Fourth Industrial Revolution for the Earth

Harnessing Artificial Intelligence for the Earth

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pwc

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 Environment and the Fourth Industrial Revolution. 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 leverages 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 cutting edge research departments and its deep connections with the Silicon Valley technology community together with the global insight and strategic analysis on business, technology, investment and policy issues that PwC offers. Together with other interested stakeholders, this unique partnership is exploring how 4IR innovations could help drive a systems transformation across the environment and natural resource security agenda.

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Preface

The Fourth Industrial Revolution and the Earth

Industrialisation 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 industrialisation.

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

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 realising 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 maximise gains for society and our environment.

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.

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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 civilisations to thrive. However, in a short space of time, industrialisation 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 is expected to grow 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 extraordinary, 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 (IoT), robots, autonomous vehicles, biotechnology, nanotechnology and quantum computing, among others.[14] It is characterised 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 – the idea of a good future 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 democratisation 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 standardisation 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 optimised 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 personalisation of consumer products or utilising 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 realise 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 organisations continue to invest in tools, data optimisation, people, and AI-enabled innovations, the realised 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 optimisation 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).

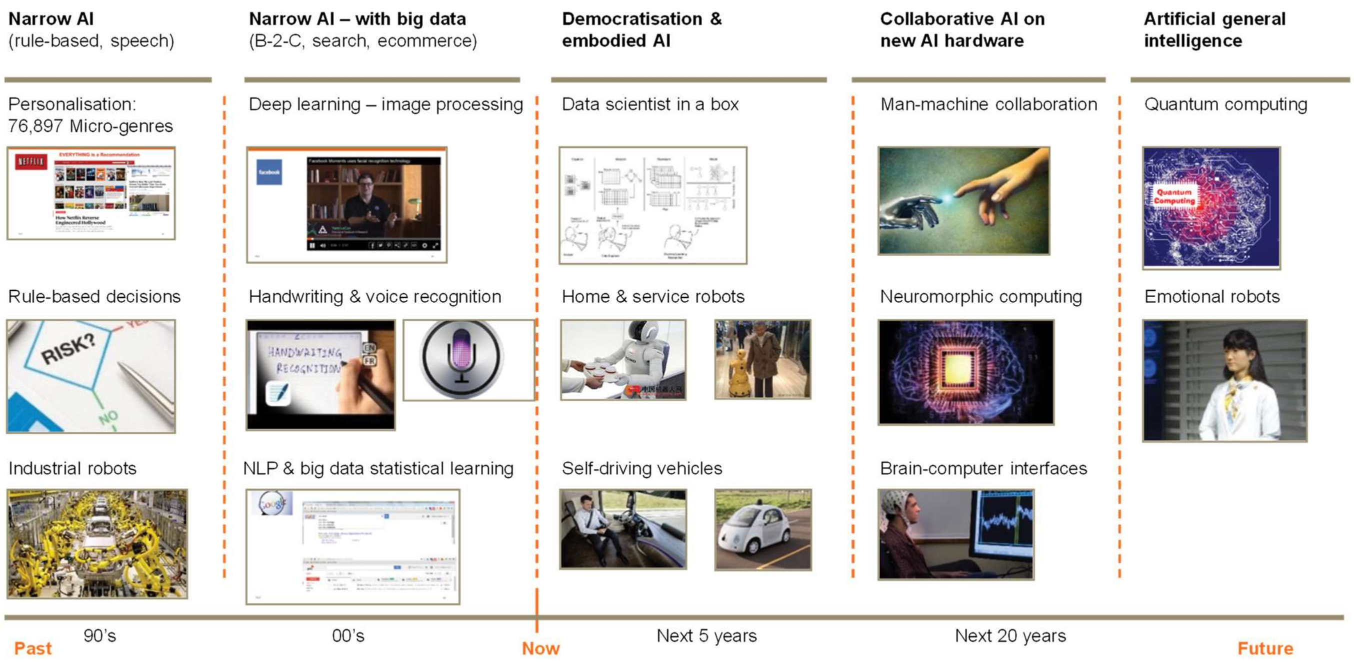
In addition, the shift towards 'explainable AI', which aims to create a suite of machine learning techniques that produce more explainable models whilst maintaining high performance levels, will facilitate wider adoption of machine learning techniques and potentially become best practice or even inform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

Past is not prologue when it comes to artificial intelligence



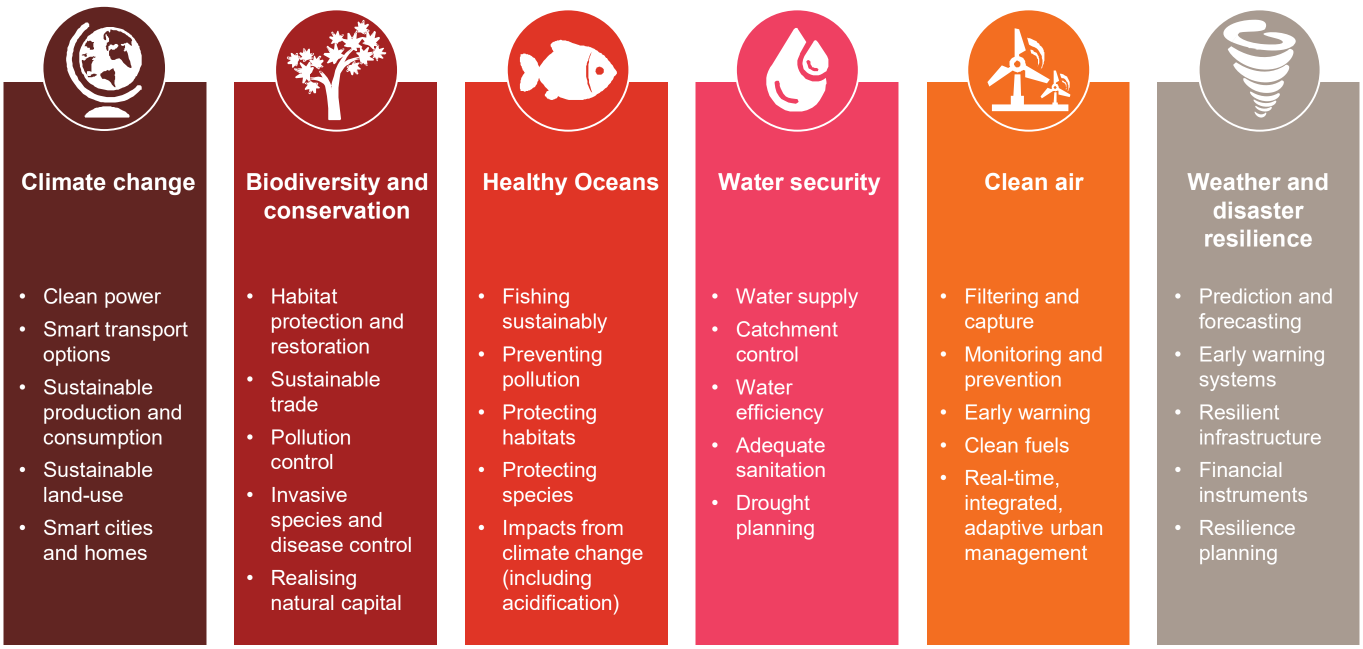
Source: PwC research

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 research

In meeting these challenges, there is wide scope for innovation and investment. AI in particular has immense potential to help unlock solutions. Indeed, the annex section provides a summary of research into more than 80 existing AI use cases for the environment that we uncovered through desk-based research and interviews with a range of stakeholders at the forefront of applying AI across industry, big tech, entrepreneurs, research and government.

In the next section, we highlight, by environmental challenge area, the broad range of emerging use cases across relevant action areas. As can be seen from the Figure 3, each priority Earth challenge stands to benefit in a myriad of ways from AI. The snapshots are not meant to be exhaustive, but to be representative of the most prominent innovations, and to provide an initial overview.

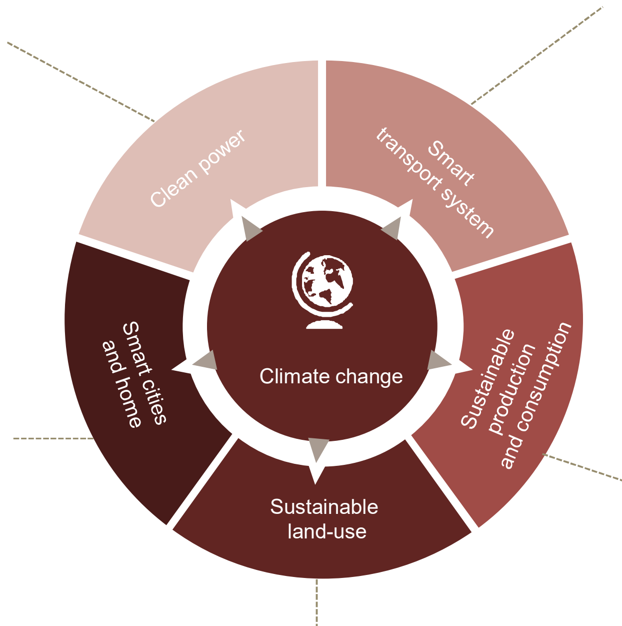
Currently, most of these applications focus on automated and assisted intelligence to unlock value from large unstructured real-time datasets. Future applications will likely involve more systems propelled by autonomous decision-making where AI acts independently, thus creating new opportunities and 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 use.

Figure 3: AI applications by challenge area

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

- 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



- 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

- 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

Source: PwC research

AI has the potential to transform the way in which climate change is tackled. In clean power, for example, machine learning is being used to match energy generation and demand in real-time, realising more fully the potential of “smart grids”, decreasing unpredictability, and increasing efficiency, power balancing, use, and storage of renewable energy[21]. For example, Agder Energi[22] is using AI and the Cloud to predict and prepare for changing energy needs in Norway, particularly given the rapidly-increasing penetration of electric vehicles. Such approaches can also lower the need for excess ‘idle’ capacity. Neural networks for renewable power are also being developed to improve the energy efficiency and reliability. For example, DNV GL use sensors attached to solar and wind power generation plants to supply data for machine learning monitoring capability, enabling remote inspection of sites, predictive maintenance, and energy resource forecasting[23]. This increases control and maintenance efficiency lowering costs of solar and wind energy.

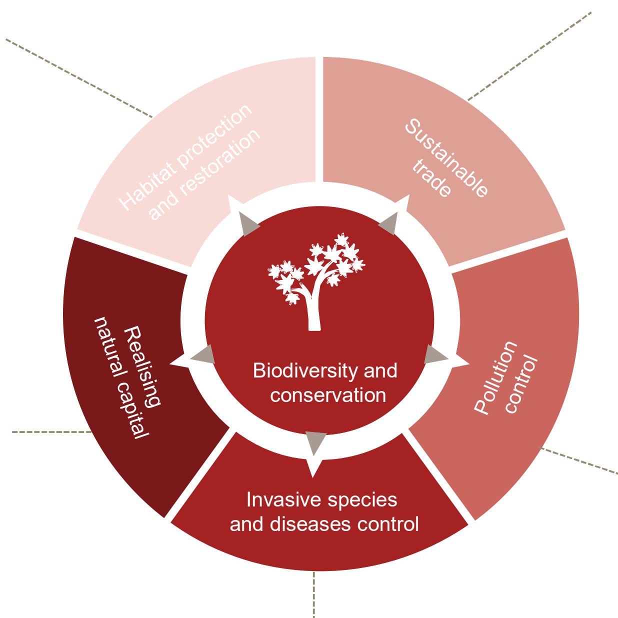
Within buildings, machine learning algorithms are also being deployed to analyse data from millions of smart sensors and meters to provide predictions on energy usage requirements and cost[24]. AI is also being used to provide auditory cue responsive lighting and heating from buildings to streets to optimise energy use, while JTC[25] of Singapore is using AI to monitor, analyse and optimise energy efficiency in buildings. Machine learning algorithms are also being used at the design phase to model energy efficient building layout further optimising buildings' efficiency in both the production and, more important, in-use phase[26].

For smart transport, machine learning algorithms employing car-sourced information are already widely used to optimise navigation (e.g., Waze and Google Maps) and increase safety, congestion and traffic flows (e.g., Nexar)[27,28]. At the urban-level, these capabilities translate to an ability to integrate public and private modes of transport to create an efficient city mobility service by looking for patterns in transport demand, optimising routes and improving efficiency and safety.[29] AI guided autonomous vehicles (AVs) - including machine vision algorithms and deep neural net techniques - will enable a transition to mobility on demand over the coming years, and decades[30]. Connected AVs present opportunities to unlock substantial greenhouse gas reductions for urban transport: examples include route optimisation that reduces driving miles and congestion, eco-driving algorithms that prioritise energy efficiency, programmed "platooning" of cars to traffic, and autonomous ride-sharing services that reduce vehicles miles travelled and car ownership[31]. Key considerations for maximising environmental impact include generating synergies with mass transit solutions and ensuring that AV fleets are in fact also zero-emissions fleets.

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

- 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



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

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

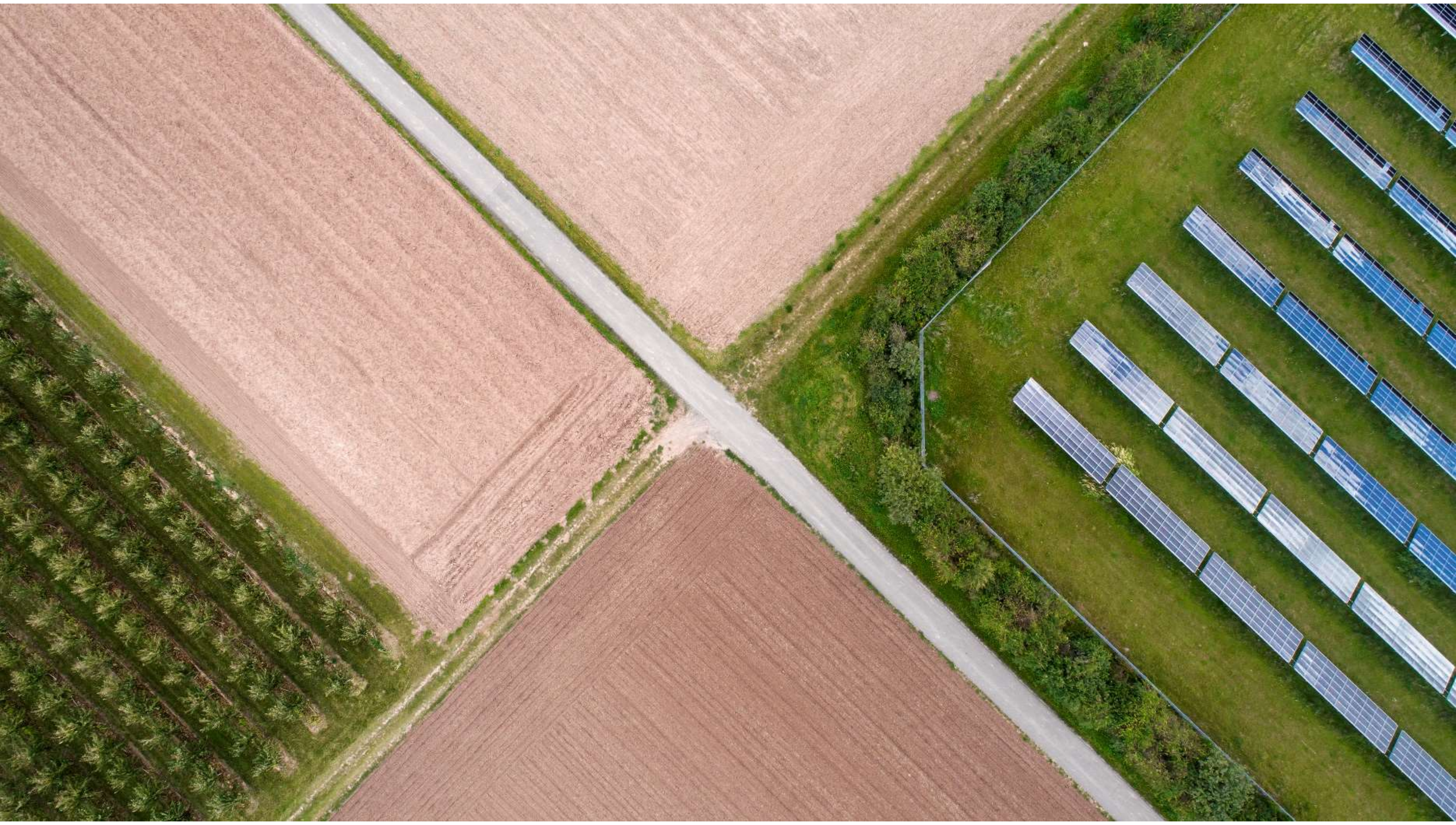
- Machine-automated biodiversity analysis
- Smart mosquito traps
- Plant disease identification & detection

Source: PwC research

AI has the potential to transform the ways by which we monitor and conserve habitats. For example, AI provides the backbone for applications that, combined with satellite imagery, can automatically detect land-use changes, including cover analysis and forests, vegetation and monitoring of floods. For example, PlanetWatchers insights - using precision monitoring of landscapes - provides a resource for management of forest habitats to address the challenges presented by climate change related disturbances such as pests, damage, drought and fire.[32]

To monitor and control invasive species, machine learning and computer vision are being used to identify the presence of invasive species and diseases in plants by tracking them and eliminating them. For example, Blue River Technology uses computer vision and AI to detect and identify biodiversity changes, including the presence of invasive weeds[33].

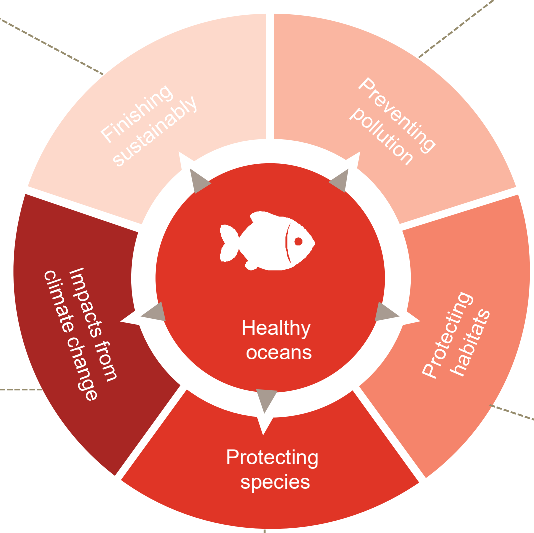
Protection of wildlife trade is being realised by combining AI with drone aerial footage, for example, Neurala is working with the Lindbergh Foundation to track African wildlife, such as rhinos and elephants, and spot potential poachers in order to prevent their killing[34]. Objects of interest can be identified from sensory streams, and assist humans by sifting through terabytes of video, in real time, and identifying animals, vehicles, and poachers, both during daytime and nighttime.



Healthy oceans

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

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



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

- 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

Source: PwC research

AI techniques are opening up various new approaches to protect and sustainably manage oceans.[35] Systems that use AI in combination with other techniques to gather data in hard-to-reach ocean locations support efforts to track provenance and fish sustainably, protect species and habitats, and to monitor the impacts of climate change.

AI is also unlocking new solutions to tackle illegal fishing. Machine learning techniques are being pioneered to guide more accurate patrol schedules, and early efforts are underway to apply vessel algorithmic patterns to satellite data combined with Automatic Identification System (AIS) data from ships to monitor illegal fishing activities (e.g., Global Fishing Watch)[36]. Such tracking will enable authorities to prevent overfishing and to control fisheries.

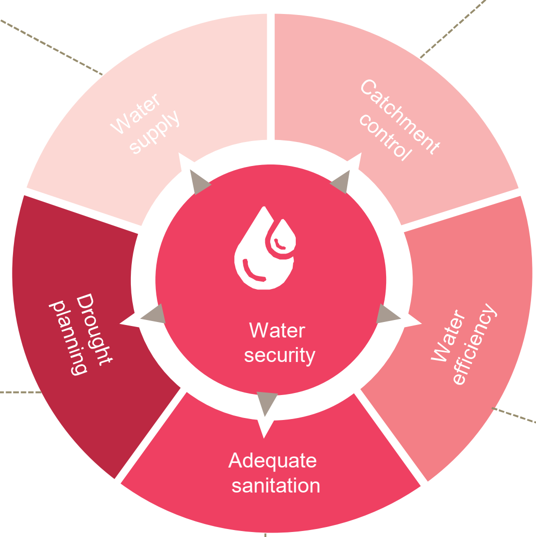
For species protection, some systems use image analytics and machine learning to track the numbers and locations of invasive species. One industry-NGO partnership with the Ocean Alliance uses drones to collect mucus samples from whales off the coasts of Patagonia, Mexico and Alaska to obtain DNA information, and scientists use AI to gauge the mammals' health – and by extension, measure the ocean habitat in which they live – in real-time[37].

Ocean conditions can also be monitored using AI-powered robots for detecting pollution levels and tracking changes in temperature and pH of the oceans due to climate change. Moreover, NASA uses satellite imagery and machine learning computer modelling to predict the current and future conditions of the world's oceanic phytoplankton[38]. Autonomous ocean exploration technologies - utilising advances in AI, robotics and nanotechnology - are also under development to help survey the ocean floor at high resolution to help with species identification and mapping and natural resource management.[39]

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-centered 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

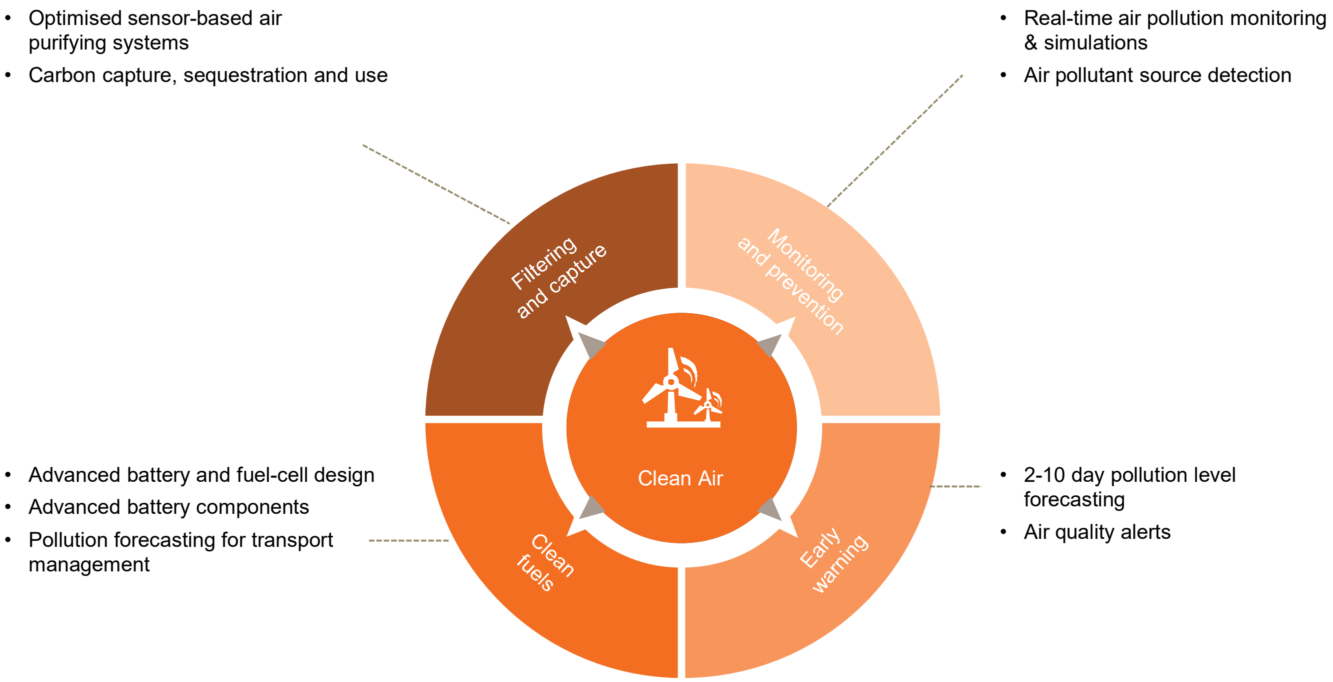
Source: PwC research

Water is at the nexus of food, energy, environment and urban issues. Enabled by AI, scientists and engineers can simulate the performance of reservoirs and project water usage for a geographical area, in combination with weather forecasts, making better informed policy decisions. Valor Water Analytics, meanwhile, is combining AI with industry intelligence and operational interactions to manage smart meter assets[40]. Their approach enables them to identify leaks, understand water flows in real-time, and see whether meters are malfunctioning. Elsewhere, Water Smart Software offers a data analytics platform, utilising machine learning, to provide utilities with information and strategies, including the ability to check water flows or spot anomalies[41]. Moreover, Flo Technologies uses machine learning to provide real-time data on water quality sending alerts to user's smartphones.

Syracuse, N.Y. uses an AI system to analyse its aging water infrastructure to identify specific locations of leaks-prone pipes to repair[42]. While Water Planet's IntelliFlux incorporates AI to analyse data from pressure sensors and determine optimal performance of filtration systems, minimising water loss[43].

As well as supply and efficiency, AI - working with satellite data - can help forecast weather patterns and analyse soil and surface water conditions to predict drought conditions to help people and sectors affected[44]. Scientists can also use machine learning combined with physical models to conduct water plan scenarios and evaluate capital investments, crisis management plans, and potential outcomes of water-planning decisions.

Clean air



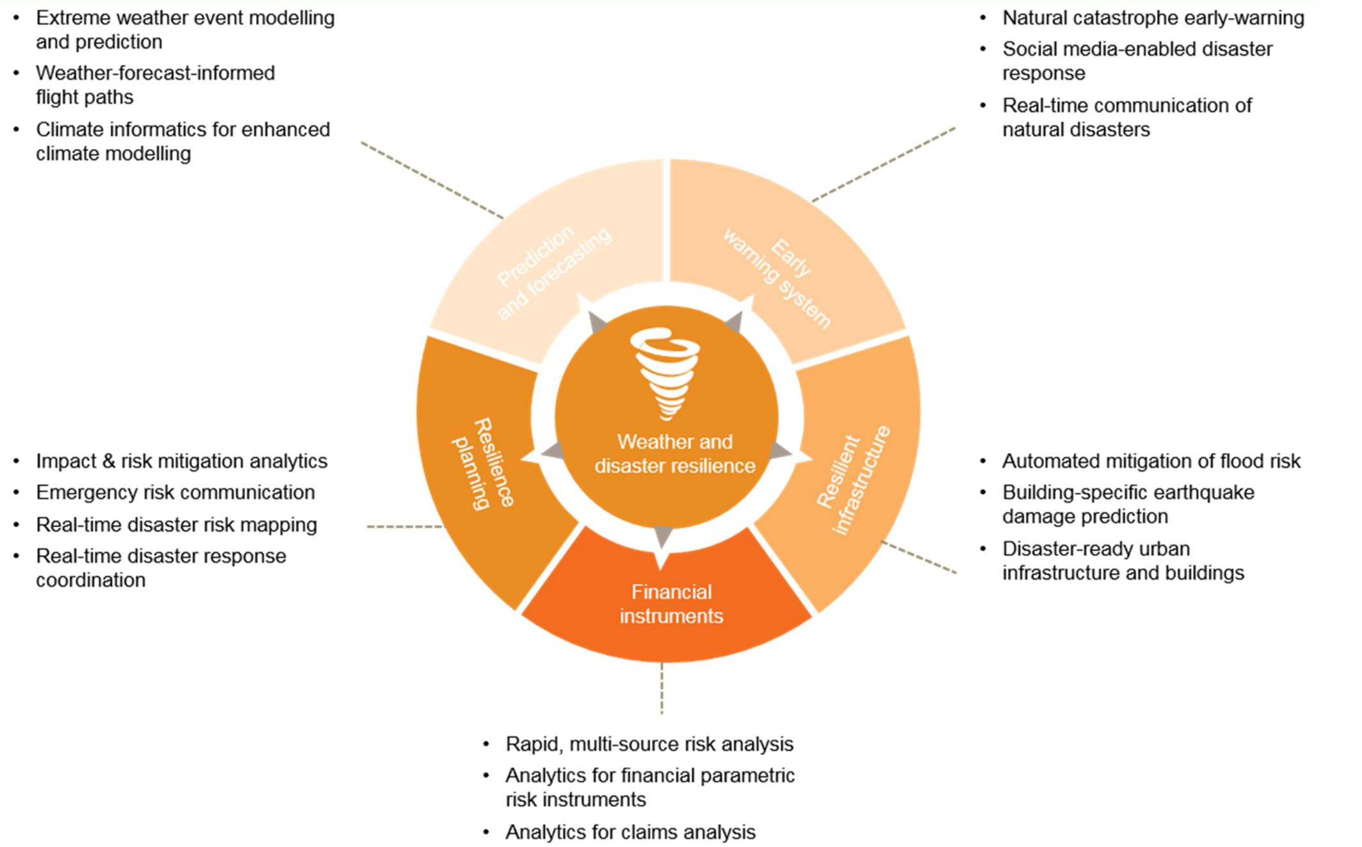
Source: PwC research

For clean air solutions, some of the early examples concentrated around filtration and capture. For filtration, air purifiers (e.g. ARCADYA's) use machine learning to record air quality and environment data in real-time and adapt filtration efficiency[45]. AI applications are also driving advances in real-time air quality monitoring; for example, the company AirTick uses smartphone cameras as a proxy for air pollution sensors harnessing image recognition and machine algorithms to analyse images across a city at low cost[46]. Elsewhere, air pollution forecasting tools are being developed by start-up AirVisual, IBM, and Microsoft for cities like Beijing[47]. IBM's Green Horizons initiative combines machine learning and IoT, harnessing data from air quality stations and more widespread sources, such as traffic systems, weather satellites, and stations, as well as industrial activity, topographic maps, and even social media, to develop predictive analytics for 2 to 7-10 day forecasts[48]. Both IBM's and Microsoft's tools blend traditional physics-based models of atmospheric chemistry and weather with machine learning models.

In terms of air quality alerts, such AI-based systems can now provide forecasts of resource intensive and polluting behaviours. Simulations powered by AI can enable residents of urban areas, such as Beijing, to receive warnings about air quality.[49]

Moreover, the use of AI in new connected platforms that harness data from vehicles, radar sensors, and cameras to optimise traffic flow in urban areas is also improving air pollution due to its impact on reducing stationary vehicles and stop-start driving.[50] In terms of mobility, AI is also being used to optimise advanced battery design to improve the effectiveness and efficiency of electric vehicles, whose increased uptake will further improve air quality.

Weather and disaster resilience



Source: PwC research

Many of the emerging applications for weather and disaster resilience focus on the ability to forecast extreme weather and natural disasters. Predictive analytics powered by AI, along with IoT, drones, blockchain, and advanced sensor platforms can help governments and the scientific communities monitor tremors, floods and windstorms, as well as sea level changes and other possible natural hazards, in real-time with thresholds for automated triggers, that enable early evacuations when needed. In Indonesia, PetaBencana.id combines multiple open-source sensors, AI, and people's social media reports for real-time flood mapping in the capital, Jakarta.[51] AI is also being used with image analytics to process social media information to provide real-time extreme weather forecasts based on people's images and posts, for example, IBM building on The Weather Company whom they acquired[52]. In addition, The Yield[53] is a Tasmanian agtech company using sensors, analytics and apps to produce real-time weather data, helping growers make smarter decisions reducing water and other inputs.

A number of meteorological agencies, tech companies (e.g. IBM, Palantir), insurers, and utilities are also using big data analytics and AI combined with more traditional physics-based modelling approaches to model the impact of extreme weather events on infrastructure and systems to inform disaster risk management strategies. The models can be used to predict direct damages in addition to loss amplification due to business interruption risks from electricity outages or transport closures. AI simulations are also being applied to evaluate disaster resilience strategies.

In addition to predicting extreme weather and natural disasters, natural language processing and machine learning techniques are increasingly being used to communicate disaster information to the public in response to queries. Moreover, in terms of real-time response planning, deep-learning algorithms and image analytics can use seismic data, structural data for buildings (age of structure, materials used etc.), social media data, and also satellite images to coordinate and prioritise disaster relief efforts, from determine which parts of a city will be most at risk to monitoring the flow of people and resources[54].

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. Realisable 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 transform fundamentally 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 decentralised and optimised 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 optimising 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. Further, 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 the energy industry. For the environment, the use of AI to make distributed energy possible at scale is critical for decarbonising 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 optimise 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 optimise 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 optimise 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 decentralised 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 involve increasingly 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 optimise 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 tech[55] 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 optimise production and trigger important actions such as adding moisture.[56] Drones are increasingly being used to monitor conditions and communicate with sensors and AI-enabled systems.[57]

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 change fundamentally 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 transform fundamentally weather forecasting (including prediction of extreme events) and to improve understanding of the effects of climate change.[58] 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.[59] 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 formalise, organise and promote the emerging scientific discipline of AI for weather and climate science, including international coordination (for example, through the World Meteorological Organisation 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 organisations 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 organisations 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.[60] 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 standardise approaches, define methodologies for leveraging APIs and ML tools to access vital data securely and accountably, and establish the terms and conditions for stakeholders to operate within the system.

6. Decentralised water

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

Household smart meters can produce large volumes of data that can be sued 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 decentralised 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 adjust autonomously their own sediment flows. Coupled with AI-informed pricing, such approaches could optimise water usage and drive behaviour change by providing incentives for water conservation.

7. AI-designed intelligent, connected and livable 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 optimise urban energy generation and demand – both city-wide and at the level of individual homes and buildings. Real-time AI-optimised 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 optimise cooling.[61]) 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 optimise 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,[62] 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 realising 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 standardised 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 originates. 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[63] 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 maximise 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 optimise 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 Amazonian Bank of Codes[64]) 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,[65] NASA's Earth Observing System and the private companies Planet, Digital Globe and Orbital Insights. These organisations 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.[66] 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 optimised 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 personalised nutrition plans optimised 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 optimised 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 to solve 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 optimising 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:*

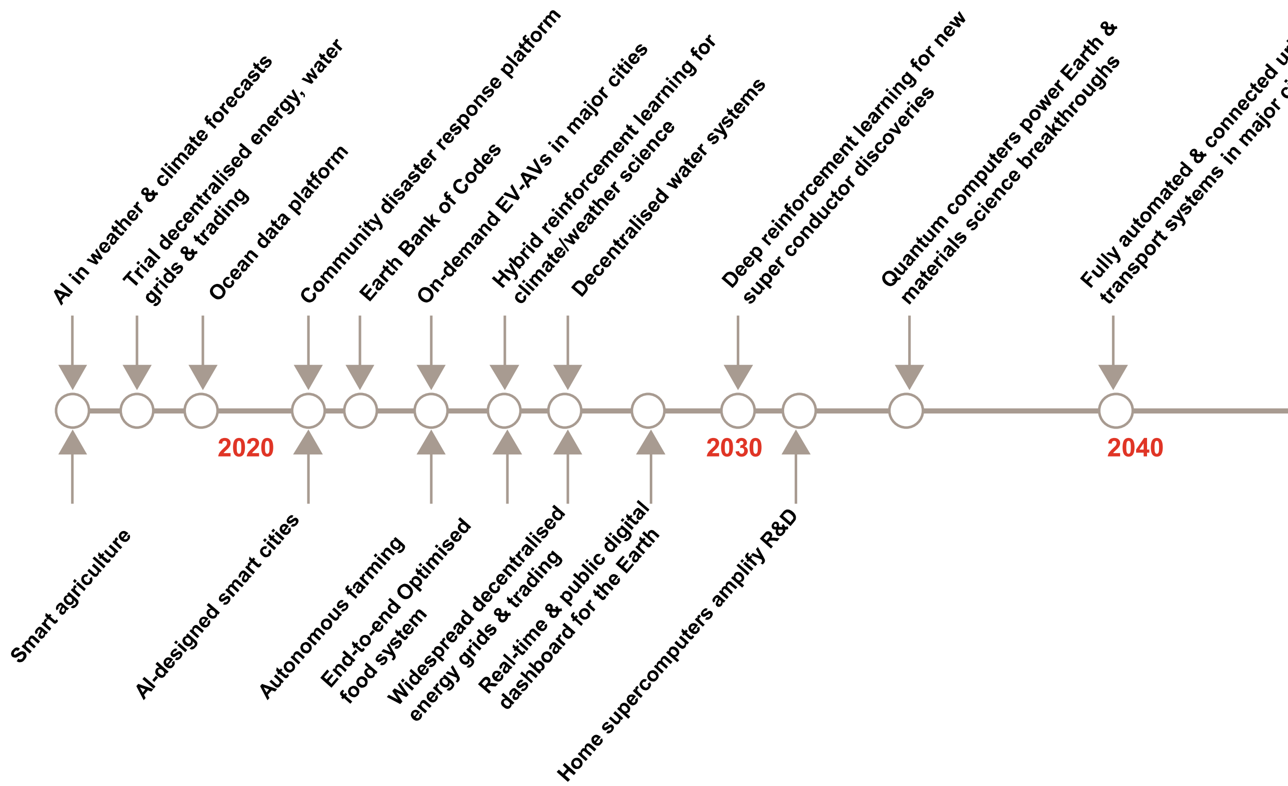
Instead of using brute force to increase the computing power of AI, innovators are increasingly exploring other advances such as deep learning chips, harnessing the move to cloud, and the ability to use distributed computing and quantum computing. All of these advances that increase computing processing power will enable large scale optimisation 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 democratised scientific progress:*

Earth science is currently one of the most computational heavy fields of scientific discovery – with supercomputing systems 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 democratised, 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 research

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, organisations, society, and the Earth.

Figure 5: Indirect impacts of AI by category

Artificial Intelligence risks

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"

Source: PwC research

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.[67]

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 optimisation 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 globalised 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 personalisation, 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 marginalise 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 weaponised AI presents an existential risk to humanity.[68]

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[69]). 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.[70] 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 recognise 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, categorised by stakeholder groups, to speed up innovation, minimise environmental risks and maximise 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.[71]
- **Collaborating for interdisciplinary solutions**: there will be a for need significantly more interaction among technologists, policy-makers, domain specialists and even philosophers to optimise 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**: realising the goal of "Earth-friendly" AI will require significant funding to support scaling and commercialisation 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, specialised 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 optimise 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 realising the potential of AI for the environment. Microsoft's new "AI for Earth" programme,[72] 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 organisations working on climate, water, agriculture and biodiversity and partnerships and investments to commercialise promising new solutions.[73]

- **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, 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 audit-able, 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 maximise 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 industry and researchers to manage potential systemic bias in algorithms and ensure a social safety net for AI. Crowd-sourced raw data that tech 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 commercialisation. 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 and how they could 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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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.

About the World Economic Forum

The World Economic Forum, committed to improving the state of the world, is the international organisation for public-private cooperation. The Forum engages the foremost business, political and other leaders of society to shape global, regional and industry agendas.

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With offices in 158 countries and more than 236,000 people, PwC is among the leading professional services networks in the world. We help organisations and individuals create the value they're looking for, by delivering quality in assurance, tax and advisory services.

Annex I:

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 II:

In this Annex, we detail a broad range of over 80 use case applications of AI for the Earth - across the same challenge and action areas. The use cases were uncovered during the course of our research, which included both desk-based research and interviews with a range of stakeholders at the forefront of applying AI across industry, big tech, start-ups, research and government.

Climate change			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
Clean power	*Optimised energy system forecasting*	Machine learning and deep learning analysis of electricity consumption patterns to make intelligent, real-time decisions in order to maximise the efficiency of energy use (multiple case studies).	More efficient production, better use of resources, and lower environmental impacts.
	Smart meter enabled smart grids	Machine learning algorithms to analyse the data from millions of smart meters to provide predictive analytics solutions for smart grids (e.g. Grid4C).	Suppliers understand the peak usage time and the downtime at the granular level and use this data to optimise overall electricity supply.
	Data-driven smart grids	AI to better analyse data gathered across electrical grids, enabling utilities to predict and meet the constantly changing energy needs and demands (e.g. Agder Energi utilising Microsoft's cloud).	A more effective, reliable and autonomous electrical grid, while encouraging customers to consume more renewable energy.
	Solar and wind energy plant assessment	Sensors attached to solar and wind power generation plants to supply data for machine learning monitoring capability, enabling remote inspection of sites, predictive maintenance, and energy resource forecasting (e.g. DNV GL).	Increase efficiency of control and maintenance tasks, in turn lowering costs of solar and wind energy.
	Solar flare prediction	The use of machine learning algorithms to forecast solar flares, e.g. using Solar Dynamics Observatory's vast data sets.	Predicting when solar flares will happen could reduce disruption to both power grids and satellites.

Climate change			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
Smart cities and homes	*Energy efficient building design*	Machine learning to simulate energy consumption during building design phase to guide energy efficiency in building design and operations (e.g. the Energy-Plus model).	Support planning of building layouts to enable optimised energy consumption.
	Energy efficiency of buildings in use	AI-enabled intelligent ecosystems that integrate different systems together, allowing to remotely monitor, analyse and optimise building systems (multiple case studies, including JTC).	Enhances energy-efficiency across systems and buildings.
Smart transport systems	*Smart traffic flow management*	Street lights with AI algorithms that uses data from radar sensors and cameras to detect traffic and build a street light timing plan that maximises efficiency of traffic flow (e.g. Surtrac) or informs optimal traffic navigation (e.g. Nexar).	AI-controlled traffic lights and real time vehicle navigation systems to ease congestion and reduce air pollution.
	On-demand response to transport mobility	AI can be used to analyse data (e.g., weather and user behaviour) to generate insights that inform the management of transport networks across a city, enabling a more efficient mobility service.	Increased efficiency and utilisation of transportation. Ultimately enables a connected autonomous fleet with energy consumption benefits.
	AI enabled autonomous vehicles	AI - including machine vision algorithms and deep neural net techniques - is critical to enabling the deployment of, and vehicle mix transition to Autonomous vehicles (AVs). Multiple use cases of application by Tech Firms, start-ups and Automotive companies.	Connected AVs present opportunities to energy usage reductions including route optimisation, eco-driving algorithms that prioritise energy efficiency, programmed “platooning” of cars to traffic, and autonomous ride-sharing services that reduce vehicles miles travelled and car ownership.
	AI enabled electric cars	Electric car drive time data (weather conditions, traffic volumes, tyre wear and driver behaviour) and machine learning to predict journey energy requirements with increased accuracy (e.g. Spark EV Technology software).	Journey prediction information can be used to increase the efficiency of energy-use between vehicle charges, and increases vehicle range.

Climate change			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
Sustainable land-use	*Reduced losses in the supply chain*	Machine learning to better forecast the amount of food grocery stores and consumers need each day and minimise waste (multiple case studies).	Assists businesses and consumers in managing and monitoring supply chains to reduce loss and waste.
	Early crop yield prediction	Remote sensing and ground data is used in deep learning models to predict crop yield with high spatial resolution (county-level) several months before harvest (multiple case studies).	Helps set appropriate food reserve levels, identifies low-yield regions - avoiding wasted resources - and improves risk management of crops.
	Precision agriculture	Drones are automated using machine learning techniques and have sensors to provide 24 hour monitoring of field conditions (plant health, soil condition, temperature and humidity), allowing farmers and field staff to immediately address any crop anomalies that the sensor may have recorded.	Better crop management and resource use through flexible rationality. Taking action to address a specific goal related to that environment.
	Data-driven farming	The application of AI enables seamless data collection from various sensors, cameras and drones, in an attempt to put data in the hands of farmers for them to improve crop yields (multiple case studies, incl. Microsoft FarmBeats collaboration).	Data-driven solutions that assist farm productivity.
	Global crop production monitoring	Satellite and weather data coupled with machine learning techniques to model complex systems, such as forestry and agriculture (e.g. Descartes Labs).	Provides high-resolution and high-accuracy forecasts to inform crop and supply management and improve crop yields.
	Hyper-local weather forecasting	Satellite imagery, soil data and hyper-local weather data to generate hyper-local weather forecast information for farmers to provide insight on when to plant, fertilize, spray, irrigate, and harvest crops (e.g. HydroBio).	Provides insights to enable maximisation of crop yield and minimisation of resource use, for instance, through informing irrigation requirements to minimise water wastage.
	Early detection of crop issues	AI for early detection of crop issues to improve crop yield and revenue for farmers (e.g. DeepFarm).	Early identification of crop yields contributes to more sustainable farming.

Climate change			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
Sustainable production and consumption	*Supply chain monitoring and transparency*	Natural language processing tools to analyse and interpret environmental, social and governance data about global supply chains. For example, water consumption, energy efficiency, workplace conditions (e.g. eRevalue).	Monitors suppliers and informs supply chain management conditions to improve efficiency and reduce deforestation an.
	Monitoring health in livestock farming	Facial recognition to track and follow individual cows in large herds, turning visual information into actionable data (e.g. Cainthus).	Reduce inefficiencies in food production and improves sustainability in supply chains.
	Smart recycling systems	Recycling stations using neural network to gather real-time feeds to select and sort the right items from the belt.	Smart bins enable identification of a wide range of food and beverage cartons so as to separate non-recyclable, from recyclable, products.

Biodiversity and conservation			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
Habitat protection and restoration	*Habitat loss detection and monitoring*	Spatial modelling uses an artificial neural network architecture to track changes in forest cover over time, and produce a map with areas at high risk for forest loss.	Inform land-use decisions and prioritise conservation efforts.
	Precision land-use mapping	Geographic Information System (GIS) and machine learning models to generate accurate land-use models, and simulate the impact of different land-use activities, and planting options (e.g. Microsoft and ESRI collaboration with Chesapeake Conservancy).	Land-use mapping under different planting scenarios enables optimised conservation to protect and restore local habitats.
	Bird habitat and migration pattern prediction	Crowd sourced bird observation reports and remote sensing data, which uses machine learning to predict where there will be changes in habitat for certain species and the paths along which birds will move during migration is collected (e.g. the eBird model).	Pattern predictions can help decision makers to decide how best to protect the habitats of birds.
	Simulation of animal and habitat interaction	Use of machine learning techniques to simulate animal behaviour in response to a variety of variable conditions.	Simulations of interactions can help people understand what form of animal activity leads to the most resource deficits.
	Precision monitoring of forest habitats	Satellite sensors, advanced machine learning algorithms, and cloud computing to monitor natural forest habitats, and predict the impact of weather and environmental changes (e.g. The PlanetWatchers program).	Precision monitoring provides a resource for management of forest habitats to address the challenges presented by climate change related disturbances such as pests, damage, drought and fire, to improve the overall productivity of the forest.
Invasive species and disease control	*Plant disease identification and detection*	AI-driven systems that uses image analytics based analysis of crowd sourced image data to understand the identification, prevention, and treatment requirements of crops (e.g. Plantix).	Supports optimal treatment and watering of crops, which helps reduce unnecessary product and water use.
	Machine automated biodiversity analysis	Computer vision and AI to detect, identify, and make management decisions about the biodiversity of a habitat. For example, the presence of invasive weeds (e.g. Blue River Technology).	Enables significant savings in the volume of pesticides being sprayed when tackling weeds, whilst optimising fertiliser use for crops.

Biodiversity and conservation			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
	Smart Mosquito traps	Machine learning systems that can differentiate between the mosquitoes that they want to trap/not trap, building a more efficient and effective trap (e.g. Microsoft).	Detects infectious diseases in the environment before they cause potentially deadly outbreaks of viruses or other dangerous diseases.
Pollution control	*Pollutant dispersal prediction and tracking*	AI-enabled modelling is used to more accurately predict the dispersion of pollutants under complex environmental conditions.	Reduction in the level of reactive nitrogen reaching natural ecosystems, reducing threats to plant diversity.
	Analysis of urban runoff quality issues	Models of various highly variable physical phenomena in the water, accurately predicting the level of biochemical oxygen demand (BOD), ammonia-nitrogen, nitrate-nitrogen, and ortho-phosphate-phosphorus.	Neural networks can monitor urban stormwater pollution levels and enable the development of better water resources management.
Realising natural capital	*Optimised breeding of plants*	Use of machine learning to leverage insights about how crops have performed in various climates, to predict which genes will most likely generate beneficial traits in plants.	Identifies genetic sequences that relate to qualities to help crops more efficiently use water, nutrients, adapt to climate change, or resist disease.
	Monitoring species	Open resource databases where pattern recognition from photograph records is used for tracking individual animals. For example, for whale shark monitoring (e.g. Wildbook).	Automated species recognition and monitoring with increased accuracy informs conservation efforts.
	Biodiversity mapping	Open resource that uses crowdsourced biodiversity data and machine learning capability for accurate identification and tracking of species (e.g. iNaturalist).	Classification of new species and monitoring numbers and location of endangered species, informing conservation efforts.
	Plant species identification	Use of deep learning to identify plant species that have been pressed, dried and mounted on herbarium sheets in order to support digitisation of natural-history museum collections.	Digitise the records of past and present biodiversity to provide a valuable resource for future conservation work.
	Machine-automated land-use detection	Urban areas can be detected in satellite imagery using various machine-learning approaches (e.g., supervised, unsupervised, and semi-supervised) which turn high-resolution imagery into land cover maps.	Provide information on how land-use is changing, helping governments to make informed decisions about when, where, and how to most effectively deploy conservation efforts.

Biodiversity and conservation			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
Sustainable trade	*Smarter fresh-food replenishment*	Machine learning allows retailers to automate formerly manual processes and dramatically improve the accuracy of customer purchasing and ordering forecasts.	Addresses the common—and costly—problem of having too much or too little fresh food in stock, diminishing wasted food.
	Detection of unauthorised animal capture	Machine learning and pattern recognition to detect the capture of animals from sensor camera images (e.g. Protection Assistant for Wildlife Security (PAWS)).	Parks are better able to protect their animals and to tackle the global trade in unauthorised animals.
	Image-based detection of illegal wildlife trade	Apps which use image and pattern recognition software, to allow users to visually verify taxonomic derivatives at various taxonomic levels.	Supports elimination of the illegal wildlife trade and enables effective monitoring of the legal wildlife trade.
	Poacher route prediction and high risk animal tracking	Machine learning to track and predict the paths of both at-risk animals and the poachers who are hunting them (e.g. Neurala).	Information used to counteract and respond to illegal poaching activities (e.g. in Africa).

Healthy oceans			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
Fishing sustainably	*Detection of unlawful fishing practices*	Software devices use machine learning to inform scientists and regulators on what creatures are caught to provide them with a full picture of legal harvests and detect unlawful operations.	Monitors legal and illegal catches to support sustainable fishing.
	Overfishing prevention and control	Algorithms embedded into fully automated software that workers use in fishing operations to identify fish and classify them by species.	Reduces the number of protected animals such as sharks and turtles that are accidentally caught along with tuna.
	Automated fish catch thresholds	Video footage from fishery operations is used for preliminary fish recognition using artificial neural networks, alongside counting and shape recognition, to arrive at an accurate estimate of how many fish can be caught.	Enables a more accurate estimation of numbers of fish and a better understanding of marine ecosystems informs fishing threshold decisions.
	Monitoring illegal fishing activities	Automatic Identification System (AIS) data from ships combined with other datasets and machine learning to monitor illegal fishing activities (e.g. Google Fishing Watch)[1].	Predicts commercial fishing behaviour in near real-time and helps to reveal ships where AIS transponders may be turned off, supporting law enforcement of protected marine areas.
Impacts from climate change (incl. acidification)	*Real-time monitoring of ocean pollution, temperature and pH*	AI-powered robots used for detecting pollution levels and tracking changes in temperature and pH of the oceans.	Provides accurate data on ocean pollution and pH which is used for developing biodiversity conservation action plans.
	Phytoplankton distribution detection and prediction	Machine learning to understand the distribution of phytoplankton in the oceans. And satellite imagery and computer modeling to predict the current and future conditions of the world's oceanic phytoplankton (e.g. NASA).	Valuable information for researchers attempting to understand the effect of changes in atmospheric CO2 on our planet.

[1] Clark, Liat, *Google's Global Fishing Watch is using 'manipulated' data*, Wired, November 2014, available at: http://www.wired.co.uk/article/global-fishing-watch-false-data-windward

Healthy oceans			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
Preventing pollution	*Marine litter prediction*	AI techniques to define general litter categories that occur on beaches, and assess litter pollution occurrence (e.g. researchers in Turkey).	Fast and reliable estimations of litter categories inform research studies and management priorities of beaches.
	Robotic fish to fight pollution	AI-enabled robotic fish technology that detect potentially hazardous pollutants in the water, for instance from a leaking underwater pipe (e.g. European Commission-funded research).	Enables early identification of pollutants in water, which enables management activities to be undertaken before the pollutant level increases.
	Drones to analyse whale health	AI and drone capabilities to analyse data that drones collect via the blow, or snot, exhaled from whales when they surface to breathe (e.g. Intel are collaborating with Parley for the Oceans on its SnotBot initiative)[2].	Informs marine conservation efforts.
Protecting habitats	*Coral reef mapping*	Autonomous drones are AI-enabled to use machine learning to map the coral reef and automatically sift through data to track changes in the reef formation.	Monitoring the reef on an ongoing basis provides a valuable resource for conservation activities.
	Monitoring marine habitats for change	Drones are being developed to take detailed imagery of marine habitats and use machine learning algorithms to process data and determine the best location for planting as to ascertain which species are best fit for the area.	Drones are used to economically restore degraded ecosystems, for example, by planting mangroves.
Protecting species	*Predicting the spread of invasive species*	A system that uses image analytics and machine learning to track the numbers and locations of invasive species.	Track levels of invasive species in order to inform control activities.
	Prevention of illegal wildlife trafficking	Machine learning tools to processes data from the "dark web" to penetrate organised crime for protected marine wildlife (e.g. DeepDive).	Tools to prevent illegal trafficking of wildlife.

[2] Gilbert, Elissa, Scientists equipped "SnotBots" — drones using sophisticated AI programs — to learn about whales, oceans and even human health, August 2017, available at: https://iq.intel.com/whale-snot-hold-secret-ocean-health/?cid=sem43700027467499372&intel_term=parley+for+the+oceans&gclid=EAIaIQobChMIhO6LzPqW2AIVAtVkCh1kMgRSEAAYAiAAEgL5p_D_BwE&gclsrc=aw.ds&dclid=CKuCpfP6ltgCFVIFgQodTewB-g

Water security			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
Adequate sanitation	*Drones for real-time river quality monitoring*	Algorithms that use monitoring data from drones to automate the delivery of water quality reports (e.g. The University of Toronto).	Monitors the health of a body of water resourcefully, and provides recommendations for waterways management.
	Adequate sanitation of water reserves	Artificial Neural Network models have been developed and validated for predicting the pH at different locations of the distribution system of drinking water.	Monitors the quality of drinking water in urban areas.
	Real-time monitoring and management of household water supply	User-friendly cloud-based system for real time monitoring and management of household water supply. For example, Flo Technologies creates intelligent water monitoring and control system for single family homes.	Limit wastewater while also ensuring high quality water supply.
	Harmful algal blooms detection and monitoring	Machine learning techniques to train a smart device (cellular phone or tablet) to detect the presence of cyanobacteria in a small surface portion of a freshwater.	Reduce volume of harmful algal blooms which have severe impacts on human health and aquatic ecosystems.
Catchment control	*Stream-flow forecasting*	Machine learning techniques for modelling non-linear hydrological conditions, in order to generate short and long term streamflow forecasts and automate catchment management infrastructure.	Short-term (real-time) forecasting (e.g., hourly and daily) enables reliable operation of flood and mitigation systems. Long-term forecasting (e.g., weekly, monthly and annual), is important in the operation and planning of reservoirs, hydropower generation, sediment transport, and irrigation management decisions.
Drought planning	*Accurate drought planning*	Machine learning enables accurate drought forecast by means of multiple drought-related attributes from precipitation, satellite-derived land cover vegetation indices, and surface discharge (multiple case studies).	Drought planning over a lead-time of 3 to 6 months, which can be crucial for agricultural planning, reservoir management, and authorities' allocation of water resources.
Water efficiency	*Residential water use monitoring*	Machine learning algorithms to detect inaccuracies or anomalies in water meter data (e.g. Valor Water Analytics).	Monitors water flow in real-time to maximise efficiency of water use by customers.
	Underground leaks detection	Detection of underground leaks in potable water supply systems through analysis of satellite imagery and machine learning (e.g. Utilis).	Enables more leaks to be detected and a reduction in water loss.

Water security			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
	Industrial water use optimisation	Machine learning algorithm to analyse disparate water data to develop optimal management and control protocols for the water management by utilities and industrial users (e.g. Pluto AI).	Automated identification of optimal water management to ensure efficiency of water use and associated energy conservation.
	Predictive maintenance of water plants	Machine learning to quickly and effectively analyse hundreds of variables that have an impact on a pipe's likelihood of failure.	Estimates current pipe corrosion and deterioration to ensure high water quality standards.
	Early-warning for water infrastructure maintenance	Machine learning models that assign risk scores to individual water mains on a map.	Analysis to help city planners prioritise mains for maintenance and replacement.
Water supply	*Self-adaptive water filtration*	Machine-learning to analyse data from flow and pressure sensors continuously to determine optimal performance of filtration systems in environments where water quality varies. For example, the oil and gas sectors (e.g. Water Planet's IntelliFlux software).	Filter enables effective and high quality water filtration where influent water quality is variable, thereby minimising water loss.
	Water quality simulation	Numerical models used to simulate flow and water quality processes in coastal environments, with the emphasis traditionally being placed on algorithmic procedures to solve specific problems. AI has made it possible to integrate technologies into numerical modelling systems in order to bridge the gaps (multiple case studies).	Optimise water management decision-making.
	Water asset maintenance	Systems to integrate computer modelling with local authority planning, policy interventions and decision making, using dynamic feedback from the field, to modify models and decision making (e.g. Pluto AI).	Lengthens the lives of water assets, reducing leaks, and lowering water expenditure and loss.

Clean air			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
Clean fuels	*Pollution forecasting for transport management*	AI leverages pollutant (e.g., carbon dioxide, and nitrogen oxides) and environmental data (humidity, solar irradiation, and temperature) to predict transport pollution intensity in urban areas (e.g. multiple case studies).	Pollution forecasting used for management response to minimise pollution impacts (e.g., congestion charge, traffic restrictions).
	Advanced battery and fuel-cell design	Advanced AI-enabled material modelling to improve battery-electric and fuel-cell cars (e.g. Toyota).	Improve battery-electric and fuel-cell car technology in order to reduce the cost of technology and enable transition to electric vehicle fleets.
Early-warning	*Pollution level forecasting*	Predicting air pollution levels by combining data from several different models. For example, Microsoft currently provide China's Ministry of Environmental Protection a forecast for Beijing for the following 12 hours, achieving 60 percent accuracy.	Manage urban air quality to protect the health of the public.
Filtering and capture	*Sensor-based air purifying systems*	Air quality sensors built into tablet devices. Using machine learning to analyse air quality while considering individual preferences, to adapt filtration efficiency (e.g. ARCADYA'S air purifying system).	Provides clean air at a personalised level to meet individual's needs.
Monitoring and prevention	*Real-time air pollution monitoring*	Machine learning tool to estimate air pollution levels from photographic evidence (e.g. AirTick).	Accurate real-time estimates of the air quality in individual's neighbourhoods to adapt behaviour accordingly.
	Air pollutant source detection	Smart indoor air quality monitors using neural network algorithms to associate a pollutant with a source in a given environment.	Provide real-time information of pollutant sources enabling individuals to manage scenarios.

Weather and disaster resilience			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
Early-warning systems	*High impact weather event prediction*	Machine learning tools to improve the prediction skill for multiple types of high-impact weather, including thunderstorms and tornadoes (e.g. The US NOAA, UK Met Office).	Improves early prediction accuracy of high-impact weather events, to facilitate effective preparation.
	Social media enabled disaster response	Machine learning models integrating disaster crisis data from social media (e.g., tweets) to provide information that relates to particular crises, to inform disaster response activities (e.g. Qatar Computing Research Institute (QCRI)).	Assists during natural disasters, prioritising the efforts of first responders.
	Real-time natural disaster communication	The use of the latest web technologies, cloud computing, natural language processing, and machine intelligence techniques to communicate disaster information to the public in real time (e.g. IBM and Weather Company).	Processes and analyses social media feeds in real-time for improving flood monitoring and prediction, supporting flood preparedness, recovery and response.
Financial instruments	*Rapid, multi-source risk analysis*	Machine learning algorithms to scan web content to generate high-frequency, objective, and actionable risk scores, including social, geopolitical and climate risk (e.g. GeoQuant).	Inform smart climate and extreme weather policy and investment decisions.
	Smart investment decisions	Machine learning to filter and process resources from across the web (news, academic journals, press releases) to provide sustainable investment advice to clients (e.g. NewsConsole).	Supports evaluation of capital investment decisions under different scenarios (e.g., climate change).
Prediction and forecasting	*Extreme weather risk prediction and preparedness*	AI combined with more traditional physics-based modelling approaches to model the impact of extreme weather events on infrastructure, including AI downscaling techniques (multiple use cases involving Met Offices, utilities, and tech firms),	Prediction and risk quantification to aid disaster preparedness decision-making for communities, businesses and governments.
	Weather-forecast-informed flight paths	Integrated public source data, and data from airplane sensors, to make predictions about weather conditions along flight paths (e.g. Panasonic).	Enables airlines to adjust their routes to reduce fuel use and improve on flight safety.

Weather and disaster resilience			
Action area	**AI use application**	**Description of the role of AI**	**Potential environmental outcomes**
	Real-time weather predictions	Machine learning solutions that use sensors and data analytics to produce real-time weather data (e.g. The Yield, UK Met Office).	Helps growers to make smarter decisions that can reduce their water use and other inputs, while also increasing yield.
Resilience planning and disaster response	*Emergency risk communication*	Natural language processing and machine intelligence tools to communicate disaster information to the public (e.g. IFIS Knowledge Engine).	Users can receive answers to their questions on flooding (e.g., flood conditions, forecast, flood risk) in order to mitigate risk of natural disasters.
	Earth systems' response prediction	Machine learning to create 3-D living models of the entire planet. The vast amounts of data will enable the modelling of different conditions and predict how Earth's systems will respond (e.g. National Science Foundation and EarthCube, Planet Labs).	Support scientists to avoid catastrophic events or plan for unavoidable events (e.g., flooding) before they occur.
	Real-time flood mapping	Tools that combine data from open source sensors and social media reports to use machine learning for real-time flood mapping (e.g. PetaBencana.id in Jakarta).	Provides accurate and up to date flood information for governments and local residents, for flood planning and response.
Resilient Infrastructure	*Automated mitigation of flood risk*	Computing and machine learning to automatically control the flow of water through flood gates in response to changing conditions.	Constructs and manage natural landscapes that benefit biodiversity or mitigate the risk of natural disasters (e.g., flooding).
	Building-specific earthquake damage prediction	AI-enabled modelling using seismic data and structural data from buildings (age, materials, etc.) to prioritise which parts of a city will be most at risk from earthquakes.	Helps inform earthquake response management in order to mitigate impacts.

Annex III:

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 organisation, 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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