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Fourth Industrial Revolution for the Earth Series

Harnessing Artificial Intelligence for the Earth

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 multistakeholder collaboration.

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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 policymakers, 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 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 looks at artificial intelligence and the Earth.

Foreword

Celine Herweijer
Partner, PwC UK, Innovation and Sustainability Leader

Dominic Waughray
Head of Public-Private Partnership and Member of the Executive Committee, World Economic Forum

The proliferation of artificial intelligence (AI) is having a significant impact on society, changing the way we work, live and interact. AI today is helping the world diagnose diseases and develop clinical pathways. It is also being used to adapt lesson plans for students with different learning needs. Elsewhere, AI is matching individuals' skill sets and aptitudes with job openings. However, as AI acts increasingly more autonomously and becomes broader in its use, AI safety will become even more important. Commonly discussed risks include bias, poor decision-making, low transparency, job losses and malevolent use of AI (e.g. autonomous weaponry).

Developing approaches to guide "human-friendly" AI is arguably one of the biggest unsolved AI problems today. As the scale of the economic and human health impacts from our deteriorating natural environment grows, it is becoming increasingly important to extend the rapidly growing field of AI safety to incorporate "Earth-friendly" AI. As the technology evolves, its direct and indirect applications for the environment will need to be better understood in order to harness the opportunities, while assessing the potential risks and developing approaches for mitigating them. For example, AI could be developed to support the creation of distributed, "off-grid" water and energy resources; to improve climate modelling; or to improve natural disaster resilience planning. Ongoing cooperation among governments, technology developers, investors and civil society will be essential to realizing this vision. As AI is the "electricity" for the Fourth Industrial Revolution, harnessing its potential could help to create sustainable, beneficial outcomes for humanity and the planet we inhabit.

As this report shows, the AI opportunity for the Earth is significant. Today's AI explosion will see us add AI to more and more things every year. The AI itself will also become smarter with each passing year – not only more productive but developing intelligence that humans don't yet have, accelerating human learning and innovation. As we think about the gains, efficiencies and new solutions this creates for nations, business and for everyday life, we must also think about how to maximize the gains for society and our environment at large.

We live in exciting times: it is now possible to tackle some of the world's biggest problems with emerging technologies such as AI. It's time to put AI to work for the planet.

Our planet: The challenge and opportunity

The challenge

There is mounting scientific consensus that Earth systems are under unprecedented stress. The model of human and economic development developed during past industrial revolutions has largely come at the expense of the planet. For 10,000 years, the Earth's relative stability has enabled civilizations to thrive. However, in a short space of time, industrialization has put this stability at risk.

Scientists have identified nine "processes and systems (that) regulate the stability and resilience of the Earth System", and say four of the nine – climate change, loss of biosphere integrity, land-system change and altered cycles in the globe's chemistry – have now crossed "boundary" levels, due to human activity.[1] This elevates the risk that human activities will lead to "deterioration of human well-being in many parts of the world, including wealthy countries".

The United Nations Sustainable Development Goals provide another lens for the challenges facing humanity. Six of the 17 goals apply directly to the environment and humans' influence over it: combating climate change, using ocean and marine resources wisely, managing forests, combating desertification, reversing land degradation, developing sustainable cities and providing clean affordable energy.[2]

This report uses these two lenses to illuminate six critical challenges that demand transformative action in the 21st century:

- **Climate change.** Today's greenhouse gas levels may be the highest in 3 million years.[3] If current Paris Agreement pledges are kept, global average temperatures in 2100 are still expected to be 3°C above pre-industrial levels,[4] well above the targets to avoid the worst impacts of climate change.

- **Biodiversity and conservation.** The Earth is losing its biodiversity at mass extinction rates. One in five species on Earth now faces eradication, and scientists estimate that this will rise to 50% by the end of the century unless we take urgent action.[5] Current deforestation rates in the Amazon Basin could lead to an 8% drop in regional rainfall by 2050, triggering a shift to a "savannah state", with wider consequences for the Earth's atmospheric circulatory systems.[6]

- **Healthy oceans.** The chemistry of the oceans is changing more rapidly than at any time in perhaps 300 million years, as the water absorbs anthropogenic greenhouse gases.[7] The resulting ocean acidification and warming are leading to unprecedented damage to fish stocks and corals.[8]

- **Water security.** By 2030, we may fall 40% short of the amount of fresh water needed to support the global economy[9] as pollution and climate change affect the global water cycle.

- **Clean air.** Around 92% of the world's people live in places that fail to meet World Health Organization (WHO) air quality guidelines.[10] The WHO has reported that around 7 million people die annually from exposure to air pollution – one death out of every eight globally.[11]

- **Weather and disaster resilience.** In 2016 the world suffered 772 geophysical, meteorological, hydrological and climatological "natural loss events" – triple the number in suffered in 1980.[12]

Taken together, these six issues pose an urgent global challenge. As the world's current population of around 7 billion grows to 9.8 billion by 2050, it will increase the demand for food, materials, transport, and energy, further increasing the risk of environmental degradation and affecting human health, livelihoods, and security. Can humanity preserve the planet for future generations?

The opportunity

While these challenges are urgent and unprecedented, they coincide with an era of unprecedented innovation and technological change. The Fourth Industrial Revolution offers unparalleled opportunities to overcome these new challenges.[13]

This industrial revolution, unlike previous ones, is underpinned by the established digital economy and is based on rapid advances in artificial intelligence, the Internet of Things, robots, autonomous vehicles, biotechnology, nanotechnology and quantum computing, among others.[14] It is characterized by the combination of these technologies, which are increasing speed, intelligence and efficiency gains.

This report focuses on AI – the fundamental and most pervasive emerging technology of the Fourth Industrial Revolution. AI is a term for computer systems that can sense their environment, think, learn, and act in response to what they sense and their programmed objectives.

Of all the Fourth Industrial Revolution technologies, AI is expected to have the deepest impact, permeating all industries and playing an increasing role in daily life. By combining with other new technologies, AI is becoming the "electricity" of the Fourth Industrial Revolution, as innovators embed intelligence into more devices, applications and interconnected systems. Beyond productivity gains, AI also promises to enable humans to develop intelligence not yet reached, opening the door to new discoveries.

AI is already transforming traditional industries and everyday lives. New breakthroughs powered by AI often don't work alone but in combination with other Fourth Industrial Revolution technologies.[15] As entrepreneurs, businesses, investors, and governments look to deploy and scale these technologies to create strategic advantage, there are also important opportunities to apply them to today's immediate and pressing Earth challenges and to generate opportunities for today and the future.

AI for the Earth

Although AI presents transformative opportunities to address the Earth's environmental challenges, left unguided, it also has the capability to accelerate the environment's degradation.

The focus of this report is on harnessing AI systems today, and as they evolve, to create maximum positive impact on urgent environmental challenges. It suggests ways in which AI can help transform traditional sectors and systems to address climate change, deliver food and water security, protect biodiversity and bolster human well-being. This concern is tightly linked with the emerging question of how to ensure that AI does not become harmful to human well-being.

To develop "safe" AI, the ultimate goal is to ensure that it becomes value-aligned – that its idea of a good future is aligned with humanity's values, promising safe application of the technology for humankind. In practice, this means that checks and balances developed to ensure that evolving AI systems remain "friendly" must incorporate the health of the natural environment as a fundamental dimension.

The AI revolution

Why now?

The first practical steps towards artificial intelligence were taken in the 1940s. Today, AI is in use in our daily lives and has reached a historical moment because of six converging factors:

– **Big data:** Computers have given us access to vast amounts of data, both structured (in databases and spreadsheets) and unstructured (such as text, audio, video and images). All of this data documents our lives and improves humans' understanding of the world. As trillions of sensors are deployed in appliances, packages, clothing, autonomous vehicles and elsewhere, "big data" will only get bigger. AI-assisted processing of this information allows us to use this data to discover historical patterns, predict more efficiently, make more effective recommendations, and more.

– **Processing power:** Accelerating technologies such as cloud computing and graphics processing units have made it cheaper and faster to handle large volumes of data with complex AI-empowered systems through parallel processing. In the future, "deep learning" chips – a key focus of research today – will push parallel computation further.

– **A connected globe:** Social media platforms have fundamentally changed how individuals interact. This increased connectivity has accelerated the spread of information and encouraged the sharing of knowledge, leading to the emergence of a "collective intelligence", including open-source communities developing AI tools and sharing applications.

– **Open-source software and data:** Open-source software and data are accelerating the democratization and use of AI, as can be seen in the popularity of open-source machine learning standards and platforms such as TensorFlow, Caffe2, PyTorch and Parl.ai. An open-source approach can mean less time spent on routine coding, industry standardization and wider application of emerging AI tools.

– **Improved algorithms:** Researchers have made advances in several aspects of AI, particularly in "deep learning", which involves layers of neural networks, designed in a fashion inspired by the human brain's approach to processing information. Another emerging area of research is "deep reinforcement" in which the AI agent learns with little or no initial input data, by trial and error optimized by a reward function.

– **Accelerating returns:** Competitive pressures have fuelled the rise of AI, as businesses have used improved algorithms and open-source software to boost their competitive advantage and augment their returns through, for example, increasing personalization of consumer products or utilizing intelligent automation to increase their productivity.

The convergence of these factors has helped AI move from *in vitro* (in research labs) to *in vivo* (in everyday lives). Established corporations and start-ups alike can now pioneer AI advances and applications. Indeed, many people are already using AI-infused systems, whether they realize it or not, to navigate cities, shop online, find entertainment recommendations, filter out unwanted emails or share a journey to work.

AI is already here, then, and many corporate executives perceive its potential value. In a 2017 PwC survey of global executives, 54% reported making substantial investments in AI, while a lack of digital skills remains an important concern.[16] As organizations continue to invest in tools, data optimization, people, and AI-enabled innovations, the realized values are expected to take off: growing from $1.4 billion in annual revenue from AI-enabled systems in 2016 to $59.8 billion by 2025, according to one research study.[17]

AI capabilities: past, present and future

The spectrum of AI is also expanding and now includes:

– **Automated intelligence** systems that take repeated, labour-intensive tasks requiring intelligence, and automatically complete them. For example, a robot that can learn to sort recycled household materials.

– **Assisted intelligence** systems that review and reveal patterns in historical data, such as unstructured social-media posts, and help people perform tasks more quickly and better by using the information gleaned. For example, techniques such as deep learning, natural language processing and anomaly detection can uncover leading indicators of hurricanes and other major weather events.

– **Augmented intelligence** systems that use AI to help people understand and predict an uncertain future. For example, AI-enabled management simulators can help examine scenarios involving climate policy and greenhouse gas emissions, as pioneered by MIT's John Sterman.[18]

– **Autonomous intelligence** systems that automate decision-making without human intervention. For example, systems that can identify patterns of high demand and high cost in home heating, adapting usage automatically to save a homeowner money.

Research on AI algorithms has been moving quickly, especially since big data has been combined with statistical machine-learning algorithms.

Narrow, task-driven AI techniques, already important in many industrial applications, are now working with big data to allow pattern recognition in unstructured text and images. The potential of deep learning using neural network architecture continues to grow – as computers become faster and big data becomes ever more prevalent – enhancing performance in fields such as language translation and autonomous cars.

The latest advances in unsupervised deep reinforcement learning, from DeepMind's AlphaGo Zero research, show that in certain situations AI can be surprisingly powerful even without input data or labels.[19] In situations where the boundary conditions are known, reinforcement learning needs substantially less time and computer processing power than older methods. This research also developed an intelligence that was new to humans, accelerating the natural selection cycles of intelligence, but in machines. To date, reinforcement learning has been primarily used for AI gaming agents, but should also help in corporate strategic analysis, process optimization and many other domains where the rules and different states of play are well known. However, this is often not true for many systems encountered in the real world and a central research priority is to identify the real-world systems where reinforcement learning would be most useful.

Experts expect that supervised and unsupervised learning techniques will become increasingly blended and that such hybrid techniques will open the way for human-machine collaborative learning and for AI to develop more advanced, human-like, capabilities.

Progress in AI may accelerate as new techniques are developed to overcome existing challenges with machine learning (deep learning in particular) and to solve problems in the field. Two such techniques are synthetic data creation and transfer learning (transferring the model learnt from a task in a certain domain and applying it to a related problem in that domain). Both of these enable AI to "learn" more quickly, tackling a wider range of problems (particularly those for which there is less historical data available).

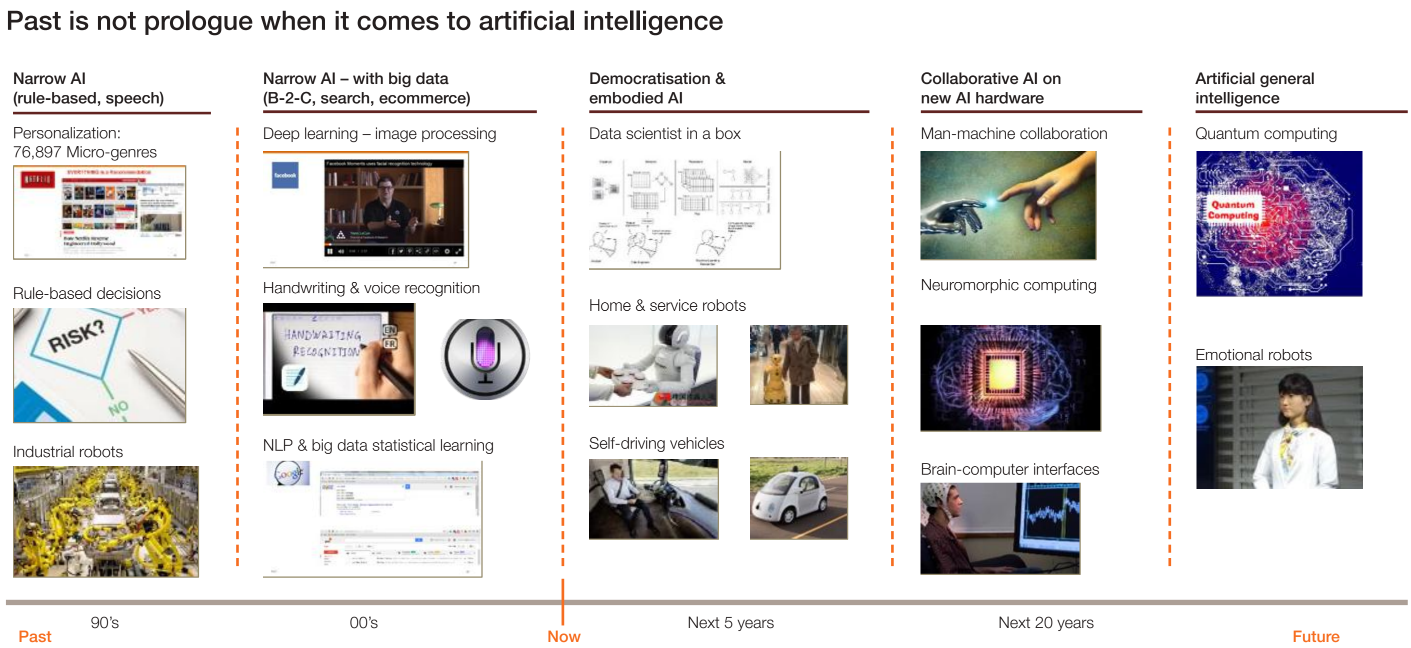
In addition, the shift towards 'Explainable AI', which aims to create a suite of machine learning techniques that produce more explainable models whilst maintaining high performance levels, will facilitate wider adoption of machine learning techniques and potentially become best practice or even inform regulatory requirements.

Ultimately, all this culminates in the quest for artificial general intelligence (AGI), at which point, the AI begins to master reasoning, abstraction, communication and the formulation and understanding of knowledge. Here the critical need for progress in AI safety becomes fully apparent. This will involve the development of algorithms with safety considerations at their core.

Future advances in AI will need advanced computing power (currently it takes around 83,000 processors operating for 40 minutes to run the equivalent of one second of computations performed by just 1 percent of the human brain),[20] so advances in quantum computing, distributed computing and deep-learning chips will be essential. In addition, further understanding of advanced cognitive and emotional tasks will help bring about new applications.

Figure 1: Timeline of AI developments

Source: PwC



The AI opportunity for our environment

The most important consideration in the development of AI is, arguably, to ensure that it benefits humanity, which includes being both “human-friendly” and “Earth-friendly”.

Figure 2 highlights priorities for six of the world’s most pressing environmental challenges and the priority action areas for successfully addressing them:

Figure 2: Priority action areas for addressing Earth challenge areas

Source: PwC

Climate change

- Clean power
- Smart transport options
- Sustainable production and consumption
- Sustainable land-use
- Smart cities and homes

Biodiversity and conservation

- Habitat protection and restoration
- Sustainable trade
- Pollution control
- Invasive species and disease control
- Realizing natural capital

Healthy Oceans

- Fishing sustainably
- Preventing pollution
- Protecting habitats
- Protecting species
- Impacts from climate change (including acidification)

Water security

- Water supply
- Catchment control
- Water efficiency
- Adequate sanitation
- Drought planning

Clean air

- Filtering and capture
- Monitoring and prevention
- Early warning
- Clean fuels
- Real-time, integrated, adaptive urban management

Weather and disaster resilience

- Prediction and forecasting
- Early warning systems
- Resilient infrastructure
- Financial instruments
- Resilience planning

In meeting these challenges, there is wide scope for innovation and investment. AI in particular has immense potential to help unlock solutions. Indeed, an accompanying Technical Annex: Overview of AI Applications for Solving Environmental Challenges provides a summary of research into more than 80 existing AI use cases for the environment.

Figure 3 provides a glimpse of such AI applications by environmental challenge area. Currently, most of these focus on automated and assisted intelligence to unlock value from large unstructured real-time datasets. Future applications will likely involve more systems propelled by autonomous decision-making where AI acts independently, thus creating new opportunities and risks. The challenge for innovators, investors and governments is to identify and scale these pioneering innovations, and also to make sustainability considerations central to wider AI development and usage.

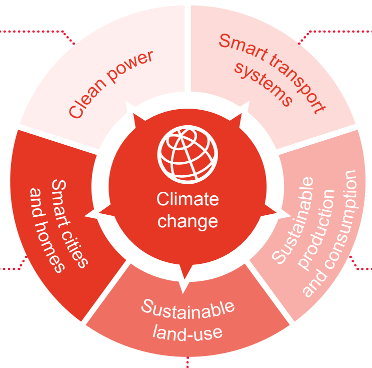
Figure 3: AI applications by challenge area

Source: PwC

Climate change

- Optimised energy system forecasting
- Smart grids for electricity use
- Predict solar flares for protecting power grids
- Renewable energy plant assessments
- Optimised decentralised & peer-to-peer renewable energy systems
- Optimised virtual power plants

- Smart traffic light & parking systems for urban mobility management
- Optimised sustainable building design
- Energy-efficient building management systems
- Auditory responsive lighting & heating
- Optimised urban-level energy generation and use
- Analytics & automation for smart urban planning



- On-demand shared transport mobility
- AI-enabled electric cars
- Autonomous vehicles for efficient transport
- Vehicle to infrastructure communication and optimisation
- Optimised traffic flows
- Integrated cost-efficient transport systems
- Demand-response charging infrastructure

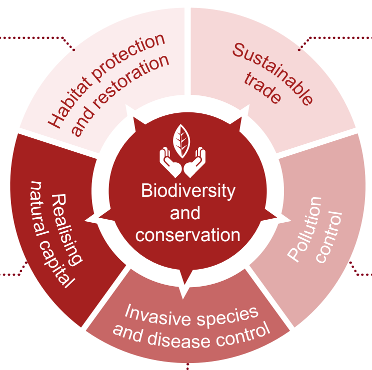
- Supply chain monitoring and transparency
- Active optimisation of industrial machinery & manufacturing
- Digital twins for lifespan performance optimisation
- Smarter fresh-food replenishment
- Smart recycling systems
- Integrated municipal & industrial waste management

- Early crop yield prediction
- Precision agriculture & nutrition
- Hyper-local weather forecasting for crop management
- Early detection of crop issues
- Automated & enhanced land-use change detection for avoided deforestation
- Monitoring health & well-being in livestock farming

Biodiversity and conservation

- Precision monitoring of ecosystems
- Bird habitat and migration pattern prediction
- Simulation of animal and habitat interaction
- Habitat loss detection and monitoring
- Micro drones for pollination
- Optimised breeding of plants

- Register & trading of biological & biomimetic assets
- Plant species identification
- Machine-automated land-use detection linked to ecosystem payments



- Detection of unauthorised animal capture
- Image-based detection of illegal wildlife trade
- Poacher route prediction and high risk animal tracking
- Food value chain optimisation
- Supply-chain monitoring & origin tracking

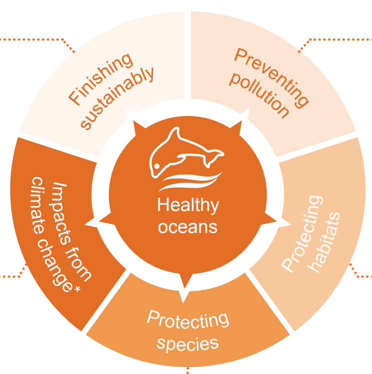
- Pollutant dispersal prediction and tracking
- Analysis of urban runoff quality issues

- Machine-automated biodiversity analysis
- Smart mosquito traps
- Plant disease identification & detection

Healthy oceans

- Overfishing prevention and control
- Automated fish catch thresholds
- Insights for fishermen
- Aquaculture monitoring
- Monitoring & detection of illegal fishing activities
- Optimising patrol schedules

- Real-time monitoring of ocean temperature and pH
- Phytoplankton distribution detection and prediction
- Monitoring of ocean currents
- Monitoring of coral reef ecosystems



- Marine litter prediction
- Robotic fish to fight pollution
- Real-time monitoring of pollution levels

- Monitoring marine habitats for change (e.g. marine dead zones)
- Habitat conservation assessments
- Coral reef mapping
- Autonomous vehicle deep sea assessments

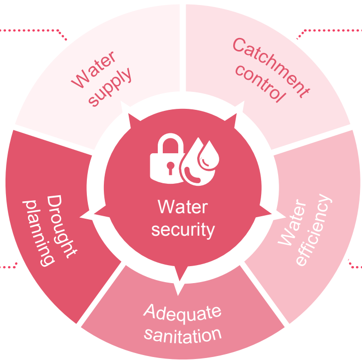
- Monitoring location and quantities of ocean species
- Predicting the spread of invasive species
- Monitoring & prevention of illegal trafficking of marine wildlife
- Drones & AI to analyse whale health

**including acidification*

Water security

- Water supply monitoring and management
- Water quality simulation & data alerts
- Self-adaptive water filtration
- Asset maintenance on critical water and wastewater expenditures

- Harmful algal blooms detection and monitoring
- Streamflow forecasting
- Automated flood centred infrastructure



- Drought prediction
- Simulations for drought planning
- Drought impact assessments

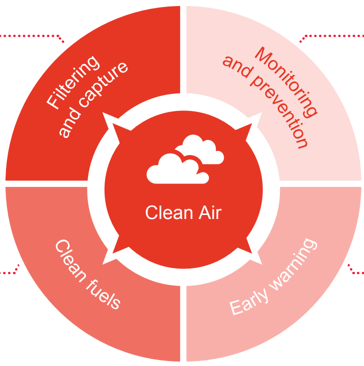
- Residential water use monitoring and management
- Optimisation of industrial water use
- Predictive maintenance of water plants
- Early warning system for water infrastructure
- Detect underground leaks in potable water supply systems
- Smart meters in homes

- Drones and AI for real-time monitoring of river quality
- Ensuring adequate sanitation of water reserves
- Real-time monitoring and management of household water supply

Clean air

- Optimised sensor-based air purifying systems
- Carbon capture, sequestration and use

- Real-time air pollution monitoring & simulations
- Air pollutant source detection



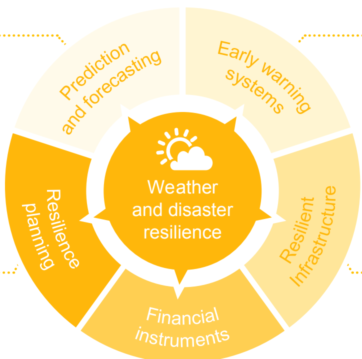
- Advanced battery and fuel-cell design
- Advanced battery components
- Pollution forecasting for transport management

- 2-10 day pollution level forecasting
- Air quality alerts

Weather and disaster resilience

- Extreme weather event modelling and prediction
- Weather-forecast-informed flight paths
- Climate informatics for enhanced climate modelling

- Natural catastrophe early warning
- Social media enabled disaster response
- Real-time communication of natural disasters



- Impact & risk mitigation analytics
- Emergency risk communication
- Real-time disaster risk mapping
- Real-time disaster response coordination

- Automated mitigation of flood risk
- Building-specific earthquake damage prediction
- Disaster-ready urban infrastructure and buildings

- Rapid, multi-source risk analysis
- Analytics for financial parametric risk instruments
- Analytics for claims analysis

AI game changers for the Earth

In addition to enhancing current efforts to address environmental issues, there is enormous potential to create AI-enabled "game changers" in which the application of AI, often in combination with other Fourth Industrial Revolution technologies, has the potential to deliver transformative solutions.

The following set of potential game changers are defined by five key features:

1. Transformational impact (i.e. it could completely disrupt or alter current approaches)
2. Adoption potential (i.e. the potential population size is significant)
3. Centrality of AI to the solution (i.e. AI is a key cog in the solution)
4. Systems impact (i.e. the game changer could really shift the dial across human systems)
5. Realizable enabling environment, including political and social dynamics (i.e. the enabling environment can be identified and supported)

Some such possible game changers are listed individually below. But often, cross-sectoral combinations of these game changes offer the greatest potential to fundamentally transform human systems. Autonomous electric vehicles, for example, could work in combination with distributed-energy grids, so that the charging stations, and thus the vehicles, are fed by a decentralized and optimized renewable-energy grid and ultimately become sources in this grid themselves.

Emerging AI game changers

1. Autonomous and connected electric vehicles

AI will be vital in the widespread transition to autonomous connected electric vehicles (EVs), which will ultimately transform short-haul mobility while reducing greenhouse gas emissions and delivering cleaner air. Machine-learning-enabled autonomous electric vehicles will improve the efficiency of transport networks as connected vehicles communicate with one another and with transport infrastructure to identify hazards while optimizing navigation and network efficiency. EV charging will become more affordable via demand-response software programs enabled by big data (such as Auto Grid). Clean, smart, connected and increasingly autonomous and shared short-haul transport will combine AI with other Fourth Industrial Revolution technologies, notably the Internet of Things, drones and advanced materials (in battery breakthroughs, for example).

Increased demand for transport could offset some efficiency gains, but overall a smart transport system enabled by AI can be expected to lower emissions. Improved efficiency may also encourage car sharing and reduce car ownership, further reducing emissions from manufacturing and operating vehicles.

Still, the transition to connected autonomous fleets in cities will be gradual and will vary from country to country. It may be decades before fully autonomous urban fleets are the norm. In addition to developing the technology, challenges related to public acceptance, legal and insurance liability questions, and the provision of charging infrastructure will need to be addressed. Furthermore, the vehicle replacement cycle takes approximately 15– 20 years.

While full "Level 5" vehicle autonomy (with no human intervention at all) may still be decades away, "Level 4" AVs (highly automated, but with driver takeover when needed) may be tested on roads as early as 2021. At this level, cars can drive in cities and provide mobility-on-demand services. More substantial emission-reduction benefits also begin to appear.

2. Distributed energy grids

In the energy grid, the application of machine learning, including deep learning, is increasingly widespread in industry. For the environment, the use of AI to make distributed energy possible at scale is critical for decarbonizing the power grid, expanding the use of (and market for) renewables and increasing energy efficiency. AI can enhance the predictability of demand and supply for renewables, improve energy storage and load management, assist in the integration and reliability of renewables and enable dynamic pricing and trading, creating market incentives. AI-capable "virtual power plants" (VPPs) can integrate, aggregate, and optimize the use of solar panels, microgrids, energy storage installations and other facilities. Distributed energy grids may also be extended to incorporate new sources such as solar spray or paint-coated infrastructure of vehicles, and to allow AI-enabled "solar roads" to expand, connect and optimize the grid further. In solar roads, for example, AI could allow a road to learn to heat up to melt snow, or to adjust traffic lanes based on vehicle flow.

Smart grids will also use other Fourth Industrial Revolution technologies, including the Internet of Things, blockchain (for peer-to-peer energy trading) and advanced materials (to increase the number of distributed sources and optimize energy storage).

All of this will require sufficient regulation to assure the security and integrity of the software, ownership and control of intellectual property rights (which may help unlock investment and innovation), management of, and responsibility for, operational elements that are powered by machine learning, and regulatory frameworks for transferring and trading energy, often virtually. As economies and settlements move away from "heavy infrastructure" towards "smart" infrastructure with a low environmental footprint, the decentralized nature of distributed energy grids mean they have the potential to be used globally.

3. Smart agriculture

Precision agriculture (including precision nutrition) is expected to increasingly involve automated data collection and decision-making at the farm level – for example to plant, spray and harvest crops optimally, to allow early detection of crop diseases and issues, to provide timed nutrition to livestock, and generally to optimize agricultural inputs and returns. This promises to increase the resource efficiency of the agriculture industry, lowering the use of water, fertilizers and pesticides, which are creating runoff that currently finds its way into rivers, oceans and insect populations, causing damage to important ecosystems.

Here the key Fourth Industrial Revolution technologies that will combine with AI include robot labour (such as Blue River[21] products and core intelligence chatbots), drones, synthetic biology (in crop genome analysis, for example) and advanced materials. Machine and deep learning will also work in tandem with the Internet of Things and with drones. Sensors measuring conditions such as crop moisture, temperature and soil composition will give AI the data needed to automatically optimize production and trigger important actions such as adding moisture.[22] Drones are increasingly being used to monitor conditions and communicate with the sensors and AI-enabled systems.[23]

Regulation of data ownership, pricing algorithms for commodity goods and cross-border data flows will need to keep pace with these fast-growing technological advances. "Smart agriculture" has the potential to fundamentally change agriculture even more than 20th century mass-farming methods did. And these changes may spread more rapidly than previous ones.

4. Weather forecasting and climate modelling

A new field of "Climate Informatics" is already blossoming, harnessing AI to fundamentally transform weather forecasting (including prediction of extreme events) and to improve understanding of the effects of climate change.[24] This is promising because the weather and climate-science community already has large amounts of data and continues to collect more, providing a fine test bed for machine and deep learning applications. Until now, use of these frequently updated datasets has demanded substantial high-performance computing power and limited the accessibility and usability for the scientific and decision-making communities. AI can solve these challenges, increasing both the performance of weather and climate modelling, and making it more accessible and usable for decision-making.

Public agencies including the UK Met Office and NASA, and private-sector actors such as IBM and Microsoft, are using AI and machine learning to enhance the performance and efficiency of weather and climate models.[25] These models process complicated physical equations – including fluid dynamics for the atmosphere and oceans – and heuristics for elements that can't be fully resolved (for example, aspects of atmospheric chemistry such as ice particles turning to water). The complexity of the governing equations requires expensive, energy-intensive computing, but deep-learning networks can emulate some aspects of these climate simulations, allowing computers to run much faster and incorporate more complexity of the 'real-world' system into the calculations. AI techniques may also help correct biases in models, extracting the most relevant data to avoid data degradation and otherwise improve computational efficiency. In all of these cases, AI, with human oversight, "supervises" to improve simulations. Over time, cheaper, faster weather and climate models unlocked through AI could reduce the need for energy-hungry supercomputers, lower the cost of research and open the field of weather and climate science to many more researchers.

Wider AI applications include simpler machine-learning techniques, combining weather models and ancillary impacts data, to help predict the effects of small-scale extreme weather events (such as windstorms and floods) on human systems, allowing better risk management. More broadly, however, the application of nascent deep reinforcement learning techniques is unchartered territory for climate and weather science. Investigation will be needed to identify the real-world physical systems in which these new tools will be most useful.

We are already seeing how better weather and climate data helps decision-makers from the public and private sectors to improve climate resilience. The UK Met Office, for example, has developed a chatbot application to demonstrate how "frictionless" data or queries can be extracted from complex big datasets, using sophisticated AI in real time and communicating to the user through a simple interface. Another example involves artificial assistants, fed by forecasts data, that can help make everyday decisions, from what to wear to when to travel.

Some companies are already working together, and with universities and government agencies, within the field of climate informatics. There is now an opportunity to formalize, organize and promote the emerging scientific discipline of AI for weather and climate science, including international coordination (for example, through the World Meteorological Organization and the Intergovernmental Panel on Climate Change), dedicated national R&D funding and cross-industry collaboration.

5. A community disaster-response data and analytics platform

The speed and effectiveness with which organizations and people can *respond* to disasters has a substantial impact on the extent of economic losses and human suffering, particularly in the most catastrophic events. But delays often occur due to a lack of information, analytical insight and awareness of the best course of action. Often the necessary data exists in large part, but is segregated among various organizations and is thus mostly inaccessible to communities.

Better resiliency planning is also an important component to mitigate the damage of future natural catastrophes. AI can be used to sort through multidimensional data about a region and identify which aspects have the biggest impact on resilience. AI can run and analyse simulations of different weather events and disasters in a region to seek out vulnerabilities and identify the resiliency plans that are most robust across a range of event types.

New hybrid systems of rules and tools can use data and AI techniques to build a "Community Distributed Data Escrow" system that could enhance disaster preparation and response through coordination of emergency information capabilities.[26] When a disaster strikes, predefined uses of data would be activated to equip first responders with better tools for understanding the local context and take precise action. For example, machine learning combined with natural language processing algorithms could identify the best station points and routes for distribution and evacuation, the amount of relief required and optimal relief-effort timetables. Here AI would work in combination with other Fourth Industrial Revolution technologies including drones and the Internet of Things. Deep reinforcement learning may one day be integrated into disaster simulations to determine optimal response strategies, similar to the way AI is currently being used to identify the best move in games like AlphaGo.

Harnessing AI to provide better disaster response and planning will require public-private partnerships. A community of technical, legal and accounting experts, for example, would need to specify key datasets and standardize approaches, define methodologies for leveraging APIs and machine learning tools to access vital data securely and accountably, and establish the terms and conditions for stakeholders to operate within the system.

6. Decentralized water

Machine and deep learning could enable a step-change in the optimization of water-resource management. Increasingly, AI has the potential to create distributed "off-grid" water resources, analogous to decentralized energy systems.

Household smart meters can produce large volumes of data that can be used to predict water flows, spot inconsistencies and check leaks. The next stage will be to combine machine learning, the Internet of Things and blockchain to create a truly decentralized water system, where local resources and closed-loop water recycling gain value. Water resources could even be traded via blockchain.

Furthermore, machine learning, predictive modelling and robotics can be combined to transform current approaches to building and managing water infrastructure and to accelerate innovation in environmental engineering. Rivers, for example, could be engineered to autonomously adjust their own sediment flows. Coupled with AI-informed pricing, such approaches could optimize water usage and drive behaviour change by providing incentives for water conservation.

7. AI-designed intelligent, connected and liveable cities

Beyond autonomous vehicles, deep learning also promises better urban planning, leading to resilient, human-centric cities with minimal air pollution and environmental impact. AI could also be used to simulate and automate the generation of zoning laws, building ordinances and floodplains. Combined with AR and VR, AI-generated data could be used by city planners and infrastructure investors, along with officials responsible for ensuring disaster preparedness and, when needed, reconstruction.

AI, smart meters and the Internet of Things can also help forecast and optimize urban energy generation and demand – both city-wide and at the level of individual homes and buildings. Real-time AI-optimized energy efficiency can have an immediate and substantial impact on energy consumption (Google, for example, cut power use in its data centres by 40% by using DeepMind's reinforcement learning algorithms to optimize cooling.[27]) AI-enabled smart grids will also be critical for fast-growing emerging cities, and are in fact already being piloted, from Brazil to the Philippines.

Combining real-time city-wide data on energy and water consumption and availability, traffic flows, people flows, and weather could create an "urban dashboard". With the addition of AI this could optimize water and energy use across the city, potentially reducing the need for costly additional infrastructure while reducing pollution and congestion – thereby reducing the city's environmental footprint and increasing its liveability.

8. Oceans data platform

Real-time monitoring with AI can improve decision-making in fields ranging from species management and protection to natural resource management to climate resilience. One early example is the Ocean Data Alliance,[28] which has started to work together to develop and implement open-source solutions to provide the data needed for comprehensive monitoring of ocean resources, from satellites to data from ocean exploration technologies. Developed fully, this approach could allow decision-makers to use machine learning to monitor, predict and respond to changing conditions such as illegal fishing, a disease outbreak or a coral-bleaching event.

New processing capabilities could provide close-to-real-time transparency by enabling authorities, and even the general public, to monitor fishing, shipping, ocean mining and other activities. Vessel algorithmic patterns could identify illegal fishing, biological sensors could monitor the health of coral reefs and ocean current patterns could improve weather forecasting.

One of the main challenges to realizing such a platform is the processing power required: ocean modelling is second only to astrophysics in its hunger for computing power. But as the cost of data storage and processing declines, new possibilities to model human activities and how they impact our oceans will become available. To prevent the emergence of multiple competing platforms, which could reduce effectiveness and increase the overall costs of collecting, managing, and using ocean data, an open-access platform could be created that enables data from different sources to continually be uploaded in a standardized format. Public-private partnerships may be needed to ensure trust, governance and accuracy.

9. Earth bank of codes

Bio-inspired innovations (such as blood-pressure medication derived from viper venom) aim to replicate nature's products and processes. Historically, the revenues from such activities have not been shared with the indigenous and traditional communities from which the knowledge comes. For the first time in history, the fair sharing of benefits and a significant new stream of conservation finance is now possible using a combination of blockchain, artificial intelligence, advanced sensors and the Internet of Things.

The Amazon Third Way initiative[29] is developing the Earth Bank of Codes (EBC), a project to create an open, global public-good digital platform that registers nature's assets, recording their spatial and temporal provenance and codifying the associated rights and obligations. (This helps to implement the Nagoya Protocol of the Convention on Biological Diversity.) A fusion of AI and complex systems analytics will be vital to bundling the biological, biomimetic and traditional-knowledge assets from a biodiversity hotspot to maximize economic and conservation value simultaneously. In addition, an AI-driven "biological search engine" will allow users to understand more fully the planet's web of life, which could optimize scientific discovery, catalyse a myriad of bio-inspired innovations and improve conservation outcomes by creating new sources of economic value. AI techniques will include natural language processing, deep learning, computer vision, probabilistic programming and an array of statistical machine-learning techniques.

This project is building a coalition of willing stakeholders to co-design and co-implement the EBC in the Amazon Basin (called the Amazon Bank of Codes[30]) before replicating and scaling in other biomes on land and in the oceans.

Further-off AI game changers

By the 2030s, further advances in AI and other Fourth Industrial Revolution technologies may bring us more innovations for the environment. These could include:

1. A real-time digital dashboard of the Earth

A real-time, open API digital geospatial dashboard for the planet would enable the monitoring, modelling and management of environmental systems at a scale and speed never before possible – from tackling illegal deforestation, water extraction, fishing and poaching to air pollution, natural disaster response and smart agriculture. We have the AI methods to do this, but we need more information, more frequently received and at greater resolution than at present. The challenge is to build something truly transformational, easy to use in real-time, open-access and data-dense (meaning that the information is high-resolution, scalable and aggregates environmental and human exposure data). This will require collaboration among entrepreneurs, industry, government and the non-profit sector.

Public and private systems that can help amass the necessary data include the European Space Agency's Copernicus,[31] NASA's Earth Observing System and the private companies Planet, Digital Globe and Orbital Insights. These organizations can provide comprehensive Earth observation from space. However, this data would need to be aggregated and retrieved in context, which requires tools to extract and label the relevant information. AI can help tackle this challenge as we build a dashboard with usable data, including both environmental- and hazard-data layers, along with exposure layers. The implications for natural-resource management (including investment, policy-making and dispute settlement) could be profound.

At least two steps are already being taken in this direction. The US National Science Foundation's EarthCube initiative uses machine learning and simulation modelling to create a 3D living model of the entire planet. And the US company Planet has put over 180 micro-satellites into orbit, to image the whole planet's landmass daily, at a resolution of 3–5 metres.[32] Platforms like this one could bring a breakthrough: Planet plans to incorporate computer vision developments and machine learning to make an index of the planet, tracked over time. Crucially, it is developing practical ways to extract data and is collaborating with NGOs and governments to develop public-good analytics for Earth-systems management.

2. Autonomous farming and end-to-end optimized food system

AI could enable farms to become almost fully autonomous. Farmers may be able to grow different crops symbiotically, using AI to spot or predict problems and to take appropriate corrective actions via robotics. For example, should a corn crop be seen to need a booster dose of nitrogen, an AI-enabled system could deliver the nutrients. AI-augmented farms could also automatically adjust crop quantities, based on supply and demand data. This kind of production could be more resilient to earth cycles.

Our understanding of human dietary needs is likely to improve in the coming decades, as we learn how individuals process their food intake, based on data from many individual bodies. Applying machine learning to this data could generate personalized nutrition plans optimized for individuals. When combined with autonomous farming, autonomous delivery vehicles, in-house robotic chefs and in-house vertical farming, entire food supply chains could be optimized and transformed, creating minimum-waste supply chains while providing high yields. The same principles could also be applied to livestock.

3. Reinforcement learning for natural sciences breakthroughs

Deep reinforcement learning could evolve to enable its application to real-world problems, including solving problems addressed by Earth scientists. This could enable scientific progress and discovery in scientific areas where the boundary conditions of a system are known but input data is lacking, and/or the complexity of a system is such that it requires access to currently infeasible computing architecture.

Technically, step one is to understand what the optimal "real world" natural and human-natural systems are, in which we can most fully define the boundary conditions, to enable the application of reinforcement learning. A hybrid approach that combines supervised and unsupervised learning will likely be most successful, given the challenges of fully defining the boundary conditions of real world problems. Understanding which real world systems can be codified and optimizing for reinforcement learning will require collaboration between AI pioneers and domain experts including climate scientists, materials scientists, biologists, and engineers. For example, DeepMind co-founder, Demis Hassabis, has suggested that, in the materials science space, a descendant of AlphaGo Zero could be used to search for a room temperature superconductor — a hypothetical substance that allows electrical current to flow with zero lost energy, further allowing for incredibly efficient power systems. As was done with Go, the algorithm would start by combining different inputs (in this case, the atomic composition of various materials and their associated qualities) until it discovers something the humans had missed.

4. Quantum and distributed computing to dramatically scale computational power for AI for the Earth

Instead of using brute force to increase the computing power of AI, innovators are increasingly exploring other advances such as deep learning chips, harnessing the move to cloud, and the ability to use distributed computing and quantum computing. All of these advances that increase computing processing power will enable large scale optimization of big data analytics and AI, scaling and transforming their application and impact for environmental challenges. But advances in quantum computing, in parallel, could offer fundamentally new opportunities for scientific discovery. Classical computers cannot compute things the way nature does (which operates in quantum mechanics); they are limited to the human made binary code (of zeros and ones) rather than the natural reality of continuous variables. In other words, with classical computers we are currently modelling the Earth system in a way that it does not actually function. Quantum computers open the door to solving the quantum problems as they exist in nature and discovering ways in which the Earth system really works: from key applications in quantum chemistry, to quantum physics and mechanics. This could lead to the discovery of new advanced materials, new biological processes (e.g. energy transference, cellular growth, or ecosystem dynamics), and progress in the modelling of planetary physics.

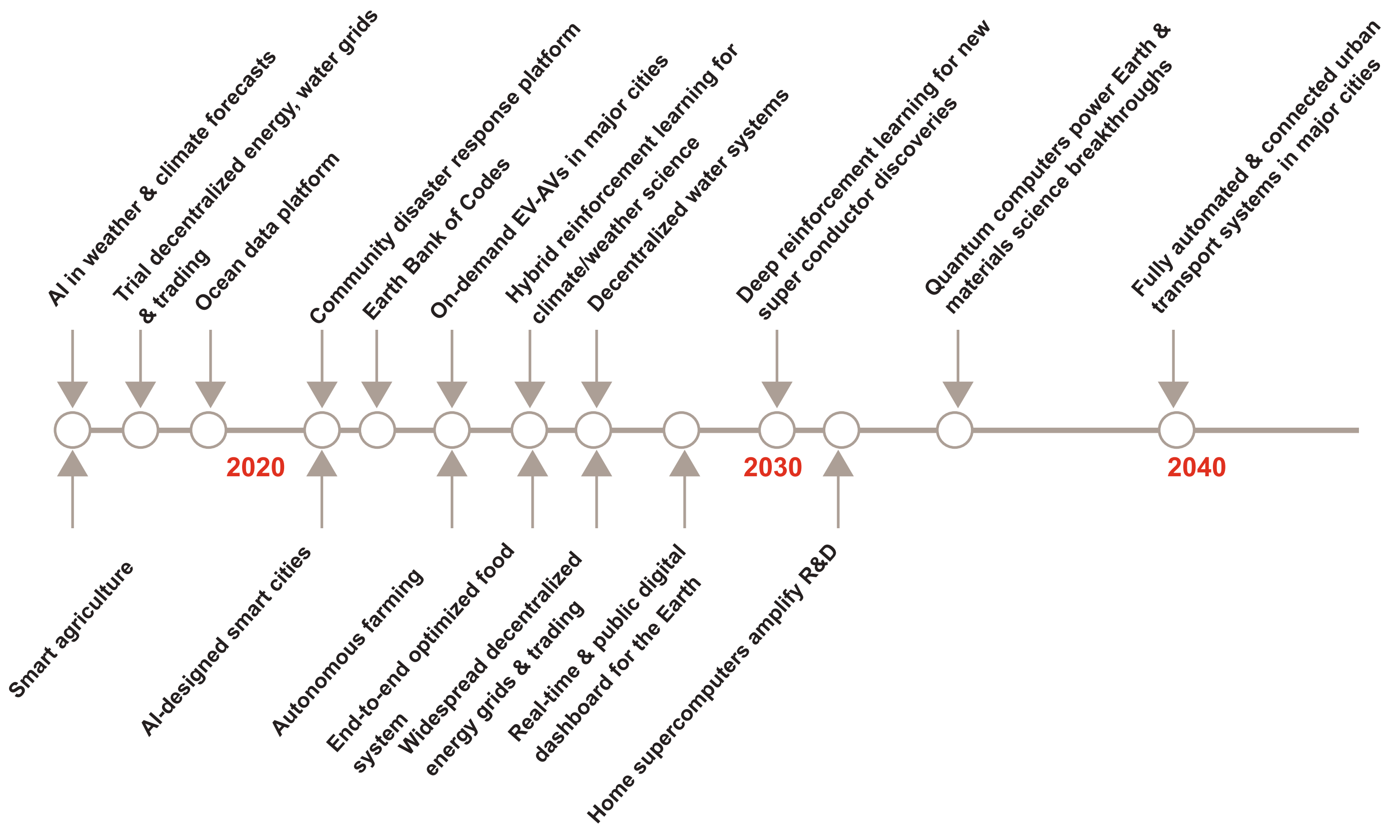
5. The home supercomputer and AI research assistants for democratized scientific progress

Earth science is currently one of the most computational heavy fields of scientific discovery – with supercomputing systems currently in widespread use across the field and climate researches using some of the largest and most powerful systems available today. The cost of building, accessing and running supercomputers inhibits access to researchers and limits the pace at which new modelling and research can be undertaken. Over the coming decade or two, computational power and advances in AI algorithms will likely reach a point in which the average home computer will have as much power as today's supercomputers.

In parallel, machine learning more broadly will also unlock faster and cheaper earth system and climate models, and AI will begin to replace many of the labour-intensive and time-consuming tasks that scientists now do (e.g., trawling through data archives, converting files) – acting in effect as an 'AI research assistant'. The result is that the pool of scientists and practitioners that have access to computing power and AI tools could increase vastly, progress in Earth science and its application could become democratized, and scientific productivity could be substantially boosted with a subsequent acceleration in discoveries. Again these could include breakthroughs in understanding of weather risk, future regional and local climate impacts, and more challenging areas including climate feedback loops and tipping points.

Figure 4: AI for the Earth game changers: Indicative timeline

Source: PwC



AI unguided: Unintended consequences for the Earth

For all the enormous potential AI offers for building a sustainable planet for future generations, it also poses short- and long-term risks. These can be divided, broadly speaking, into six categories with varying impacts on individuals, organizations, society, and the earth.

Figure 5: Artificial Intelligence risks

Source: PwC

1 Performance risks
- Risk of errors
- Risk of bias
- Risk of opaqueness or "black box" risk
- Risk of explainability
- Risk of stability of performance

2 Security risks
- Cyber intrusion risks
- Privacy risks
- Open-source software risks

3 Control risks
- Risk of AI going "rogue"
- Inability to control malevolent AI

4 Ethical risks
- "Lack of values" risk
- Value alignment risk
- Goal alignment risk

5 Economic risks
- Job-displacement risks
- "Winner-takes-all" concentration of power risk
- Liability risk
- Reputation risk

6 Societal risks
- Risk of autonomous weapons proliferation
- Risk of "intelligence divide"

Performance risks
For the most part, the outputs of AI systems are determined within a "black box'" and with little transparency, these outputs may not be trusted. By their nature, AI algorithms (which are self-learning and continuously adapting) are difficult to explain and in many cases may not be explainable to humans at all. An inability to understand the rationale behind AI outputs also makes it difficult to ascertain whether the performance or outputs of AI algorithms are accurate or desirable. Significant risks are therefore conceivable. The emerging field of explainable AI (XAI) research aims to create new AI methods that are accountable to human reasoning. But this field is still in its early days. Meanwhile, ongoing research aims to reduce "model bias" resulting from biases in training data, and to increase the stability of model performance. As AI solutions are deployed, one unintended consequence is the over-reliance on AI algorithms with variable performance. It is essential that humans stay "in the loop" on auditing algorithm outputs to mitigate these unintended biases and wider performance risks.

Example: Early-warning systems for natural disasters such as flooding are trained using historical data on weather patterns. However, if there is a lack of understanding of factors driving model predictions due to poor explainability, there is a significant risk of false alarms or false negatives, particularly in situations that are not represented in the data used to train the AI model.[33]

Security risks
Misuse of AI via hacking is a serious risk, as many algorithms being developed with good intentions (for example, for autonomous vehicles) could be repurposed for harm (for example, for autonomous weaponry). This raises new risks for global safety. Good governance is required to build explainability, transparency and validity into the algorithms, including drawing lines between beneficial and harmful AI. Machine-learning (especially deep-learning) models can also be duped by malicious inputs known as "adversarial attacks". For example, it is possible to find input data combinations that can trigger perverse outputs from machine-learning models, in effect hacking them.

Example: Hackers could access automated warning systems, distributed energy grids or connected autonomous transport platforms, and cause regional disruptions. Appropriate governance will be required to ensure human and earth-friendly AI and prevent misuse. Misuse of AI could also occur when systems fall into the wrong hands. For example, poachers could profit from AI-enabled endangered-animal tracking tools meant for conservation efforts.

Control risks

AI systems work autonomously and interact with one another, creating machine-centred feedback mechanisms that can cause unexpected outcomes. For example, chatbots interacting with one another have created their own language that humans cannot understand. In 2010 a financial crash was caused by the interactions of multiple AI bots speed-trading, which created artificial market inflation. Proactive control, monitoring and safeguards are necessary to catch these issues before they become a problem.

Example: Smart-energy optimization across buildings and infrastructure will create interactions between energy-use decisions within each building and at the regional level. Each building would operate individually, assessing overall demand patterns to determine low-cost energy-use approaches. Depending on circumstances, individual building decisions will interact with regional ones, potentially altering demand in ways that could crash regional energy systems.

Economic risks

As companies adopt AI, it may alter the competitive landscape, creating winners and losers. Those able to improve their decision-making most quickly through AI may find the benefits accelerate very quickly, while slower adopters may be left behind. Companies that struggle in the AI transition may be forced to reduce investment, possibly impairing their sustainability performance. Tax-base erosion presents another economic threat as the current system, based on "bricks-and-mortar" and nation-states, struggles to keep pace with the globalized digital economy. Tax erosion could be a drag on public spending, including investment in, for example, programmes designed to reduce greenhouse gas emissions. Current tax systems may need re-evaluation as automation changes workplaces, potentially reducing the number of jobs available.

Example: Increased productivity from automation, plus rising consumption from improved personalization, product design and AI-informed marketing, could increase resource use, waste and demand for energy.

Social risks

Large-scale automation threatens to reduce employment in transportation, manufacturing, agriculture and the service sector, among others. Higher unemployment rates could lead to greater inequality in society. In addition, algorithms designed by a subset of the population at a national and global level have the potential for unconscious bias, possibly leading to results that marginalize minorities or other groups. Autonomous weapons also pose a significant threat to society, possibly permitting bigger, faster conflicts. Once unleashed, this might lead to rapid and significant environmental damage, even to a "doomsday" scenario where weaponized AI presents an existential risk to humanity.[34]

Example: Autonomous trucks and cars, along with energy-efficient Internet of Things manufacturing, offer considerable environmental benefits but could also lead to a considerable loss of employment. (Goldman Sachs estimates that the US alone will lose an estimated 300,000 jobs per year when AV saturation peaks).[35] Regional economic decline and widening social inequality and unrest could also follow in manufacturing towns or along truck routes.

Ethical risks

The ethical and responsible use of AI involves three main elements: the use of big data; the growing reliance on algorithms to perform tasks, shape choices and make decisions; and the gradual reduction of human involvement in many processes. Together, these raise issues related to fairness, responsibility, equality and respect for human rights.[36] Additionally, while biased AI outcomes can raise significant privacy concerns, many insights and decisions about individuals are based on inferred group or community attributes. Accordingly, consideration of the harm AI could do must be framed beyond the individual level and recognize that privacy is not the only issue.

Example: Autonomous emergency food- and disaster-relief delivery systems that are trained using reinforcement learning or historical demand patterns will route supplies to specific regions during natural disasters. This could create ethical dilemmas relating to accountability for delivery dysfunctions, priority-setting and results.

Conclusions and recommendations

Conclusions

AI systems, and their ability to control machines automatically and remotely, have caught the public's imagination. The opportunity for AI to be harnessed to benefit humankind and its environment is substantial. The intelligence and productivity gains that AI will deliver can unlock new solutions to society's most pressing environmental challenges: climate change, biodiversity, ocean health, water management, air pollution, and resilience, among others.

However, AI technology also has the potential to amplify and exacerbate many of the risks we face today. To be sure that AI is developed and governed wisely, government and industry leaders must ensure the safety, explainability, transparency and validity of AI applications. It is incumbent on authorities, AI researchers, technology pioneers and AI adopters in industry alike to encourage deployments that earn trust and avoid abuse of the social contract.

Achieving this requires a collaborative effort to ensure that as AI progresses, its idea of a good future is aligned to human values and encapsulates a future that is safe for humanity in all respects – its people and their planet.

Recommendations

Leveraging AI technologies, not only for business and short-term growth prospects, but also for sustainable and resilient growth, requires decisive action. Public-private dialogue and partnerships will be crucial to develop solutions, assure good governance and overcome financial barriers.

This section lists some recommendations, categorized by stakeholder groups, to speed up innovation, minimize environmental risks and maximize environmental benefits from the application of AI. Three overarching areas, however, are particularly pertinent to all stakeholders:

– **Delivering "responsible AI":** To ensure that sustainability principles are embedded alongside wider considerations of AI safety, ethics, value and governance. This applies to decisions by private and public sector actors about investment in, design of, and operation of AI systems. It also incorporates efforts to advance and implement AI accountability, along with the development of governance frameworks, particularly in relation to data and algorithms. Definitions and standards relating to the "misuse of AI" will also be needed that incorporate misuse for environmental as well as human harm. The Partnership on AI is a positive step in this direction.[37]

– **Collaborating for interdisciplinary solutions:** There will be a need for significantly more interaction among technologists, policy-makers, domain specialists and even philosophers to optimize the design and deployment of AI applications for the Earth, both at a broad systems level and in relation to individual applications. In conjunction, academic and research institutions will need to develop interdisciplinary educational and research programmes to reflect this multifaceted and multidisciplinary approach.

– **Directing finance for innovation:** Realizing the goal of "Earth-friendly" AI will require significant funding to support scaling and commercialization of new solutions. This includes large-scale basic and applied R&D investment that bridges the technology and environmental disciplines, impact capital directed at technology solutions, specialized venture and growth capital, and government financial instruments that catalyse private sector innovation, for example through innovation accelerators, price support mechanisms and targeted patient capital.

Priority actions for each stakeholder group include the following:

For companies

– **Companies from all sectors:** Firms should establish board-level AI advisory units to ensure that companies' boards understand AI, including safety, ethics, values and governance considerations. Companies should also ensure that their technology strategies build in and optimize the effect AI will have on sustainability outcomes, both to capture new business opportunities and to manage risks.

– **Technology pioneer companies:** Both start-ups and established technology firms developing AI need to embed environmental considerations into design principles. Technology pioneers also have an opportunity to innovate in realizing the potential of AI for the environment. Microsoft's new "AI for Earth" programme,[38] an example of co-innovation, includes grants to entrepreneurs tackling Earth challenges to help them access AI technology; AI training for universities and non-governmental organizations working on climate, water, agriculture and biodiversity; and partnerships and investments to commercialize promising new solutions.[39]

– **Leadership on "responsible AI":** Responsible companies, in alliance with governments, could assume a leadership role in embedding sustainability principles alongside wider AI safety, ethics, values and governance considerations.

- **AI accountability:** Data access will be essential to building many of the AI applications that deliver environmental benefit. However, robust and well-governed data security, use, consent and processing are critical to building societal trust and confidence. Data (and in some circumstances algorithms) will in many cases have to be auditable, particularly in collaborations with public-sector institutions. Industry cooperation will also be important to advance AI accountability.

- **Industry collaboration on AI standard-setting:** To develop industry-wide and industry-regulator teamwork to aid in AI standard-setting (for example, through consensus protocols and smart contracts that include efficiency principles, or which require common agreement and governance).

- **Interdisciplinary solutions:** Many emerging AI solutions could have enormous impacts on the ways we live and work, but industry-led solutions may be designed and developed by a small group of people with a limited perspective. Increasingly, there will need to be diversity in AI development and use, including significantly more interaction among technology practitioners, domain and sectoral experts and philosophers, lawyers, psychologists and others, in order to develop, deploy and champion holistic AI mechanisms and solutions.

For governments

Given the potential for disruptive social and environmental consequences, it will be essential to develop sophisticated national and international governance structures for the new AI-enabled digital economy. These governance mechanisms – collaborating with industry and civil society – can help ensure that AI advances support inclusive growth that is aligned with the UN's Sustainable Development Goals. Within these frameworks, the following policy considerations should be advanced:

- **R&D investment:** Coordinated and targeted large-scale funding commitments could encourage research and funding collaboration on "AI for good", connecting industrial, academic and government research agencies. Research priorities will need to encourage interdisciplinary research – bridging technology, social, and environmental disciplines will be essential. This could include funding new specialist programmes and international research collaborations – for example, on the application of AI to weather prediction and climate modelling under the governance of the World Meteorological Organization and national meteorological and climate agencies.

- **Responsible technology policy:** The development of 'responsible technology' policies could set clear parameters for technology innovators and ensure alignment with human values and international frameworks such as the Sustainable Development Goals. Stakeholders could develop a definition and standard regarding the misuse of AI, while ensuring that social and environmental considerations are incorporated into national digital strategies.

- **Better data, trusted data:** Creation of better data environments, including for data access and data skills, could maximize the use of machine learning for sustainable solutions. Efforts could focus on improving the systems and protocols by which data is defined, gathered, accessed and manipulated. This includes government initiatives for open public data, industry-government collaboration on data and code verification or audits and policy frameworks (or agreements) to make strategic data available to specific users – with specified safeguards – in order to enable AI applications for societal and environmental benefits.

- **Algorithm assurance and transparency:** Governments have a role in regulating the use of "black box" AI models for high-risk, high-impact environmental domains such as autonomous vehicles. Regulations could be accompanied by a process for evaluating the robustness of algorithms ("algorithmic assurance") on an ongoing basis.

- **Algorithmic bias:** Policy frameworks will need to support technology companies, other industries and researchers to manage potential systemic bias in algorithms and ensure a social safety net for AI. Crowd-sourced raw data that technology companies use in their algorithms typically reflect the biases and prejudices inherent in society at large. Policy frameworks are needed to balance concerns about unfairness and discrimination in publicly sourced big data with the technical and ethical challenges of monitoring and the potential censorship of data.

- **Innovative finance mechanisms and partnerships:** There is a need to align both incentives and risks for private-sector innovation and scaling of AI applications for the environment, including support for early-stage commercialization. This could include government-backed innovation incubators, accelerators, funds and prizes; price-support mechanisms; and targeted patient and/or concessional capital to enable scaling of technological solutions for the public (including environmental) good.

For investors

- **Sustainable portfolios:** Angel investors, venture capitalists, accelerators and impact investors should build and support a portfolio of Fourth Industrial Revolution technology companies that address sustainability challenges within their remits. This approach could enable the impact investment community to complement traditional development projects with efforts that could speed up the transformational impact – and the commercial opportunity – of investments in technologies of the Fourth Industrial Revolution.

- **Investment criteria:** Mainstream institutional investors and asset managers should embed sustainability considerations into investment portfolios on AI (and other Fourth Industrial Revolution) technologies.

For research institutions

- **Bias & XAI research:** Further research is needed to identify algorithmic bias and to find ways to improve the explainability of AI, specifically for environmental applications that support government and company efforts to harness AI for the Earth. As each domain has nuances of how data or algorithmic bias influence the system, there needs to be further evaluation of the risks associated with environmental impact.

- **Interdisciplinary programmes:** Research institutions should help lead the interdisciplinary approach by further developing and disseminating educational programmes that bring together environmental and technology/data scientists and practitioners, while highlighting the use, impact and risks of AI for the environment.

- **Educational partnerships:** To ensure vocational-school and university graduates are ready to enter the job market with practical tools that integrate digital and sustainability. Partnerships between academia, governments and the private sector could support the integration of environmental, societal and governance themes into AI and data and computer science degrees, and vice versa.

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Lead authors
Celine Herweijer (PwC UK), Benjamin Combes (PwC UK), Pia Ramchandani (PwC US), Jasnam Sidhu (PwC UK).

Other contributors
Anand Rao (PwC), Nishan Degnarain (Central Bank of Mauritius), Juan Carlos Castilla Rubio (Space Time Ventures), Alberto Arribas (Met Office), Pierre-Philippe Mathieu (European Space Agency), Lucas Joppa (Microsoft), Lloyd Treinish (IBM), Erica Lee (DeepFarm), Katherine Hsiao (Palantir), David Hunt (Cainthus), David Hunter (Optimal Labs), Will Marshall (Planet Labs), Chadwick Manning (ElectrIQ Power), Andrew Scheuermann (Arch Systems), Kaila Colbin (SingularityU Australia Summit), Michael Gardner (Aqaix), Rob McCargow (PwC UK), Andy Townsend (PwC UK), Lizzy Fitzgerald (PwC UK), Mary Davies (PwC UK), Giulia Volla (PwC UK), William Hoffman (World Economic Forum), Kay Firth-Butterfield (World Economic Forum), Jahda Swanborough (World Economic Forum).

Fourth Industrial Revolution for the Earth Initiative:

Advisory Group
Celine Herweijer (PwC UK), Dominic Waughray (World Economic Forum), Steve Howard (We Mean Business Coalition), Jim Leape (Stanford University), Usha Rao-Monari (Global Water Development Partners).

Project Team
Benjamin Combes (PwC UK), Gaia Felber (World Economic Forum), Sarah Franklin (PwC US), Jerica Lee (World Economic Forum), Victoria Lee (World Economic Forum), Jahda Swanborough (World Economic Forum).

Contact
For questions about the Fourth Industrial Revolution for the Earth series of publications, contact:

Jahda Swanborough, Lead, Environmental Initiatives, World Economic Forum: Jahda.swanborough@weforum.org (series lead)

For questions about the Fourth Industrial Revolution for the Earth Initiative, contact:

Gaia Felber, Project Specialist, Environmental Initiatives, World Economic Forum: gaia.felber@weforum.org (Geneva)

Victoria Lee, Project Lead, Environmental Initiatives – 4IR for the Earth, World Economic Forum: Victoria.lee@weforum.org (San Francisco)

Annex 1:
Glossary of AI terms

AI glossary

AI consists of a number of areas, including but not limited to those below:

Main AI areas	Description
Large-scale machine learning	Design of learning algorithms, as well as scaling existing algorithms, to work with extremely large datasets.
Deep learning	Model composed of inputs such as image or audio and several hidden layers of sub-models that serve as input for the next layer and ultimately have an output or activation function.
Reinforcement learning	An area of machine learning that teaches computers to identify optimal behaviour in different environments through a cumulative reward function.
Natural language processing (NLP)	Algorithms that process human language input and convert it into understandable representations.
Collaborative systems	Models and algorithms to help develop autonomous systems that can work collaboratively with other systems and with humans.
Computer vision (image analytics)	The process of pulling relevant information from an image or sets of images for advanced classification and analysis.
Algorithmic game theory and computational social choice	Systems that address the economic and social computing dimensions of AI, such as how systems can handle potentially misaligned incentives, including self-interested human participants or firms and the automated AI-based agents representing them.
Soft robotics (robotic process automation)	Automation of repetitive tasks and common processes such as IT, customer servicing and sales without the need to transform existing IT system maps.

Annex 2:
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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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744

contact@weforum.org
www.weforum.org