Fourth Industrial Revolution for the Earth Series

Harnessing the Fourth Industrial Revolution for Oceans

In collaboration with PwC and Stanford Woods Institute for the Environment

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About "The Fourth Industrial Revolution for the Earth" series
"The Fourth Industrial Revolution for the Earth" is a publication series highlighting opportunities to solve the world's most pressing environmental challenges by harnessing technological innovations supported by new and effective approaches to governance, financing and multi-stakeholder collaboration.

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The Fourth Industrial Revolution and the Earth

Industrialization has led to many of the world’s current environmental problems. For example, climate change, unsafe levels of air pollution, the depletion of fishing stocks, toxins in rivers and soils, overflowing levels of waste on land and in the ocean, loss of biodiversity and deforestation can all be traced to industrialization.

As the Fourth Industrial Revolution gathers pace, innovations are becoming faster, more efficient and more widely accessible than before. Technology is also becoming increasingly connected; in particular we are seeing a merging of digital, physical and biological realms. New technologies are enabling societal shifts by having an effect on economics, values, identities and possibilities for future generations.

We have a unique opportunity to harness this Fourth Industrial Revolution, and the societal shifts it triggers, to help address environmental issues and redesign how we manage our shared global environment. The Fourth Industrial Revolution could, however, also exacerbate existing threats to environmental security or create entirely new risks that will need to be considered and managed.

Harnessing these opportunities and proactively managing these risks will require a transformation of the “enabling environment”, namely the governance frameworks and policy protocols, investment and financing models, the prevailing incentives for technology development, and the nature of societal engagement. This transformation will not happen automatically. It will require proactive collaboration between policy-makers, scientists, civil society, technology champions and investors.

If we get it right, it could create a sustainability revolution.

This “Fourth Industrial Revolution for the Earth” series is designed to illustrate the potential of the Fourth Industrial Revolution innovations and their application to the world’s most pressing environmental challenges. It offers insights into the emerging opportunities and risks, and highlights the roles various actors could play to ensure these technologies are harnessed and scaled effectively. It is not intended to be conclusive, but rather to stimulate a discussion between diverse stakeholders to provide a foundation for further collaborative work. This paper, with special thanks to Jim Leape, William and Eva Price Senior Fellow, Woods Institute, and Co-Director, Center for Ocean Solutions, Stanford University, looks at the Fourth Industrial Revolution and oceans.

Foreword

Jim Leape, William and Eva Price Senior Fellow, Woods Institute, and Co-Director, Center for Ocean Solutions, Stanford University

The world's oceans represent 99% of the living space on Earth.[1] They provide livelihoods and protein for more than 3 billion people, bringing $3 trillion into the global economy each year.[2] Oceans provide half the oxygen we breathe and they stabilize and drive our climate, absorbing most of the sun's radiation and sharing heat from the tropics into cooler regions. And, with a large share of the Earth's biological diversity, the oceans provide a vast and largely untapped source for development of medicines, materials, and other uses.

For millennia, we have taken the oceans' bounty for granted. Ocean resources have been largely out of sight and, so, out of mind. We have extracted resources and dumped waste with confidence that the oceans were inexhaustible. Yet, today we are running up against the oceans' limits. We are taking more fish than nature can replenish and our waste is causing dead zones and ubiquitous contamination. We have relied on the oceans to mitigate climate change – they have absorbed 90% of the excess heat we have produced and 30% of our CO_2 emissions.[3 4] The result, however, is that ocean waters are becoming warmer and more acidic, which threatens to undermine the very foundation of the ocean food web and cause upheaval in ecosystems from coral reefs to the Arctic.

Oceans are classic examples of public goods. Effective management by governments is therefore vital. However, attempts to govern ocean resources have often foundered, even in countries with highly developed governance systems. In many countries, and on the high seas, governance has often been absent altogether. Ocean management has increasingly been driven by markets because global supply chains for fisheries and other resources have created imperatives and incentives for sustainability. In many places, allocation of resource rights to users and communities has allowed these stakeholders to take on a greater management role.

The innovations of the Fourth Industrial Revolution create new possibilities for all stakeholders, including governments and markets, to better understand and manage the resources upon which they depend. Ungoverned, these innovations could accelerate degradation. It is urgent that we find ways both to exploit the potential of the Fourth Industrial Revolution and to manage the risks.

The Fourth Industrial Revolution and the agenda for change

Goal 14 of the 2030 Agenda for Sustainable Development calls for UN Member States to "conserve and sustainably use the oceans, seas, and marine resources", and sets out 10 targets to drive action.[5] The Fourth Industrial Revolution offers potential to accelerate and scale proven solutions to achieve these targets. It creates new opportunities for better management of ocean resources and for capturing new value.

For the oceans, the Fourth Industrial Revolution is first and foremost a data revolution. It has been said that less is known about the seafloor than about the surface of Mars.[6] Humanity's use and management of the oceans has often been defined by a profound scarcity of information, limiting its understanding of ocean processes and conditions, resource use and impacts. But this situation is suddenly and rapidly changing. An explosion of new data sources concerning the oceans is taking place, including a rapidly proliferating array of advanced sensors carried by fleets of satellites, ocean-going drones that cruise underwater or on the surface for months at a time, buoys, boats, fishing nets, and even surfboards fitted with sensors.[7 8 9 10 11 12]

These streams of data can be translated into streams of understanding through new platforms for curating and combining diverse datasets; new analytical tools, including artificial intelligence and machine learning to extract needed information; and new tools for making this information useful to decision-makers, whether they are ocean managers, fishers, or consumers. This growing flood of information is the emerging "digital ocean". In combination with other Fourth Industrial Revolution innovations, such as biotechnologies, distributed ledgers and robots, the digital ocean will have profound implications for every aspect of the ocean challenges humanity faces.

The major areas of action needed to sustain the oceans are widely known, including curbing overfishing, reducing pollution, protecting vital habitats and species, and enabling them to adapt to a changing climate. The first UN Ocean Conference, held in June 2017, signalled renewed vigour for tackling these issues.[13] Fourth Industrial Revolution innovations will benefit each of these areas, creating new opportunities for ocean users and managers, technology developers and investors.

Fishing sustainably

An estimated 20% of the global fish catch is illegal, unreported and unregulated (IUU) – robbing governments and legitimate fishermen of $23 billion per year and undermining ocean management efforts.[14 15]

There was explosive growth in the harvest of fish from oceans in the second half of the 20th century, as large industrial ships ventured out from local waters to reach every corner of the seas, trailing miles of hooks or nets large enough to catch Boeing 747s. The result is that today two-thirds of the world's fish stocks are overexploited.[16] The cost of mismanagement is high. A recent study found that reforming management of the world's fisheries could increase the total annual catch by 16 million metric tons and increase annual profits by $53 billion, while improving the health of ocean ecosystems.[17]

Large-scale, industrial fisheries account for most of the harvest, and most of the damage, but small-scale fisheries are also crucial. They employ 90% of the world's fishers and are a cornerstone of food security, providing most of the fish consumed in developing countries.[18]

The future of fisheries that harvest wild stocks is bound up with fish farming, or aquaculture. Aquaculture is the fastest growing segment of the seafood sector, projected to account for 62% of total seafood production by 2030.[19] It has the potential to take pressure off wild stocks. But aquaculture in coastal waters has led to large-scale destruction of coastal habitats where wild fish breed. Market demand for carnivorous fish such as salmon and trout means that aquaculture now consumes nearly 70% of the global supply of fishmeal, and about 90% of the supply of fish oil.[20]

Solutions

Ensuring fisheries are sustainable requires more effective public management, in part through setting quotas that keep total harvest within sustainable bounds, and ensuring rigorous enforcement. Increasingly, management will need to be "dynamic" – able to adjust controls in real time as ocean conditions change.

Global markets can play a key role in creating incentives for better management by offering the prospect of better prices and better market access for fish that come from well-managed fisheries. Innovative tenure arrangements that give communities or fishers rights to the resource could help solve the global commons problem. Achieving sustainability in aquaculture will require better regulation of fish farms and also, critically, breaking the reliance on wild fish for feed.

The potential impact of technology

The emerging "digital ocean" enables and accelerates these solutions. Drawing on diverse advanced sensor platforms connected through advanced digital technologies, such as high-speed 5G and mesh networks, managers can better monitor fish stocks and catch, and can track individual fishing boats, spot illegal fishing and enforce laws. Where fishing rights have been allocated, timely biological and socio-economic data can help fishers and communities manage their resource.

Buyers can better manage their supply chains, through "DNA barcoding", which allows rapid identification of seafood in trade by matching fish products to a standardized genetic library for all fish species.[21] Blockchain, a distributed ledger, can also track a fish from ship to supermarket shelf, providing a clean record of the fish's origin.[22]

Biotech innovation has the potential to reduce impacts. Several start-ups are pioneering fish-free feed by engineering bacteria to produce high-protein feed from methane, for example, or from insects.[23] Others have developed genetically modified salmon that grow in half the time of conventionally farmed salmon, thus requiring less feed.[24] And some are now working to make shrimp from algae and plants.[25]

Recognizing fish

A programme called FishFace is using facial recognition technology to collect information on the species, size and numbers of fish caught at sea.[26] Now being trialled in commercial fisheries, there are plans to develop a smartphone app that could be used by artisanal and recreational fishers.

Preventing pollution

Every year, 8 million tons of trash finds its way into the oceans.[27] It is predicted that by 2050 the oceans will hold more plastics than fish.[28] There are now more than 400 oxygen-deprived "dead zones" in the world's estuaries and coastal waters.[29]

Much of the waste the world produces ends up in the oceans. Fish, birds, sea turtles and other animals ingest large pieces of trash, while tiny particles of plastic permeate the system, even into the flesh of the fish humans eat. Excess fertilizer runs off farm fields into rivers and is carried to the sea, causing harmful algal blooms that die and decompose and create "dead zones" by using up the

oxygen in the water and suffocating healthy marine life. The largest dead zone, at the mouth of the Mississippi River, reached 22,730 square kilometres in 2017, which is an area equivalent to half the size of Switzerland.[30]

Toxic pollutants that we put into the water and the air, such as pesticides on farms and mercury from coal-burning power plants, also end up in the ocean. Many of these pollutants have a half-life extending for years, which means they persist in nature and magnify in the food chain. Polar bear cubs, for example, may have concentrations of toxins that are 1,000 times higher than the levels considered safe for humans.[31]

Solutions

Pollution is best addressed upstream by reducing and eliminating waste flowing into the ocean. A key priority is to reduce the quantities and toxicity of inputs used in agriculture, as well as the emission of toxic chemicals from other sources. Reducing the use of plastic and shifting to truly biodegradable materials is also important. Ultimately, the oceans need a circular economy that reuses rather than discards. In the meantime, measures to remove waste from the oceans, such as cleaning up oil spills or plastic, will play an important role in ocean management.

The potential impact of technology

The capabilities that create the digital ocean, such as the integration of advanced sensors, machine learning and other innovations, can guide much more precise use of pesticides and fertilizer in agriculture, reducing waste and runoff. They can also facilitate regulation that tracks and identifies polluters.

Bio-innovations, such as gene editing and advanced breeding techniques, can produce crop strains that require fewer inputs. An example is Bt cotton, which has been modified with genes from insecticide-producing bacteria to create a caterpillar-resistant variety of cotton and is already widely planted around the world.[32.] Research is under way on bacteria that can clean up waste in the water.[33 34] Scientists recently discovered a microbe that can metabolize polyethylene terephthalate (PET) plastics and may be able to turn them into feedstock for new polymers.[35] Nanotechnology can also be used to detect heavy metals in marine systems and for bioremediation.

Protecting habitats

Heedless development has destroyed many coastal habitats, including one-third of the world's mangroves and seagrass beds.[36] More than 15% of the Earth's land surface is in protected areas; in the oceans the figure is only about 6.3%.[37]

As on land, the health of ocean ecosystems hinges on the protection of vital habitats. These include the mangroves, coral reefs and seagrass beds that are nurseries for fish and valuable resources for coastal communities. Vital habitats also include the rich and varied deep sea habitats, from cold-water corals to thermal vents, which are just beginning to be understood and are proving to be a rich source of genetic assets for pharmaceutical and other applications. In many places, bottom trawling has clear-cut the ocean floor, while seabed mining looms as a new threat. Once disturbed, deep sea floor systems may take centuries to recover.

Solutions

The cornerstone of habitat conservation is protection. Activities such as coastal development, fishing, and mining need to be effectively regulated to ensure they do not destroy habitats that are important to fisheries, tourism and other economic uses, as well as to the broader diversity and health of ocean ecosystems.

The potential impact of technology

New streams of information about ocean ecosystems flowing from the digital ocean can inform the design of marine protected area systems and the creation of dynamic protection regimes that can adapt to changing conditions. Digital ocean capabilities also enable more powerful enforcement of habitat protection and regulations, including the monitoring of boats, development and other activities. Innovations also have the potential to reduce the impact of economic activities, for example developing deep sea mining robots that can extract resources with less damage.[38]

Drones are now being developed that could be used to economically restore degraded ecosystems, for example by planting mangroves.[39] Flying 100 metres above ground, the drones take detailed images at 3 to 5 centimetres resolution. Through machine learning algorithms, these images are processed and assembled into a planning pattern to determine the best places to plant and which species are best fit for the area.

Biotech research is already helping to identify species that are more resilient to ocean changes through "assisted evolution".[40] Scientists can identify the corals with the strongest ability to withstand changing ocean conditions and selectively breed these strains to perpetuate the strongest traits.[41]

Enforcing protection

Large ships are required to carry Automatic Identification System (AIS) transponders, designed to avoid accidents. Satellites can track AIS signals. Three initiatives are combining AIS data with other datasets and machine learning to monitor fishing, shipping, mining and other activities.[42] These technologies can predict commercial fishing behaviour in near real time and help to reveal ships whose AIS transponders may be turned off, enabling law enforcement of protected areas or other restrictions.[43]

Protecting species

The World Wildlife Fund Living Planet Index reports a 36% decline in ocean wildlife population numbers since 1970.[44]

Extinctions of ocean species have not yet reached the scale seen on land, however, many ocean species and myriad populations are in decline. For example, the global populations of some species of baleen whales are down more than 80% from their historic numbers.[45] [46] [47] Many shark species, hunted for their fins, have also seen sharp declines. For example, whitetip shark populations declined an estimated 93% between 1995 and 2010 and one-quarter of shark and ray species are now classified as threatened on the International Union for the Conservation of Nature Red List.[48] [49]

Disease can also wreak havoc in species populations. In 2014, for example, sea star wasting disease swept from Alaska to Baja, affecting more than 20 different species, reducing some populations by 95%.[50] Invasive species, often carried in the bilges of ships, can also crowd out native plants and animals.

Solutions

The future of these species depends in part on sustaining the health of ocean ecosystems, in particular on conserving habitats. It also depends on effective protection. This requires direct action to interdict illegal hunting and intercept illegal trade. It also requires effective control of the “incidental take” of threatened species in fisheries and regulation to control the spread of invasive species and disease.

The potential impact of technology

Fourth Industrial Revolution innovations offer new potential on many fronts. Satellite tracking of ocean wildlife is providing profound new understandings of their ecology to guide conservation and in real time can help fishing fleets avoid areas where protected species are likely to be located.[51] A machine learning tool called DeepDive can be used to process “dark data” on the web to penetrate the organized crime rings that traffic protected wildlife.[52] DeepDive extracts value from the universe of data buried in text, tables, images and other sources that are unable to be processed by existing software.

Genomics has many potential applications for protecting species. Investigating the sea star wasting crisis in the Eastern Pacific, scientists were able to use metagenomics to identify a DNA virus associated with the disease that seemed to be triggered in response to different ocean stressors.[53] DNA sequencing of tissue samples can be used to determine the species and even origin of wildlife in trade.

Environmental DNA sequencing can be used to sample bilge water to determine whether a boat has been carrying illegal or unwanted species or to sample water from the open ocean to detect the presence of protected species. Genetic engineering can also be used to control invasive species. To address the invasion of North American bluegill fish in Japan, researchers genetically modified male bluegills to produce sterile female offspring.[54]

Avoiding bycatch

Bycatch is the incidental capture of non-target species such as dolphins, marine turtles and seabirds. Scientists can map the location and path of turtles by attaching transmitters to their shells, which send a signal to a satellite each time the turtle surfaces for air.[55] Satellite tracking of endangered leatherback turtles in the Pacific Ocean inform conservation efforts and can reduce conflict with fisheries.[56]

Building resilience to climate change and acidification

Since 1955, more than 90% of the excess heat retained by the Earth as a result of increased greenhouse gases has been absorbed by the oceans.[57]

Climate change is already having multiple, profound impacts on the oceans. The melting of the ice caps in Greenland and Antarctica is raising sea levels globally, while the melting of the Arctic ice cap is opening up access to a whole new ocean. These changes threaten to disrupt the global ocean currents, such as the Gulf Stream, that shape our weather. As the oceans warm, the CO_2 emissions that cause climate change are also making the oceans more acidic. The twin assaults of warming and acidification are causing profound upheaval in ocean ecosystems and promise to be transcendent challenges in the decades ahead.

Coral reefs are among the most vulnerable to these changes. When global temperatures reached record levels in 2015 and 2016, a global bleaching event swept across 70% of the world's coral reefs.[58] As oceans warm, fish and other wildlife tend to move to higher latitudes in search of cooler waters. These shifts alter ecosystem interactions and function. They also threaten economic disruptions. Many countries are facing the loss of fisheries that are vital to their food supply or their economy. Tuna revenues can account for as much as one-third of GDP and 60% of government revenues in some small island states.[59] Some of these states will face a fiscal calamity if tuna stocks leave their territorial waters.

Solutions

Urgent action to reduce greenhouse gas emissions and stabilize the climate is the overriding imperative for oceans. The upheaval caused by warming, acidification and other stresses on ocean ecosystems will require much more agile and adaptive management to anticipate and to respond effectively to changes that may sometimes unfold very rapidly. Success will also require investments in building resilience by reducing stresses, identifying and protecting areas that are less affected by stresses, and identifying and perhaps disseminating resilient species.

The potential impact of technology

The manifold capabilities of the digital ocean will be essential to managing marine resources in this era of upheaval. Drawing upon diverse streams of data about ocean conditions and use, the digital ocean enables sophisticated modelling and data analysis to improve our understanding of the risks posed by the multiple stresses humans are putting on the oceans, including through climate change.

The data also enables real-time monitoring to provide early warnings of potential crises. Biotech innovations will be essential to identify species resilient to warming and acidification and the key traits that enable resilience.[60] Metagenomics has enabled scientists to develop a better understanding of coral-microbial associations, which provides a better understanding of the functioning of coral reef ecosystems, particularly in light of increasing ocean stressors.[61]

Figure 1: Development level of Fourth Industrial Revolution technology applications that address challenges for oceans

Fourth Industrial Revolution technologies	Challenges for oceans				
	Fishing sustainably	**Preventing pollution**	**Protecting habitats**	**Protecting species**	**Building resilience to climate change and acidification**
3D printing					
Advanced materials		Being Explored			
Advanced sensor platforms	Being Scaled	Being Scaled	Being Scaled	Being Scaled	Being Scaled
Artificial intelligence	Being Scaled	Being Scaled	Being Scaled	Being Scaled	Being Scaled
Bio-technologies	Being Explored	Being Scaled	Being Explored	Being Explored	Being Explored
Blockchain	Being Explored	Being Explored	Being Explored	Being Explored	
Drones and autonomous vehicles	Being Scaled	Being Scaled	Being Scaled	Being Explored	Being Scaled
The internet of things	Being Scaled	Being Scaled	Being Explored	Being Explored	Being Explored
Robotics	Being Scaled	Being Scaled	Being Scaled	Being Scaled	Being Explored
New computing technologies	Being Scaled	Being Scaled	Being Scaled	Being Scaled	Being Scaled
Virtual, augmented and mixed realities					

Being Explored – Fourth Industrial Revolution technology being explored or in early stages of implementation to address this challenge.

Being Scaled – Fourth Industrial Revolution technology implemented in numerous applications to address this challenge.

Transforming business as usual in the oceans

The use and management of ocean resources has to a large extent been defined by twin realities: that oceans are vast, remote and largely invisible and that they are public goods. The Fourth Industrial Revolution has the potential to transform business as usual in the oceans by changing these realities by bringing global visibility to the condition and use of ocean resources and enabling new lines of governance.

Robust and vivid information offers the potential to change possibilities and incentives. Governments that are trying to better manage their ocean resources, and perhaps their use of resources beyond their own jurisdictions, will have new tools. Governments that are less committed may be faced with new pressure for action.

Businesses and consumers will have a new level of power in the marketplace, as they are able to know what they are buying and may favour sustainable producers. Communities and fishers who depend on ocean resources for their livelihoods will be better equipped to shape their futures. Similarly, the distant "high seas" may soon grow in proximity, creating new challenges and perhaps appetites for national and international governance. This could result in new management strategies, regulation, enforcement mechanisms and alliances. Beyond this information explosion, Fourth Industrial Revolution innovations will also offer new technologies that can help meet humanity's growing demands for food, transport and recreation, while sustaining the health of the oceans.

Following are five potential game-changers powered by the Fourth Industrial Revolution.

1. Real-time and predictive ocean information

Real-time information on ocean conditions enables agility and real-time monitoring of activities in the ocean enables action. The types and value of ocean information will grow exponentially. For example, underwater drones can piece together detailed, real-time views of the ocean floor to monitor deep water species.[62] Profiling buoys equipped with digital sensors and GPS trackers can measure a variety of environment measures, including water temperature, salinity and nutrient levels.[63 64]

This new digital ocean will allow ocean managers to monitor and respond to rapidly changing conditions, such as an emerging bleaching event, the sudden decline of a fishery, a disease outbreak or a growing dead zone.

The data will increasingly allow governments to detect infractions that until today have been largely invisible and to enforce their laws. Digital ocean capabilities will also allow authorities to identify and track individual vessels to monitor fishing, shipping, mining and other activities. Machine learning algorithms can help identify prohibited behaviour.[65 66] Citizen monitoring through social media could provide a valuable complement to this work.[67]

2. Accountability in markets

When commercial fishing went global, the market for seafood became opaque and largely impenetrable to buyers and consumers. Mining, shipping, oil extraction and other activities have also been largely out of sight. The onset of the Fourth Industrial Revolution represents the cusp of an accountability revolution for oceans – radical transparency combined with robust traceability.

The emerging capabilities that bring new power to law enforcement offer unprecedented transparency for global markets. Project Eyes on the Seas, for example, aggregates data from various monitoring platforms such as radar, ships' transponders and databases of authorized and blacklisted vessels to assist regulators and governments to monitor the oceans worldwide.[68] Global Fishing Watch has made similar capabilities publicly available.

Inexpensive satellite trackers used through the Smart Track Project bring this transparency to small-scale fisheries, helping to ensure boats in the Philippines are only fishing for yellowtail tuna within allowable zones.[69] The trackers, similar to those used for commercial cargo, are attached to fishing boats, which can then send their vessel routes via cellular or satellite networks. The transparency allows fishermen to demonstrate that they are fishing in legal zones.

Powerful new tools can ensure that products can be traced from the boat all the way to the store shelf, ensuring the product's legality, sustainability, quality and safety. These tools could also help to reduce the market for operators using forced labour on fishing vessels. Distributed ledgers, like blockchain, promise secure traceability locked in the cloud.[70] For some products, Radio Frequency Identification (RFID) tags can automate traceability. For trade not secured by these technologies, DNA barcoding allows rapid detection of fraudulent seafood in commerce.[71]

Blockchain enables traceability

A blockchain is a continuously growing list of records, called blocks, which are linked and secured using cryptography, which can provide proof of compliance to standards at origin and along the supply chain. Each time a fisherman hauls in new catch they can send a text message to register it, creating a new "asset" on the blockchain. Every time the fish is sold, the blockchain ID is sold with it. The blockchain provides transparency and traceability on an open platform that delivers neutrality, reliability and security.[72]

3. Empowered communities

Many coastal communities are buffeted by rapid and unpredictable changes in the ocean resources upon which they depend and are ill equipped to manage. Even where government management is strong, engaging and empowering communities can yield better outcomes. Where government is weak or absent, community-based management is essential. Fourth Industrial Revolution innovations are providing new possibilities for distributed and shared management of oceans.

For example, low-cost GPS devices allow tracking of every boat, even small ones. Increasingly robust information can be streamed to smartphones. Phones and social media can be used to allow fishermen to collect granular data on fishing activity, to optimize their operations, to guide management and provide the basis for implementing controls.

As Fourth Industrial Revolution technologies become more affordable, new tools from the digital ocean will become increasingly accessible to local communities and augment their local knowledge. These tools include machine learning for predictive analysis, DNA barcoding and blockchain-based traceability. They could also allow small-scale fishermen to demonstrate sustainability and provide the traceability demanded by global markets.

Smartphone solutions

mFISH put smartphones in the hands of artisanal fishermen in Indonesia. By streaming data on weather, fish stocks and market prices, mFISH helps fishermen optimize their operations. At the same time, it enables the collection of data on where they fish and what they catch, which supports better management.[73]

4. Farming that protects ocean resources

Information technology enables "precision agriculture", which ensures that fertilizer, pesticides and water are applied only as needed. Information technology also facilitates the regulation of aquaculture, from the placement of fish farms to monitoring effluents.[74] For example, aquaculture farms can now raise fish in large spherical net pens that drift on the currents in the open ocean. They are remotely monitored through sensors, automated devices and digital connectivity. These offshore aquaculture operations promise to reduce the habitat destruction and pollution caused by fish farms in coastal waters.[75]

Biotech innovations could also play a major role. New crop breeds that are pest-resistant or drought-resistant can reduce reliance on fertilizer and pesticides; Bt cotton, discussed above, illustrates the potential. Microbial seed treatments can enable precision nourishment of plants.[76] In aquaculture, genetically guided breeding can screen out vulnerability to disease and reduce the dependence on large-scale application of antibiotics.[77] Most critically, Fourth Industrial Revolution technologies could break the dependence of aquaculture on wild-caught fish by producing fish-free feed.[78 79]

Reducing disease

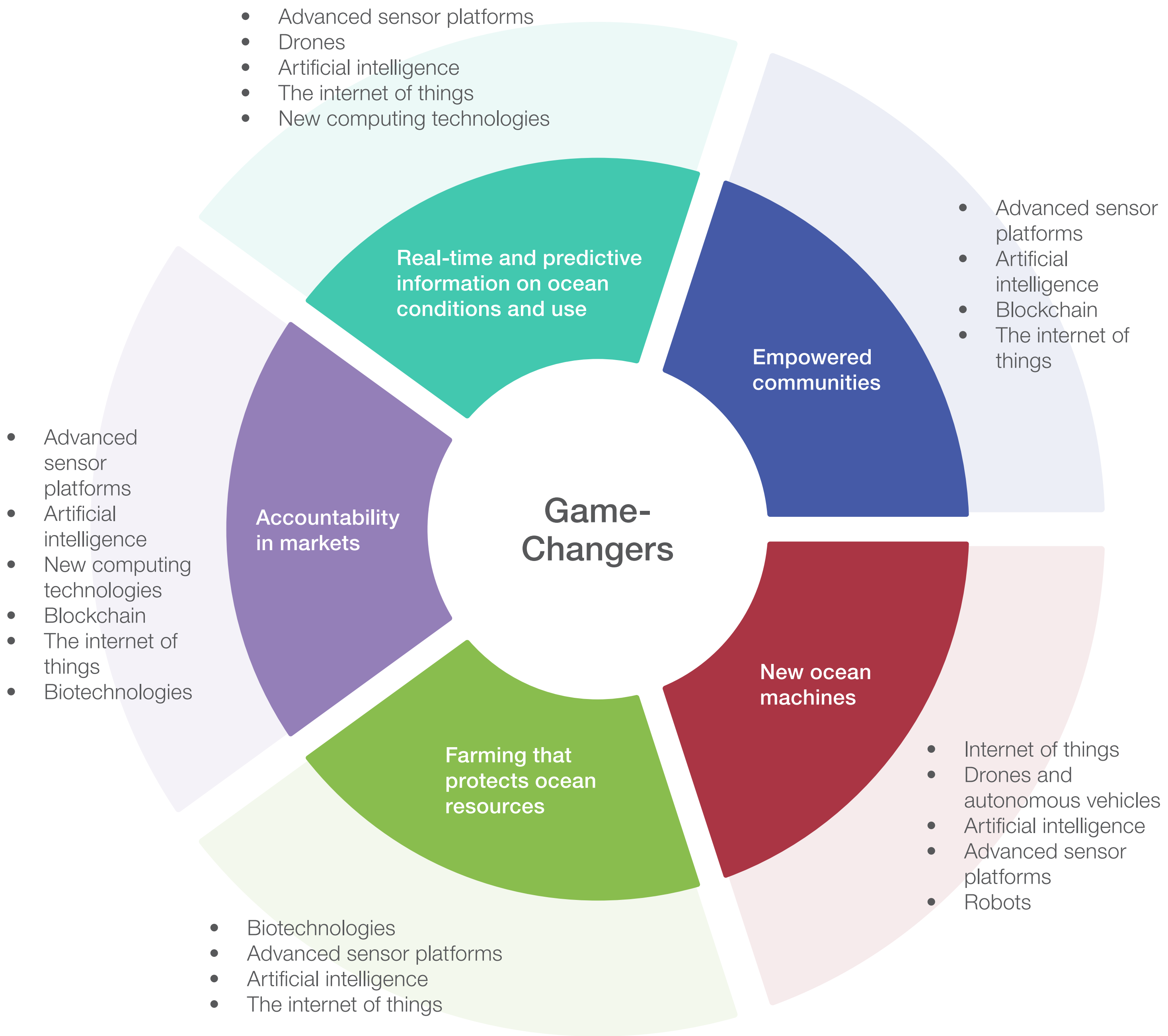
Researchers in Scotland have identified genetic markers that enable the selection of salmon species that are resistant to the infectious pancreatic necrosis virus (IPN) virus, reducing mortality in salmon farms from 25% to almost zero.[80]

5. New ocean machines

Autonomy is coming to the oceans just as it is to highways. Autonomous cargo ships promise to reduce the risks of accidents, which are most often caused by human error. Surface water drones can cruise the oceans for as long as a year at a tiny fraction of the cost of research vessels.[81] Aerial drones can carry a wide array of sensors to monitor ocean health or count fish. They can also be used to patrol remote areas to regulate fishing fleets or enforce protected areas.[82 83]

Autonomous underwater vehicles expand the possibilities for exploring and developing mineral resources on the seabed, and for providing cheaper and more regular inspection of undersea pipelines. These vehicles also create new opportunities to study the unique creatures that have adapted to the oceans' harshest extremes, from the frozen polar regions to the extreme pressure and heat of deep-sea thermal vents, which provide rich sources of genetic innovation for medical and commercial applications.[84] The deep water Discodermia sponge, for example, has been shown to inhibit cell proliferation and may be effective to treat breast cancer and other types of cancers that have developed resistance to other types of drugs.[85] It is currently in clinical trials.[86]

Figure 2: The Fourth Industrial Revolution's game-changers for oceans



Challenges and risks of the Fourth Industrial Revolution transition

The Fourth Industrial Revolution offers exciting opportunities to better manage oceans. However, there are formidable challenges to be met if we are to capitalize on these opportunities and manage the significant risks.

Challenges

Efforts to realize the potential of the Fourth Industrial Revolution face technical and market-based challenges and pose new challenges for existing institutions. Some of the most exciting opportunities lie in the creation of powerful new information on ocean resources and use. Because for-profit companies have created many of these technologies and data-streams, it can be difficult to integrate data sets that are on different proprietary platforms. Harnessing these innovations to solve social problems, especially in emerging markets that are not yet highly profitable, will require the creation of new business models to support these applications.

One of the most important opportunities enabled by Fourth Industrial Revolution technologies is a shift to more agile management. This shift will often require governments to overhaul long-established regulatory and management systems with deeply entrenched constituencies.

The marine sector is atomized and there are particular challenges in engaging smaller actors. Small companies may be less susceptible to market pressures; small boats are often exempt from legal requirements, such as AIS. Both will need technologies that are adapted to their technical and financial capabilities.

Many of the opportunities depend on infrastructure and capacity. Small coastal communities in developing countries may need to have smartphones and broadband access to take advantage of technologies that allow them to better manage their fisheries and access global markets. Many users, including individual fishers, government managers and procurement officers will need training to put these innovations into practice.

Risks

Many of the technologies that can enable better fisheries management could also be used to accelerate exploitation. This has been the story of the past half-century as technological advances have fuelled a vast increase in pressure on ocean resources. Industrial fishing, ever deeper oil development and industrial agriculture have challenged governance and degraded our oceans.

Fourth Industrial Revolution innovations pose a new set of risks. Rich new streams of information on ocean conditions, fish stocks and activities can enable even more intensive fishing, for example by helping boats to find prime target stocks and catch every last fish, and perhaps helping illegal users escape enforcement. Data on the location and habitats of protected species can guide poachers. On land, some poachers are using tourists' geo-tagged photos posted on social media to find endangered animals.[87]

Advanced robots may allow sensitive exploitation of minerals on the seabed floor. However, new technology is also producing massive underwater mining machines that could cause needless damage in fragile deep-sea ecosystems. Autonomous ships may be less likely to have accidents, as most accidents at sea are a result of human error. But there is concern that they may be less able to respond quickly and effectively when crises occur.

Genetic engineering may pose trade-offs because engineering for one trait may undermine others. It also poses risks of unintended consequences. Genetically engineered fish may improve productivity and reduce the footprint of aquaculture, but they could be destructive competitors to native populations if they escape into the wild. Genetically engineered microbes may help clean up pollution, but they could have broader unforeseen impacts on the ecosystem.

Ensuring the Fourth Industrial Revolution is a sustainable revolution

The implications of the Fourth Industrial Revolution for the oceans and success in realizing the benefits and managing the risks will depend on humanity's ability to meet the formidable challenges of governance and finance. These challenges loom large because the ocean is often poorly governed and poorly served by markets. Success will require governance that is open and agile, but also strong when needed. Success will depend on innovation in finance with new business models and new investment vehicles that can enable and incentivize solutions and be applied at scale. Success will also require an investment in assessment and learning, so that stakeholders can better understand and address the environmental, economic and social effects of these often disruptive technologies.

Governments and ocean stakeholders each have roles to play. Most importantly, they need to find ways to work together.

Governments and international organizations

Governments and international organizations have an important role to play in fostering Fourth Industrial Revolution innovations for the oceans. Markets alone will not offer adequate incentives. Most of the world's oceans are in the territories of low-income countries or the unowned territory of the high seas. Governments must find a way to keep pace with rapid innovation. They must also identify and manage the risks in fast advancing domains such as biotech. As innovation enables even more intensive exploitation of fisheries, seabed minerals and other resources, the weaknesses of today's governance are thrown into sharp relief. The Fourth Industrial Revolution demands stronger governance from the governments that own the resources and governments whose companies seek to exploit them.

It is crucial that governments find ways to seize the opportunities created by the Fourth Industrial Revolution to successfully manage ocean resources that are now increasingly in crisis. That means creating room for experimentation by allowing states and communities to take advantage of new capabilities to find better ways of managing their resources. Enabling market solutions, such as certification, to play stronger roles is also important. Countries could follow the lead of the Netherlands and Iceland, which have established programmes to help all their fisheries achieve Marine Stewardship Council (MSC) certification. Lastly, it means reforming long-established, often ossified, management regimes to take advantage of the tools now becoming available for dynamic management of resources, more effective law enforcement, and better understanding and control of risks. Early examples show the potential. The TurtleWatch programme in the United States provides the Hawaiian swordfish fishery with near real-time data to identify turtle "hotspots" and facilitates dynamic management of fishing activity to reduce bycatch.[88] In 2015, the Pacific island nation of Kiribati used Global Fishing Watch to catch a fishing vessel operating illegally in the Phoenix Islands Protected Area, and to collect a $2 million fine.[89]

Companies and entrepreneurs

Technology companies and entrepreneurs have a central role to play to create business models that can support the development and global application of innovations for the oceans. Whether for fleets of satellites, drones that can provide vital new data streams, or for the algorithms and apps that can translate those streams into tools for better use and management, new business models are needed that provide a viable proposition for governments and communities or that combine profitable commercial use with availability for the public good.

Many of these innovations are most powerful when they are brought together. An example is combining several different data streams to provide much more robust information for anticipating and managing risk in coastal waters or apprehending pirate fishers. It is crucial that the companies in the sector are willing to work together and to support interoperable, open source capabilities to solve ocean problems.

Companies outside the tech sector also have crucial roles to play. As seen in the recent commitment by leading retailers and processors to demand full traceability in the tuna sector, companies across the ocean sector can create the demands that drive innovation.

Integrating data

A new Ocean Data Alliance, instigated by the World Economic Forum, is a promising effort to crack the challenge of sharing date. The alliance brings together companies with diverse data capabilities, oceanographic institutions and conservation NGOs to create an open source platform for ocean data and an Ocean Data Fund to launch the initiative.[90]

Investors and funders

There is ample profit to be made in sustainably developing the oceans. As noted above, a recent study estimates that better fisheries management could yield $53 billion a year. The Ocean Data Alliance envisions that investing in better transparency of tuna fishing can yield handsome returns for governments. Foundations, impact investors and governments will often have to provide the upfront investment that allows capabilities to be created and demonstrated, and paves the way for these innovations to be picked up by markets. Innovation challenges can play a useful role and have already stimulated promising concepts on fish feed and plastics.[91 92]

Research institutions

Researchers have been in the vanguard of the Fourth Industrial Revolution and will continue to have a central role, especially in developing innovations that can help meet social challenges that are not well-served by the market. It is critical to draw upon the full breadth of research expertise in the natural and social sciences to create solutions that work, instead of technology fixes in search of a problem.

It is also urgently important that research institutions play a proactive role in illuminating and investigating the risks of new technologies, providing credible assessments for policy-makers and the public.

Civil society

International and local NGOs have many roles to play to ensure that the Fourth Industrial Revolution is a sustainable revolution in the oceans. NGOs are often best positioned to bridge needs and possibilities. NGOs work with users and managers of resources to understand their interests and needs; link them to tech innovators who can come up with solutions; and support implementation, building the capacity to use new technology successfully. The FishFace and SmartTrack initiatives are good examples.

NGOs are also indispensable watchdogs. They identify the abuse or dangers of new technology, sound alarms when necessary and mobilize response. NGOs can help ensure that rights are respected and benefits are equitably shared.

As technology provides increasingly powerful traceability of resources from the ocean to the plate, NGOs will be needed to help establish the norms and institutions that provide crucial validation that a product harvested, traced and sold was sustainably produced. The MSC, which certifies wild-capture fisheries, and the Aquaculture Stewardship Council, which certifies fish farms, will continue to play a crucial role.[93 94] More than 20,000 products, representing 10% of wild caught seafood globally, now carry MSC certification.[95]

Multistakeholder partnerships

Ensuring that the Fourth Industrial Revolution is a sustainable revolution for the oceans will require development of multistakeholder platforms to bring diverse technologies together and create the policy and market context needed to support application.

Multistakeholder collaboration will be essential as we confront the challenge of bringing together diverse commercial data sources. The example of the Global Alliance for Vaccines and Immunization (GAVI) is instructive.[96] GAVI brought together governments, NGOs, and pharmaceutical companies to find a way for companies to share their intellectual property to develop immunization programmes for children in low-income countries. The nascent Ocean Data Alliance applies this model to the ocean.

Multistakeholder collaborations also have an important role in creating market demand. Over the past 20 years, the sustainable seafood movement, involving diverse collaborations among NGOs, leading companies, fishermen and governments, has been a powerful market driver for better management of fisheries. A new multistakeholder collaboration on traceability, announced at the UN Oceans Summit in June 2017, provides a clear market signal for the Fourth Industrial Revolution innovations that can make it happen.

Traceable Tuna

At the UN Ocean Summit in June 2017, more than 40 of the largest buyers in the tuna sector – from Bumble Bee and Thai Union to Ahold and Tesco – pledged that by 2020 all tuna products in the supply chains will be sourced from socially and environmentally responsible producers, and "will be fully traceable to the vessel and trip dates".[97]

Figure 3: Implementation potential of selected applications

Environmental applications	Fourth Industrial Revolution technologies used											Implementation potential			
	3D printing	Advanced materials	Advanced sensor platforms	Artificial intelligence	Biotechnologies	Blockchain	Drones/autonomous vehicles	Internet of things	New computing technologies	Robotics	Virtual, augmented, mixed realities	**Technology readiness**	**Environmental risk of technology**	**Readiness of the enabling environment**	**Potential to scale**
Fishing sustainably															
Monitoring fish stocks and catch			x	x	x		x	x	x	x		Green	Green	Green	Green
Track fishing vessels and enforce fishing laws			x	x			x	x	x	x		Green	Green	Green	Green
Image recognition technology for fish				x								Green	Green	Amber	Green
Smart tracking and traceability of supply chains			x	x	x	x	x	x	x	x		Green	Green	Amber	Green
Genetically modified farmed fish					x							Green	Amber	Amber	Green
Lab-grown seafood substitutes					x							Amber	Green	Amber	Amber
Preventing and cleaning up pollution															
Precision agriculture			x	x	x		x	x	x	x		Green	Green	Green	Green
Genetically engineered crops					x							Green	Amber	Amber	Green
Circular economy and biodegradable materials		x			x					x		Amber	Green	Amber	Green
Plastic and oil clean-up		x	x		x	x	x			x		Green	Green	Green	Green
Bioremediation		x			x							Amber	Green	Amber	Green
Protecting habitats															
Real-time monitoring of resource use			x	x	x	x	x	x	x	x		Green	Green	Green	Green
Drones for ecosystem restoration				x	x				x	x		Amber	Green	Amber	Amber
Identification and breeding of resilient species				x	x				x	x		Green	Amber	Red	Green
Deep-sea mining robots			x							x		Green	Red	Amber	Amber
Monitoring and management of protected area boundaries			x	x		x	x	x	x	x		Green	Green	Green	Green
Protecting species															
Tracking and management of species and catch			x	x	x	x	x	x	x	x		Green	Green	Amber	Green
Species DNA sequencing				x	x				x	x		Green	Green	Amber	Green
Environmental DNA sequencing				x	x				x	x		Green	Green	Amber	Green
Gene-edited invasive species				x	x				x	x		Amber	Amber	Red	Green
Dark data search tools				x								Green	Green	Amber	Green
Building resilience to climate change and acidification															
Real-time ocean monitoring			x	x			x	x	x	x		Green	Green	Green	Green
Modelling and data analysis to assess and manage risks			x	x			x	x	x			Green	Green	Green	Green
Identification and breeding of resilient species				x	x				x	x		Green	Green	Amber	Green
Metagenomics to understand marine ecosystems				x	x				x	x		Green	Green	Green	Amber

Note: Ongoing research and exploration will be required to better understand and improve the implementation potential – including technical, social, governance, policy and investor readiness – of these innovative environmental applications and to explore how the most effective applications can be scaled.

Key

- **Technology readiness level**[98]
  - Red – Technology Readiness Level 1 to 4
  - Orange – Technology Readiness Level 5 to 7
  - Green – Technology Readiness Level 8 to 9

- **Environmental risk of technology**
  - Red – Risks exist, with no or limited mitigation options available
  - Orange – Risks exist, with multiple mitigation options available
  - Green – No foreseen environmental risks

- **Readiness of the enabling environment**
  - Red – Extensive roadblocks inhibit the implementation of this application (e.g. insufficient social acceptance, governance systems, policy frameworks, and investor readiness)
  - Orange – Multiple roadblocks inhibit the implementation of this application (e.g. insufficient social acceptance, governance systems, policy frameworks and investor readiness)
  - Green – Minimal roadblocks inhibit the implementation of this application (e.g. insufficient social acceptance, governance systems, policy frameworks and investor readiness)

- **Potential scale**
  - Red – Potential application is niche
  - Orange – Potential application is broad
  - Green – Potential application is extensive

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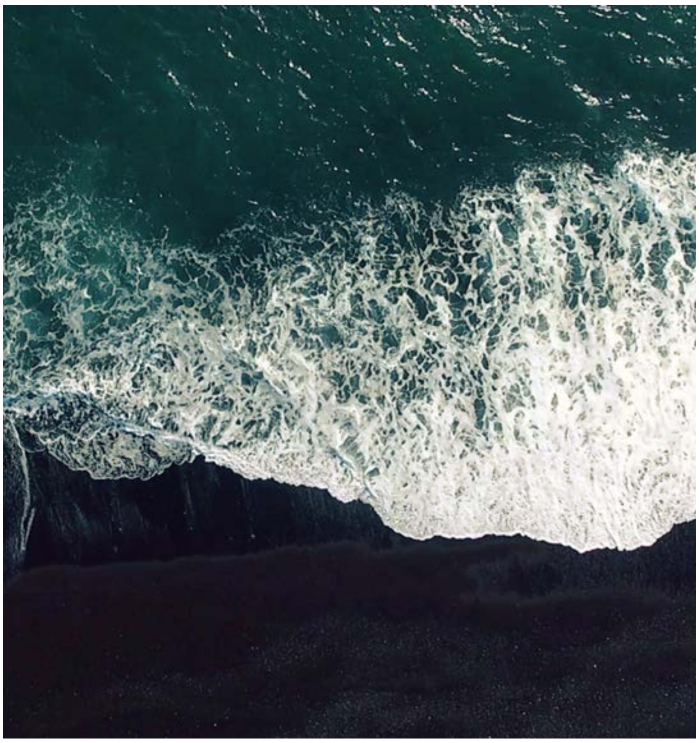
About the Fourth Industrial Revolution for the Earth Initiative

The World Economic Forum is collaborating with PwC as official project adviser and the Stanford Woods Institute for the Environment on a major global initiative on the Fourth Industrial Revolution for the Earth. Working closely with leading issue experts and industry innovators convened through the World Economic Forum's Global Future Council on the Environment and Natural Resource Security, and with support from the MAVA Foundation, this initiative combines the platforms, networks, and convening power of the World Economic Forum and its new Center for the Fourth Industrial Revolution in San Francisco. It also brings Stanford University's Woods Institute for the Environment's researchers and their networks in the technology community together with the global insight and strategic analysis on business, investment and public-sector issues that PwC offers. Together with other interested stakeholders this partnership is exploring how Fourth Industrial Revolution innovations could help drive a systems transformation across the environment and natural resource security agenda.



Annex I
List and description of Fourth Industrial Revolution technology clusters most relevant for environmental applications

Fourth Industrial Revolution technology clusters

The following descriptions are provided as background and are not intended to be exhaustive.[99]

- **3D Printing**. Additive manufacturing techniques used to create three-dimensional objects based on "printing" successive layers of materials.
- **Advanced Materials** (including nanomaterials). A set of nanotechnologies and other material science technologies, which can produce materials with significantly improved or completely new functionality, including lighter weight, stronger, more conductive materials, higher electrical storage (e.g. nanomaterials, biological materials or hybrids).
- **Artificial Intelligence**. Computer science learning algorithms capable of performing tasks that normally require human intelligence and beyond (e.g. visual perception, speech recognition and decision-making).
- **Robotics**. Electro-mechanical, biological and hybrid machines enabled by AI that automate, augment or assist human activities, autonomously or according to set instructions.
- **Drones & autonomous vehicles**. Enabled by robots, autonomous vehicles can operate and navigate with little or no human control. Drones fly or move in water without a pilot and can operate autonomously or be controlled remotely.
- **Biotechnologies**. Encompassing bioengineering, biomedical engineering, genomics, gene editing, and proteomics, biomimicry, and synthetic biology this technology set has applications in areas like energy, material, chemical, pharmaceutical, agricultural and medical industries.
- **Energy capture, storage, and transmission**. New energy technologies range from advanced battery technologies through to intelligent virtual grids, organic solar cells, spray-on solar, liquid biofuels for electricity generation and transport, and nuclear fusion.
- **Blockchain (and distributed ledger)**. Distributed electronic ledger that uses cryptographic software algorithms to record and confirm immutable transactions and/or assets with reliability and anonymity. It has no central authority and allows for automated contracts that relate to those assets and transactions (smart contracts).
- **Geo-engineering**. Large-scale, deliberate interventions in the Earth's natural systems to, for example, shift rainfall patterns, create artificial sunshine or alter biospheres.
- **Internet of things**. A network of advanced sensors and actuators in land, air, oceans and space embedded with software, network connectivity and computer capability, which can collect and exchange data over the internet and enable automated solutions to multiple problem sets.
- **Neurotechnologies**. Technologies that enable humans to influence consciousness and thought through decoding what they are thinking in fine levels of detail through new chemicals that influence brains for enhanced functionality and enable interaction with the world in new ways.
- **New computing technologies**. This includes technologies such as quantum computing, DNA-based solid state hard drives and the combining of Third Industrial Revolution technologies (e.g. big data, cloud) with the other technologies (e.g. IoT, advanced sensor platforms). Quantum computers make direct use of quantum-mechanical phenomena such as entanglement to perform large-scale computation of a particular class of currently impossible tasks by traditional computing approaches.
- **Advanced sensor platforms** (including satellites). Advanced fixed and mobile physical, chemical and biological sensors for direct and indirect (remote sensing) of myriad environmental, natural resource and biological asset variables from fixed locations or in autonomous or semi-autonomous vehicles in land, machines, air, oceans and space.
- **Virtual, augmented and mixed reality**. Computer-generated simulation of a three-dimensional space overlaid to the physical world (AR) or a complete environment (VR).

Annex II
The Fourth Industrial Revolution for the Earth initiative

The Fourth Industrial Revolution for the Earth initiative is designed to raise awareness and accelerate progress across this agenda for the benefit of society. In the first phase of the project, specific environmental focus areas will be considered in depth, exploring in detail how to harness Fourth Industrial Revolution innovations to better manage the world's most pressing environmental challenges. Initial focus areas will include:

– Air pollution
– Biodiversity
– Cities
– Climate change and greenhouse gas monitoring
– Food systems
– Oceans
– Water resources and sanitation

Working from these thematic areas the World Economic Forum, supported by Stanford University and PwC (as project adviser) and advised by the members of the Global Future Councils on the Future of Environment and Natural Resource Security and specific Fourth Industrial Revolution technology clusters, will seek to leverage their various networks and platforms to:

– **Develop a set of insight papers**, taking a deep dive into the possibilities of the Fourth Industrial Revolution and each of these issues.
– **Build new networks of practitioners** and support them to co-design and innovate for action on the environment in each of these issue areas, leveraging the latest technologies and research that the Fourth Industrial Revolution offers.
– Design a **public-private accelerator for action**, enabling both government, foundational, research organization, and commercial funds to be pooled and deployed into scaling innovative Fourth Industrial Revolution solutions for the environment.
– Help government stakeholders to **develop and trial the requisite policy protocols** that will help Fourth Industrial Revolution solutions for the environment to take hold and develop.

The Fourth Industrial Revolution for the Earth initiative will be driven jointly out of the World Economic Forum Center for the Fourth Industrial Revolution in San Francisco and other Forum offices in New York, Geneva and Beijing.

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[99] Descriptions are provided in the context of the Fourth Industrial Revolution for the Earth initiative and were compiled by project partners from commonly available sources.

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