIES Japan, 2026).

Regional or high-resolution systems

- *Copernicus Regional Air Quality Services* use data from Sentinel satellites to provide air quality monitoring for Europe (CAMS, 2023).
- *NASA OCO-2 and OCO-3* are primarily CO_2-focused but data can help to model methane emissions indirectly via carbon cycle interactions (NASA ESSP, 2025).

Box 5.3 describes the ExtremeThaw project, which is examining the impacts of rapid permafrost thaw in the Swiss Alps.

Box 5.3 ExtremeThaw project, Switzerland

The ExtremeThaw project at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) investigates the impacts of rapid permafrost thaw in the Swiss Alps. Thawing permafrost releases carbon and pollutants, destabilizes slopes and may introduce ancient microbes into ecosystems and water systems. Despite its importance, alpine permafrost has been poorly monitored compared with Arctic regions. ExtremeThaw aims to fill this gap by quantifying carbon stocks and assessing the risks and impacts of permafrost thaw on ecosystem functions and services. The project focuses on four areas: GHG emissions from thawing soils, pollutant release into water systems, potential hazards from dormant microbes and opportunities for new carbon sinks as unfrozen ground supports new vegetation and microbial communities.

Researchers use over 100 existing Intercantonal Measurement and Information System (IMIS) climate stations to monitor vegetation growth, species composition and biomass as indicators of ecosystem response. Soil carbon and stability are assessed through soil profile surveys, including the study of ancient buried soils. Microbial diversity is analyzed to understand below-ground biological responses to thaw. The project also leverages the WSL permafrost and ground-ice map and long-term climate data to contextualize findings.

By combining field measurements with lab analyses, ExtremeThaw evaluates how thawing permafrost affects carbon cycling, pollutant release and potential new carbon sinks. The results aim to inform policy, improve GHG reporting and support management of alpine landscapes threatened by climate-driven permafrost degradation.

Source: WSL, 2025.

Nature- and ecosystem-based solutions to stop permafrost thaw

Rewilding of permafrost areas is a proposed strategy that would reintroduce large herbivores to recreate ecosystems like those that existed during the Pleistocene. Early experiments have been conducted in Pleistocene Park in Siberia. While potentially scalable, and reversible in the case of failure, rewilding faces challenges that include ethical concerns around species introduction, ecological uncertainty and the need for indigenous and local support (Graham, 2025). The time needed to scale this approach may not be fast enough to counter rapid Arctic warming.

Nonetheless, research has revealed the possibility of using hoofed herbivores to protect permafrost. Increasing populations of animals such as horses, bison and reindeer can help by reducing shrub cover and compacting snow. As mentioned earlier, this reduces the snow's insulating effect, allowing colder air to enter the ground and keep soils frozen(Earth.org, 2022). Caribou, in particular, have an important ecological function in northern regions, as their

grazing, movement and snow compaction can help to cool the ground and support permafrost preservation. However, caribou populations have declined significantly due to climate change and human pressures (Graham, 2025). Plants also play a significant role in regulating soil temperatures. They shade the ground from solar heat and regulate soil moisture through their roots, thereby reducing thawing (Earth.org, 2022).

Wildfire both accelerates permafrost thaw and is intensified by it, thus creating a feedback loop that increases GHG emissions and ecosystem damage. Improved fire management through prescribed burns, early suppression and land management can help reduce risks (Graham, 2025). The emergence of high-tech prediction tools for lightning-induced fires can support wildfire management. See the *Green Technology Book* Climate disaster edition for wildfire technologies.

Solar geoengineering approaches require caution

Large-scale "geoengineering" climate interventions aim to reduce the amount of solar energy reaching the Earth – for example, through space-based sunshades or atmospheric aerosol injection. These approaches operate at continental or global scales with potential impacts across entire regions or hemispheres. They would require continuous, long-term operation, as stopping them could lead to termination shock (rapid temperature rebound) (Graham, 2025). While some concepts may be relatively low-cost compared to other climate measures, they involve significant technical, governance and ethical challenges. To date, these interventions remain largely theoretical, with research limited to models and small-scale experiments, and ongoing controversy and debate regarding whether they should be pursued at all. One reason these approaches have attracted attention is their potential to slow temperature-driven cryosphere changes, including glacier retreat, sea ice loss and permafrost thaw.

The main approaches differ in where they intervene in the climate system. Stratospheric aerosol injection proposes releasing reflective particles, such as sulfur dioxide, into the stratosphere to scatter incoming sunlight, mimicking volcanic eruptions. Cloud-based methods seek to alter cloud properties to either reflect more solar radiation or release more heat. A third approach, space-based solar radiation management, would place reflective infrastructure in orbit to reduce the amount of sunlight reaching the Earth. All remain largely conceptual with significant scientific, technical and governance uncertainties (Graham, 2025).

Innovation examples

Sensing the thaw: how pore-water pressure technology reveals permafrost instability

KELLER



Source: Photo by Ted Balmer on Unsplash

KELLER Pressure's pore-water pressure monitoring technology plays a crucial role in understanding how ice-rich permafrost landscapes are responding to climate change, especially in alpine regions where permafrost degradation is accelerating. Warming temperatures increase water content in ice-rich ground, such as rock glaciers, which in turn can change internal hydrological conditions and destabilize slopes, increasing the risk of debris flows and other mass movements. Traditional monitoring techniques, such as monitoring ground temperature

alone, do not fully capture subsurface water dynamics, but pressure sensors (piezometers) provide direct measurements of pore-water pressure within permafrost – data that are vital for characterizing internal conditions and how they evolve over time. This technology gives scientists and engineers insight into the hydrological processes driving permafrost movement and water availability within rock glaciers and frozen ground, helping to improve hazard assessment and climate models. By contributing high-resolution pore-water pressure data, these sensors enhance understanding of how thaw-induced changes in water content affect stability and can inform infrastructure planning and natural hazard mitigation in mountainous permafrost regions affected by warming (Keller, n.d.; Bast *et al.*, 2024; Phillips *et al.*, 2023).

Keeping permafrost cold with solar-powered thermosyphons

U.S. Army Engineer Research and Development Center's Cold Regions Research and Engineering Laboratory (ERDC-CRREL)



Source: Arctic Foundations Inc.

The U.S. Army ERDC-CRREL evaluated whether solar energy could power active thermosyphons to cool and maintain frozen ground where traditional passive thermosyphons are limited by warmer air temperatures. Passive thermosyphons extract heat from soil only when the air is colder than the ground. Hybrid thermosyphons are fitted with an internal heat exchanger that can be cooled by an active refrigeration system when air temperatures are above ground temperatures. So, as Arctic air temperatures rise, the operating season for a passive system shortens. The project tested a hybrid system near Fairbanks, Alaska, by combining a solar array, battery storage and a refrigeration unit connected to a hybrid thermosyphon from Arctic Foundations Inc. The solar array supplied electricity to an active air-cooled condensing unit during warm periods, allowing the thermosyphon to cool subsurface soil even when ambient temperatures were above freezing. Monitoring confirmed that the system could extend ground cooling periods, improving upon the use of passive thermosyphons alone. The study also indicated the need for greater efficiency and economic viability. Future work should explore lower-power refrigeration units and configurations that could support multiple thermosyphons (Wagner *et al.*, 2021).

The following collection of technologies is divided into three groups: Proven technologies have been on the market for some time and hence are well tested, Frontier technologies are available but relatively new, while Horizon technologies are close to being available but still under development.

Proven technology solutions

Software package for simulation of permafrost thermal regimes

Simmakers



Source: Getty Images/daniloforcellini

Simmakers' Frost 3D Universal is a specialized thermal simulation tool for modeling heat transfer and phase changes in ground and permafrost environments. It allows engineers to build a 3D computational domain that includes surface topography, soil layers, pipelines, foundations, boreholes and structures, and define material thermal and hydrological properties. The software generates a computational mesh and simulates temperature, unfrozen water content and groundwater flow over time, accounting for heat exchange with climatic conditions like air temperature, snow depth and solar radiation. A built-in library of thermophysical soil and construction data supports realistic modeling. Frost 3D Universal uses advanced numerical methods, parallelized algorithms and can leverage multi-core central processing units (CPUs) and graphics processing units (GPUs) for faster problem solving. It visualizes results in 3D and sectional views for analysis. Typical applications include permafrost thaw prediction, thermal impact of pipelines and infrastructure, and ground freezing stability assessment.

- Technological maturity: Proven
- Contracting type: For licensing
- Technology level: High
- Place of origin: Russian Federation
- Availability: Worldwide
- Contact: WIPO GREEN Database

Permafrost monitoring system

PERMOS (Swiss Permafrost Monitoring Network)



Source: Getty Images/OlyaSolodenko

PERMOS is a long-standing scientific monitoring program that documents the state of and changes in mountain permafrost in the Swiss Alps. Managed by a dedicated office and supported by six academic partners along with funding from MeteoSwiss, the Federal Office for the Environment and the Swiss Academy of Sciences, PERMOS collects and openly shares field data as part of Switzerland's climate monitoring efforts. It observes conditions at 27 high-mountain sites (2,200–3,500 meters above sea level), measuring ground temperatures in boreholes and at the surface, relative ground ice content and rock glacier velocities across typical permafrost landscapes, such as rock glaciers and steep slopes.

- Technological maturity: Proven
- Contracting type: Open source
- Technology level: High
- Place of origin: Switzerland
- Availability: Switzerland
- Contact: WIPO GREEN Database

Two-phase thermosyphon

Arctic Foundations of Canada



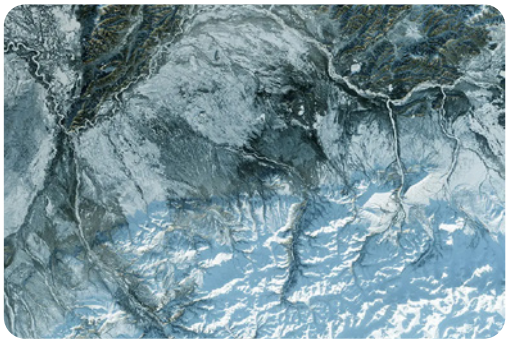
Source: Getty Images/milehightraveler

Two-phase thermosyphons are passive (and optionally hybrid active–passive) refrigeration devices that transfer heat from the ground to the air using a sealed vessel containing a two-phase working fluid. In winter, cold air condenses the fluid above ground, which then flows downward; below ground, the fluid warms, vaporizes and rises, creating a continuous heat-transfer cycle. Hybrid systems add powered condensers to operate even when ambient air is too warm. Thermosyphons are widely used in Arctic and cold-climate applications to maintain frozen ground, preventing permafrost thaw and protecting infrastructure such as roads, pipelines and foundations. This technology has been applied in over 900 installations since the 1960s, making it a mature and reliable solution. Arctic Foundations Inc. (AFI) has continuously developed and deployed thermosyphons since the 1970s with ongoing improvements in installation and efficiency.

- Technological maturity: Proven
- Contracting type: For sale/contract
- Technology level: High
- Place of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

GNSS receiver

Trimble



Source: Photo by USGS on Unsplash

The Trimble Inc. R10 Model 2 GNSS System is an advanced global navigation satellite receiver that helps land surveyors collect fast, accurate field positioning data. It uses a high-performance GNSS chipset with 672 channels to track all major satellite constellations (GPS, Global Navigation Satellite System (GLONASS), BeiDou, Galileo, etc.) for reliable location fixes even in challenging environments. The system improves battery life by around 33 percent, increases internal memory for long-term data storage, and resists signal interference and spoofing. It builds on core technologies like HD-GNSS processing for precise measurements, tilt compensation for easier data capture, and xFill to maintain centimeter-level positioning when correction signals are temporarily unavailable. It integrates with handheld controllers and mobile devices running Android or iOS to streamline data collection and boost productivity across surveying, construction, mapping and GIS workflows.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Measurement and control data logger

Campbell Scientific



Source: Campbell Scientific

The CR1000Xe is a rugged, low-power measurement and control data logger used to collect, process, store and transmit sensor data in remote and harsh environments, such as weather stations, hydrology networks, soil monitoring and infrastructure projects. It connects to a wide range of analog and digital sensors, logs data in non-volatile memory and supports flexible communication options including USB, ethernet, cellular and satellite links. The device runs on a built-in programmable language, enabling custom data collection and automation routines tailored to specific applications. It operates reliably from –55°C to +85°C, can power external devices, supports expanded memory via microSD and integrates with cloud data systems like CampbellCloud for remote IoT connectivity. Designed for long-term field deployments, the CR1000Xe is widely used in environmental monitoring, research and engineering projects where high-resolution data logging is essential.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Borehole temperature profiler

Campbell Scientific



Source: Campbell Scientific

The CS231 is a rugged SDI-12 digital temperature profiler designed for precise long-term measurement of temperature profiles in soil, water, snow, ice and boreholes. It features a slim probe assembly with up to four optional external temperature sensors that maintain exact measurement depths and protect sensors in harsh environments. Digital SDI-12 communications reduce electrical noise and eliminate analog inaccuracies, while continuous readings (about one per second averaged over 10 seconds) deliver high-resolution temperature data across multiple depths. Its sealed design makes it suitable for frost and permafrost monitoring, soil and snowpack temperature profiling, and infrastructure applications. The CS231 operates in extreme temperatures (-55°C to +85°C) and integrates easily with Campbell Scientific data loggers for remote logging and analysis.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Electrical resistivity and induced polarization (IP) data acquisition system

ABEM



Source: Guideline Geo

The ABEM Terrameter LS 2 enables non-invasive monitoring of permafrost by mapping subsurface resistivity to distinguish frozen from thawed ground, allowing detection of ice-rich layers, thaw progression and potential ground instability. It is a rugged, scalable electrical resistivity and IP data acquisition system used to image the subsurface by measuring how electrical currents flow through soil and rock. It supports 1D–4D resistivity/IP surveys for groundwater prospecting, geological mapping, environmental and engineering studies, and mineral exploration. Up to 12 measurement channels and built-in electrode switching allow high-resolution surveys and deep investigations, and external selectors can expand to over 16,000 electrodes for large area or 3D surveys. The system includes an integrated field computer with USB, ethernet, Wi-Fi and mobile connectivity, internal GPS/GLONASS positioning and expandable storage. Its rugged casing operates in harsh field conditions and a hardware licensing system lets users tailor and upgrade capabilities. The Terrameter also integrates accessories for borehole logging and complex layouts. It can be combined with borehole sensors for long-term, high-resolution permafrost monitoring.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: Sweden
- Availability: Worldwide
- Contact: WIPO GREEN Database

All-in-one multi-node resistivity and IP imaging system

Iris Instruments



Source: Photo by Daniel Fatnes on Unsplash

The Syscal Pro Switch is a robust electrical resistivity and IP system for subsurface imaging. It integrates a transmitter, receiver and multi-electrode switch, supporting up to 10 measurement channels and 24–120 electrodes for 1D–4D surveys. The system automatically adjusts current and voltage for precise resistivity and IP measurements, even in harsh field conditions, and records resistivity, self-potential and chargeability. It is widely used in environmental, geotechnical and hydrogeological studies. For permafrost monitoring, the Syscal Pro Switch maps frozen versus thawed ground, because ice-rich permafrost is highly resistive compared to unfrozen soils. By repeating surveys over time, it tracks active layer changes, thaw progression and ground stability. Data are processed and inverted via PC software to generate high-resolution subsurface images.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

Methane sensor

Li-COR



Source: Li-COR

The LI-7700 Open Path CH_4Analyzer is a rugged, low-power methane sensor designed for eddy covariance flux measurements in field environments. It uses wavelength modulation spectroscopy with an open optical path to measure ambient methane concentrations at high speed(up to 40 Hz), making it suitable for ecosystem and landscape-scale emission studies. The instrument integrates with sonic anemometers and other high-speed gas analyzers to compute real-time methane fluxes alongside momentum, heat, CO_2 and water vapor. Its low nominal power draw (≈4.5 W) and heated optics allow long-term operation in remote locations, including solar-powered deployments. Heated mirror and self-cleaning features help maintain data quality in humid or variable conditions. The LI-7700 synchronizes measurements with a precision timing protocol (PTP) for accurate flux calculations.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Thermistor strings (multi-sensor cables)

Geosense



Source: Getty Images/Tenedos

Geosense thermistor strings are multi-sensor cables used for long-term, high-precision temperature monitoring in harsh geotechnical environments. Each string consists of multiple negative temperature coefficient (NTC) thermistor sensors mounted along a multi-core cable, providing a temperature profile over depth. Sensor number, spacing and cable length can be customized to meet specific project requirements. NTC thermistors decrease in resistance as temperature rises, with high sensitivity (>4 percent per °C) that allows detection of very small temperature changes. Temperature is derived using the Steinhart–Hart equation, converting measured resistance into degrees Celsius. Readings can be collected manually with an ohmmeter or display units like the VW2106 or MP12, or automated through a data acquisition system. Thermistor strings are widely used in permafrost, slope and embankment monitoring, where they capture subsurface thermal dynamics essential for understanding thaw, stability and hydrological processes.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Pile foundation technology

PND



Source: Getty Images/Alexey_Seafarer

SPIN FIN piles are an innovative pile foundation technology with angled fins that increase capacity and stability, allowing shorter, stronger piles that perform well even in challenging soils and variable ground conditions, like those found in permafrost terrains. This foundation approach helps support structures without extensive deep excavation or disturbance to the ground, which can help minimize environmental impact in sensitive alpine or cryosphere settings by reducing soil disruption and preserving stability. They are designed to improve load capacity and resilience of foundations, especially in soft or unstable soils, which is useful where permafrost thaw and uneven ground conditions might pose risks.

- Technological maturity: Proven
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier technology solutions

Permafrost monitoring system

wanwave



Source: wanwave

wanwave's permafrost monitoring system continuously tracks ground temperature, active layer thickness and permafrost stability to detect thaw and assess ground conditions in real time. Its autonomous sensors, powered by long-life batteries, can transmit up to 50,000 messages over five years. Data are sent via network gateways, such as the Network Gateway WNG-20 and M15-2, which manage communication between sensors and the wanwave server. Key hardware also includes multichannel temperature recorders for precise thermal monitoring. The system helps protect infrastructure like roads, buildings and pipelines by identifying permafrost degradation and ground subsidence. It integrates via application programming interfaces (APIs) with environmental monitoring networks, climate models and decision-support systems, enabling centralized analysis and trend forecasting. Overall, the platform combines autonomous sensing, reliable data transmission and analytical integration to improve understanding of permafrost dynamics and enhance infrastructure resilience.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Remote permafrost sensing sensor and software using machine learning

Kryotek Arctic Innovation Inc.



Source: Kryotek Inc.

FrostLink is a permafrost monitoring system that determines whether the ground is thawed or frozen without relying on temperature measurements. Using machine learning, it predicts and measures permafrost thaw, sending automatic alerts to users if excessive thaw occurs. Its proprietary technology delivers simple, clear outputs – "thawed" or "frozen" – requiring no scientific interpretation or complex data management. The system is designed for easy deployment, with sensors installed in minutes using basic tools, and batteries and data loggers lasting up to 10 years. FrostLink serves multiple sectors, including mining, construction, climate research and shipping, enabling monitoring of infrastructure, seasonal frost, ice roads, snow roads and river crossings. By combining predictive analytics with straightforward alerts, it allows industries and researchers to respond quickly to permafrost changes.

- Technological maturity: Frontier
- Contracting type: For sale via procurement agreements and project-based contracts
- Technology level: High
- Place of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Ground-cooling technology

Stabilice Frozen Foundation Systems



Source: Simon Evans

Stabilice™ is a ground-cooling foundation technology designed for infrastructure built on permafrost or frozen soils. It actively controls soil temperature beneath structures to prevent thawing caused by climate change, which can lead to instability, settlement and structural damage. By maintaining a stable freeze–thaw boundary, the system preserves soil strength and reduces risks such as uneven foundations or water accumulation. Unlike traditional passive methods, Stabilice uses adaptive cooling to respond to changing environmental conditions. This approach can significantly lower construction and maintenance costs for Arctic and sub-Arctic infrastructure. Overall, it provides a practical engineering solution to extend the lifespan and safety of buildings in regions where warming temperatures threaten ground stability.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Gas concentration analyzer (with CRDS)

Picarro



Source: Photo by Alexey on Unsplash

Picarro G2307 gas concentration analyzer is a high-precision CRDS instrument that continuously measures methane (CH_4), formaldehyde (H_2CO) and water vapor (H_2O) with real-time data and parts-per-billion sensitivity. It uses coated internal pathways to minimize adsorption and improve response time, and offers field-deployable stability with minimal calibration needs, supporting research on GHGs and emissions in both laboratory and remote settings.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Photoacoustic GHG analyzer

Gasera



Source: Gasera

The Gasera ONE GHG analyzer is a high-sensitivity instrument designed to measure ambient methane (CH_4) and nitrous oxide (N_2O) using cantilever-enhanced photoacoustic spectroscopy combined with a mid-infrared quantum cascade laser (a highly sensitive technique that shines a special laser on a gas and detects tiny responses to measure trace amounts of GHGs). This method produces low-parts-per-billion detection limits, stable operation and a recommended 12-month recalibration interval, supporting continuous field and laboratory monitoring of GHG concentrations. The Gasera ONE GHG detects methane and other GHGs at very low concentrations, making it ideal for subtle permafrost emissions. Its compact design allows deployment in cold, remote environments, including stationary, mobile or UAV-mounted setups. Continuous, real-time measurements capture seasonal and spatial variability, supporting permafrost carbon-cycle research and monitoring thaw-driven gas release.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: Finland
- Availability: Worldwide
- Contact: WIPO GREEN Database

UAV-mounted laser methane sensor

Shenzhen BLV Technology Co., Ltd.



Source: Shenzhen BLV Technology Co., Ltd.

The BLV BL-CH4 400 is a lightweight UAV-mounted laser methane sensor that uses Tunable Diode Laser Absorption Spectroscopy (TDLAS) to detect methane and methane-containing gases from substantial distances without contact. It integrates a laser emitter, receiver, indicator, RGB camera and rangefinder on a stabilized 3-axis gimbal, enabling real-time, non-contact scanning from up to ~300 m with sensitivity around 1 ppm·m and rapid response (~5 ms). The unit records methane (CH_4) concentrations and locations with GPS/coordinate support, suitable for aerial surveys, oil & gas inspection, environmental monitoring, and emissions hotspot detection in remote or hazardous areas where ground access is difficult. Compatible platforms include DJI Matrice 350/400 drone series, and cloud platform/app software supports data visualization and mission planning.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Portable, handheld multi-gas analyzer (used with a chamber)

Cubic Instruments



Source: Photo by Maxim Tolchinskiy on Unsplash

Cubic Instruments' Gasboard-3800GHG Portable Greenhouse Gas Emission Analyzer is a handheld multi-gas instrument that uses micro-flow non-dispersive infrared (NDIR) dual-chamber sensor technology to continuously measure GHGs, including methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O), along with carbon monoxide (CO) and oxygen (O_2), with ranges down to ~200 parts per million and accuracy up to ~±1 percent full scale range (relative to the sensor's maximum calibrated range). It features an integrated heated sampling probe and portable pretreatment system, with digital/analog outputs and good resistance to cross-interference and moisture drift, making it suitable for field measurements of emissions flux in soils or localized sources.

- Technological maturity: Frontier
- Contracting type: For sale
- Technology level: High
- Place of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon technology solutions

Experimental permafrost wind turbine cooling device

Guangxi University and Guangxi Minzu University (Qin *et al.*, 2023)



Source: Getty Images/SeppFriedhuber

A new experimental permafrost cooling device uses a wind turbine to circulate a liquid coolant between the cold air and the ground, actively removing heat from the subsurface. Field trials on the Tibetan Plateau showed it cooled underlying frozen soil by about 0.6–1.0°C over two years. A phase-change-material (PCM) clutch automatically controls operation: it engages in cold conditions to enable cooling and disengages in warm periods to prevent heat gain. Field data show seasonal and daily cycling; the system is most active in winter (especially January–February), while in summer it enters "hibernation" with minimal circulation. Temperature differences between inner and outer tubes confirm when heat is actively extracted from the soil. The system is still in the experimental phase but demonstrates how renewable energy can directly influence permafrost thermal regimes.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: China
- Availability: Under development
- Contact: WIPO GREEN Database

Solar-powered thermal stabilization systems

Environmental Engineering Institute (IIE), Laboratory of Cryospheric Sciences (CRYOS), Ecole Polytechnique Fédérale de Lausanne (EPFL) (Sharaborova, 2025)



Source: Image provided by Elizaveta Sharaborova from EPFL

Researchers are developing solar-powered cooling systems designed to stabilize permafrost beneath infrastructure. The concept combines solar energy generation (photovoltaics) with active or hybrid cooling methods (e.g., heat pumps, thermosyphons or fluid circulation) to extract heat from the ground and maintain frozen conditions. Unlike purely passive systems, these approaches can operate even when natural temperature gradients are insufficient, improving reliability under warming climates. The systems are typically integrated into infrastructure such as roads, railways and foundations, where permafrost thaw threatens structural stability. This technology remains largely at the experimental or early deployment stage.

- Technological maturity: Horizon
- Contracting type: Under development
- Technology level: High
- Place of origin: Switzerland
- Availability: Under development
- Contact: WIPO GREEN Database

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Ecosystem restoration is shifting from periodic observation toward continuous environmental intelligence. By integrating satellites, AI, environmental DNA, and predictive digital twins, practitioners can forecast climate risks, simulate interventions, and deploy targeted restoration solutions.

Across land, oceans, freshwater, and the cryosphere, innovation increasingly blends engineering with nature-based approaches to restore holistic ecological function and build climate resilience. Furthermore, advanced digital monitoring, reporting, and verification systems convert ecological outcomes into verifiable assets, unlocking crucial private climate finance. Ultimately, technology alone cannot replace urgent global emissions mitigation; enduring restoration success requires combining cutting-edge tools with strong governance, public institutions, and active community engagement.

The *Green Technology Book* is a matchmaking tool. The featured technologies are linked to the WIPO GREEN Database of Needs and Green Technologies, where many more technologies can be found, technology owners can be contacted directly and new solutions uploaded.