THE ROYAL SOCIETY

CLIMATE CHANGE : SCIENCE AND SOLUTIONS | BRIEFING 9

Climate change and land: the science of working with nature towards net zero

In brief

Land plays a fundamental role in the world's climate and efforts to stabilise it. Protecting, restoring and managing the world's land sustainably can contribute to achieving net zero greenhouse gas (GHG) emissions by 2050 as well as adapting to the impacts of climate change.

Land-based mitigation could provide up to 20 – 30% of the net emissions reductions needed by 2050 to keep the global average temperature rise to 1.5 – 2° Celsius[1], but will only be effective if combined with rapid and deep reductions in fossil fuel emissions.

INSIGHTS

- Land-based mitigation options are not a substitute for immediate and aggressive emissions reduction across all sectors if the goals of the Paris Agreement are to be met[2].
- Priorities for land-based mitigation are the protection of existing carbon-rich native ecosystems, restoration of degraded ecosystems and improved management in agriculture and forestry.
- Effective land-based climate mitigation and adaptation options will involve local communities and help to deliver many of the UN Sustainable Development Goals.
- Research shows that healthy, plant-rich diet options and reduced food waste will take pressure off the land for food production. This can provide scope for land-based options to tackle climate change and enhance biodiversity.
- Clearer monitoring and standards that demonstrate that land-based options are delivering genuine GHG reductions can encourage funding by government, businesses, and others.
- Further research will identify good practice and performance metrics for land-based mitigation options, and will include consideration of benefits for indigenous peoples and local communities.

1. Land and climate change

Activities that reduce emissions include conserving forests, grasslands, coastal wetlands or peatlands – thus preventing emissions from their conversion – and more sustainable agriculture which releases less carbon. Actions that remove carbon from the atmosphere create new sinks and include restoring ecosystems, improving forest and grazing management, enhancing soil carbon and planting trees.

This briefing focuses on how interventions on land can play a role in mitigating GHG emissions by reducing emissions from use of land and using its carbon-absorbing capacity.

Data from 2015 indicate that the use of global ice-free land includes 37% for pasture, 22% as managed forests, 12% cropland, 12% barren or rock systems and 7% unforested ecosystems with minimal human use[3].

1.1 Terra infirma

Over the last few decades, human activity has expanded to affect more than 70% of the world's ice-free land, and around 25% of it has been degraded as a result[3]. Since the 1960s, the world's population has risen from three billion to nearly eight billion, driving up demand for food, feed, timber and other resources[4, 5]. More specifically, the supply of meat has more than doubled and calories consumed per person have risen by one-third, which in itself drives up GHG emissions and damages biodiversity[3]. (See briefing 10: *Nourishing ten billion sustainably*.)

1.2 How land use affects the climate

The cumulative impact of anthropogenic emissions over around 250 years has disrupted Earth's natural balance in which land emits and absorbs CO_2 through respiration and photosynthesis. Although land is estimated to have absorbed around one-third of anthropogenic emissions since 1750 and the ocean around one-quarter, around 40% have remained in the atmosphere[6], driving the concentration of CO_2 up by around 50% from pre-industrial levels and leading to a global average temperature rise of around 1.0°C[7]. (See briefing 7: *The carbon cycle*.)

Agriculture, forestry and other land use (known as AFOLU) accounts for roughly one-quarter of all anthropogenic GHG emissions, consisting primarily of carbon dioxide, methane and nitrous oxide. During the 2007-16 decade, to which the following GHG estimates from the Intergovernmental Panel on Climate Change (IPCC) apply, these amounted to around 12 billion tonnes of carbon dioxide equivalent per year ($GtCO_2e$/yr)[3].

Of this, roughly 5 $GtCO_2e$/yr consisted of carbon dioxide (CO_2), released from land-use changes such as deforestation, peatland drainage, mangrove clearance, or conversion of grassland to cropland. Methane accounted for 4.5 $GtCO_2e$/yr of the emissions, particularly from livestock farming and rice paddies. Land-based emissions of nitrous oxide totalled around 2.3 $GtCO_2e$/yr, with the use of fertiliser as the main driver. Meanwhile, land also acted as a sink for CO_2 specifically, absorbing around 11 $GtCO_2$/yr of anthropogenic emissions from all sources, just over twice as much as human activity on land emitted[3].

1.3 How climate change affects land

Climate change has already had significant impacts on land[3]:

- The global mean surface temperature on land has risen by more than 1.5°C since pre-industrial times, compared to the rise of around 1°C averaged across land and ocean.
- Land has experienced disruptions to rainfall patterns, leading in some regions to increased flooding or droughts, and has seen more wildfires, heat waves and melting permafrost.
- While some areas have become greener as land has been affected by changes in rainfall and humidity, arid lands experiencing drought have grown at 1% per year and 500 million people now live in places where deserts have expanded since 1980.
- Changes have affected the biodiversity of animals and plants, with changes to population size, distribution and seasonal behaviour patterns.

1.4 The role of land-based mitigation and nature-based solutions

There is a role for the land in addressing climate change, through a variety of interventions. Activities that reduce emissions include conserving forests, grasslands, coastal wetlands or peatlands – thus preventing emissions from their conversion – and more sustainable agriculture which releases less carbon. Actions that remove carbon from the atmosphere create new sinks and include restoring ecosystems, improving forest and grazing management, enhancing soil carbon and planting trees*.

Among the options, 'Nature-based solutions' are broadly defined as 'actions that involve working with nature to address societal goals'[8]. These goals range wider than mitigation and adaptation to climate change. In particular, at a time when plant and animal species are declining in abundance and variety, nature-based solutions protect and enhance biodiversity. They also support many aspects of sustainable development.

Not all land-based climate change mitigation options are nature-based solutions. For example, tree-planting can involve creating large monoculture plantations that sequester carbon rapidly but that may not be beneficial for biodiversity, water security or local people's resource rights. On the other hand, tree planting with a natural mix of native tree species planted in appropriate locations in ways that support biodiversity with the involvement of local communities, would be considered as a nature-based solution. Nature-based solutions may be seen as preferable to other land-based interventions because they deliver progress towards a number of societal goals as well as climate change mitigation[8].

As well as changes in land use and management, there is scope for reducing emissions through changes in food demand, including shifting diets to more plant-based alternatives and reducing food waste[9]. (See briefing 10: *Nourishing ten billion sustainabily*.)

It should also be noted that land-based mitigation options are not a substitute for immediate and aggressive emission reduction across all sectors. There is no guarantee that land will continue to absorb CO_2 as it has done historically if atmospheric levels continue to rise. Emissions also arise through self-reinforcing effects as a result of the impacts of climate change: for example, as land is degraded through forest fires which emit carbon or as permafrost melts and carbon dioxide and methane are emitted[2, 10]. The IPCC concluded that the net impact of climate change on carbon cycle processes will be 'to exacerbate the increase of CO_2 in the atmosphere'[11].

1.5 Challenges facing land-based mitigation

Despite their considerable potential, land-based mitigation options face a number of specific challenges.

Climate finance for agriculture, forestry, land-use, and natural resource management amounted to only 3%, or $16 billion, of the total investment in the sector in 2018, compared to $322 billion for renewable energy and $122 billion for low-carbon transport[12, 13, 14].

Measurement, reporting and verification of land-based mitigation is another challenge[15, 16]. The choice of a baseline date can make measuring effectiveness and subsequent compensation controversial and 'leakage' is a risk whereby conserving or restoring land in one location may lead to land clearing in a different location or country[17, 18].

Nature-based solutions may be seen as preferable to other land-based interventions because they deliver progress towards a number of societal goals as well as climate change mitigation[8].

* These ecological approaches can be further supplemented by a suite of geological methods of removing carbon from the atmosphere such as enhanced rock weathering, which involves spreading fine-grained rock dust, such as basalt, over cropland. (See briefing 5: *Carbon dioxide capture and storage*.)

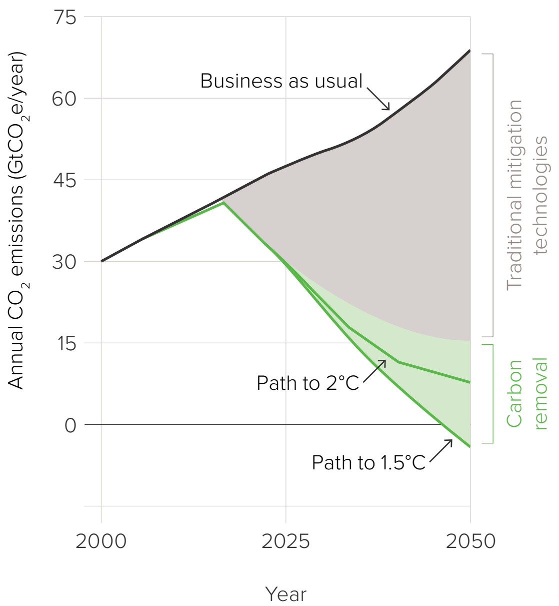
2. The potential of land-based mitigation options

If barriers to funding and implementation can be overcome, land-based mitigation has major potential in the drive to limit climate change, although this is subject to great uncertainty. IPCC-reviewed studies of what land-based interventions can achieve by 2050 to help keep the global temperature rise to 1.5°C have estimated contributions covering wide ranges such as 0.4-5.8 $GtCO_2e$/yr for reduced deforestation, 0.5-10.1 $GtCO_2e$/yr for afforestation and reforestation or 0.3 – 3.4 for agricultural measures[19].

Researchers have been seeking to generate more specific estimates for land-based measures that balance their modelled technical potential with economic potential and co-benefits. In one study[1], which provides a concise indication of the potential, scientists examined economy-wide modelled projections as well as sector-based assessments to develop a 'land-sector roadmap' to illustrate a path of action to help achieve the Paris Agreement target of limiting warming to 1.5°C. This study found that land-related measures, both supply and demand side, could in total deliver around 14 $GtCO_2e$ of emissions reduction per year by 2050, or around 15 $GtCO_2e$/yr with bioenergy with carbon capture and storage (BECCS), which represents approximately 25% of the mitigation required for a net-zero world. This implies roughly 5 $GtCO_2e$/yr of reductions by 2030[1]. The measures consist in roughly equal proportions of those that reduce GHG emissions from land, such as protecting forests, peatlands, coastal wetlands and grasslands, and those that remove CO_2 from the atmosphere, such as restoring such ecosystems. Removal of CO_2 is required to achieve net zero in any economy where some GHG emissions continue and need to be offset (see Figure 1).

FIGURE 1

The need for carbon dioxide removal



To achieve net zero emissions by 2050 in line with a pathway to stabilise the global mean temperature at 1.5°C above pre-industrial times, GHG emissions need to be reduced compared to a 'business-as-usual' trajectory[20]. Any remaining GHG emissions in 2050 need to be offset or counteracted by removing an equivalent amount of CO_2 from the atmosphere. Land-based mitigation options play a part both in reducing emissions, for example by halting destruction of forests and peatlands, and in removing CO_2, for example by restoring forests and peatlands[1].

2.1 Short-term priority actions – beginning immediately

The 'roadmap' study[1] included the following land based mitigation options to be implemented from 2021 to 2050 (see Figure 2):

- **Reducing emissions from deforestation, peatland drainage and burning, coastal wetland conversion and grassland conversion:** Particularly in tropical countries including Brazil, Indonesia and countries in Africa's Congo Basin; 70% reduction by 2030, 95% by 2050. Costs estimated at up to \$100/ tCO_2 for reducing deforestation; up to \$20/tCO_2 for reducing peatland and grassland conversion[21].

  Total estimated potential annual GHG reduction by 2050: 4.6 $GtCO_2e$/yr.

- **Reducing consumer food waste:** In developed and emerging countries, particularly from consumption in the US, Europe and China and from production in Southeast Asia and Sub-Saharan Africa; 30% reduction by 2030; 50% by 2050. This has potential cost savings as food waste is estimated to cost up to \$1 trillion per year[9, 22].

  Total estimated potential annual GHG reduction by 2050: 0.9 $GtCO_2e$/yr.

- **Dietary change:** One in five people shifting to healthy diets (less than 60 grams of meat protein per day, less than 2,500 total daily calories) by 2030 in developed and emerging countries with high meat consumption, particularly in the US, Europe, China, Brazil, Argentina, Russia and countries in the Middle East; one in two by 2050. Costs of different shifts vary and there is evidence that some types of healthy diets are unaffordable for many[23]. Research has identified needs to demonstrate food patterns that are nutrient rich, affordable, and appealing[24].

  Total estimated potential annual GHG reduction by 2050: 0.9 $GtCO_2e$/yr.

- **Restoring degraded, carbon-rich ecosystems:** Forests, drained peatlands, coastal wetlands, including sea grass and kelp; particularly in tropical countries; Total estimated cumulative GHG reduction by 2030 9 $GtCO_2e$. (equivalent to around one year of China's emissions). Costs estimated at \$10-100/ tCO_2[21].

  Total estimated potential annual GHG reduction by 2050: 3.6 $GtCO_2e$/yr.

- **Improving forest management and agroforestry:** Increasing carbon stored in, and expanding the footprint of, timber production forest and agroforestry lands – particularly in the US, Russia, Canada, Europe, Australia, Brazil, Indonesia and other tropical countries. Total estimated cumulative GHG reduction by 2030: 4 $GtCO_2$ (equivalent to around one year of the EU's total emissions). Costs estimated at \$10-100/ tCO_2[21].

  Total estimated potential annual GHG reduction by 2050: 1.6 $GtCO_2e$/yr.

- **Enhancing soil carbon sequestration:** On agricultural lands, including application of biochar – a charcoal-like product that stores carbon – and reducing fertiliser emissions across all agricultural countries particularly China, the US, Europe, Australia, India, Brazil, Argentina, Mexico, Indonesia and the countries of Sub-Saharan Africa. Total estimated cumulative GHG reduction by 2030: 3 $GtCO_2e$ (equivalent to around one year of India's total emissions). Costs estimated at \$10-100 tCO_2[21].

  Total estimated potential annual GHG reduction by 2050: 1.3 $GtCO_2e$/yr.

One study found that land-related measures, both supply and demand side, could in total deliver around 14 $GtCO_2e$ of emission reduction per year by 2050, or around 15 $GtCO_2e$/yr with bioenergy with carbon capture and storage (BECCS), which represents approximately 25% of the mitigation required for a net-zero world.

2.2 Additional actions – beginning in 2030

In the longer term after 2030, these priority actions are ratcheted up, and two additional actions are added (see Figure 2):

- **Reducing direct emissions in agriculture:** From enteric fermentation, manure management, rice cultivation; reducing methane and nitrous oxide as well as CO_2; in developed and emerging countries, Asia and Latin America. Costs estimated at $<10-100/ tCO_2[21].

  Total estimated potential annual GHG reduction by 2050: 1 $GtCO_2e$/yr.

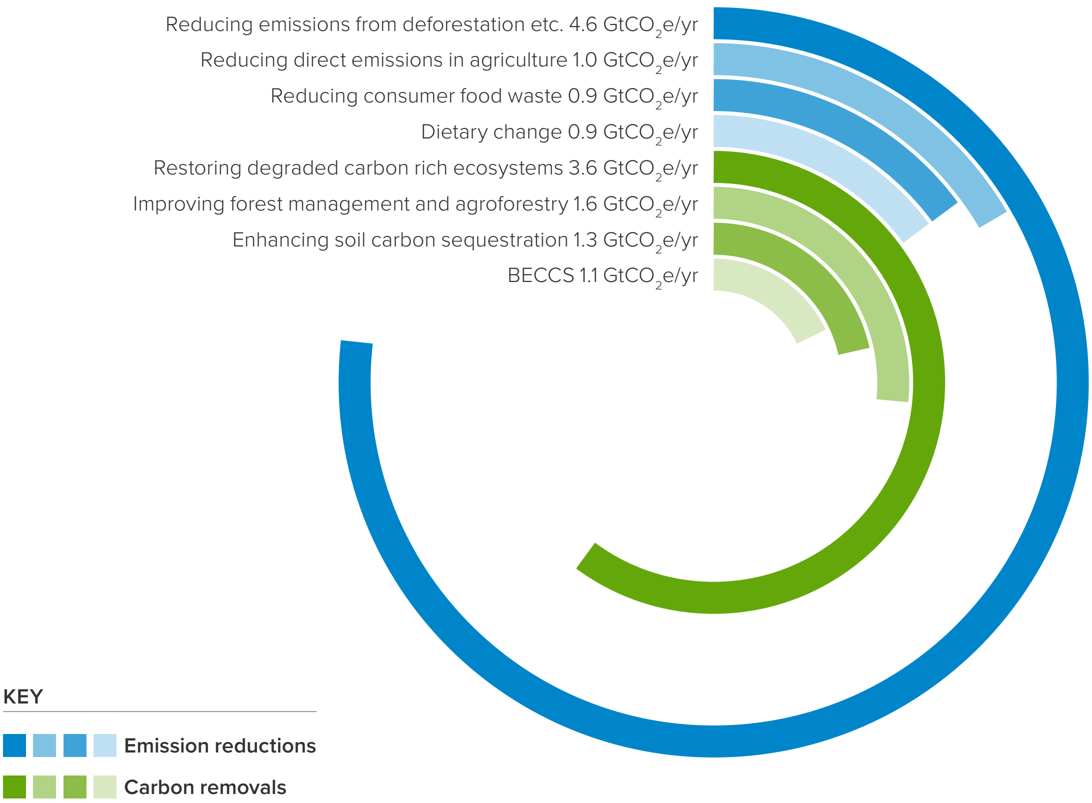
- **Bioenergy with carbon capture and storage (BECCS):** Moderately deployed over 34-180 Mha of land. Costs estimated at $<10->100/ tCO_2[21]. When applied at Gt removal scales, very large land areas are needed and land competition can be an issue for large scale BECCS and afforestation.

  Total estimated potential annual GHG reduction by 2050: 1.1 $GtCO_2e$/yr.

FIGURE 2

The eight land based mitigation options

Total estimated potential in annual GHG emissions reductions from land-based mitigation options to be implemented from 2021 to 2050 from the 'roadmap' study[1].



3. Science-based priorities for action in research and deployment

Science indicates six principles to consider in examining the potential of land-based mitigation options.

3.1 Action on land and fossil fuels: 'both-and', not 'either-or'

Researchers stress that land-based options need to be used as a complement to, and not a substitute for, rapid reductions in fossil fuel consumption and emissions. The land's capacity to absorb carbon is already being weakened by the impacts of climate change[25]. Carbon offsetting programmes cannot therefore be seen as a 'get-out-of-jail' card for emitters, tradable for any volume of fossil fuel emissions.

3.2 Serving multiple goals

Land-based mitigation options have a particular relevance in today's context of global economic recovery. Nature-based solutions can not only reduce emissions but also help build climate resilience. support healthy lives and stimulate economic development[26]. For example, afforestation and reforestation alone can potentially contribute to 13 of the 17 UN SDGs if undertaken sustainably[27].

Research on the ground has also showed that deforestation rates often tend to fall when legal forest rights are held by indigenous peoples and local communities, who manage about half of the global landmass under various forms of collective, traditional or 'customary law'[28, 29, 30]. For example, one study in Benin showed that when 70,000 landholdings were formally registered, forest loss declined with no evidence of leakage[31]. Moreover, designating certain forest areas to be managed by the local community led to them being described as 'domaine sacré' (sacred ground) and were left intact[32, 33].

3.3 A more sustainable food system

An opportunity exists to seek a more sustainable future for the food system, with lower GHG emissions but sufficient output to support a growing population. This issue can be approached from the supply side, by action on agriculture, and from the demand side, through shifts that reduce pressure for increased food production, particularly with high emissions.

Scientists warn that with food demand rising, any land policy for the climate that fails first to provide food security, regionally and nationally, is likely to fail because forests, grasslands and other ecosystems will continue to be converted to croplands[34].

The food production system can grow rapidly: it tripled in production between 1961 and 2011[35]. Over the next 30 years, it needs to grow significantly to meet demand, 50% being one UN projection[35], at the same time as reducing its carbon footprint.

One key route to reconciling these pressures is known as 'sustainable intensification', defined as 'a process or system where yields are increased without adverse environmental impact and without the cultivation of more land'[36].

Sustainable intensification can include closing 'yield gaps' – the gaps that mean for example that American farmers who can grow five times as much corn per acre as their African counterparts – as long as this is done without increasing emissions[37, 38]. A study of farming communities in Africa, for example, showed how action to improve the matching of agronomic inputs to crop requirements and adopt more productive technologies enabled farmers to close yield gaps of up to 200%, with emissions intensity falling by up to 60%[39].

Meanwhile, from the demand side, with up to around one-third of global greenhouse gas (GHG) emissions arising from the food system, 2021 provides a fresh opportunity for a respectful, science-based conversation about diet and food, and their impact on the planet. (See briefing 10: *Nourishing ten billion sustainably*.)

3.4 Conserve, restore, and sustainably manage

Land-based options exist along a spectrum of priorities where the most beneficial are sometimes the most challenging to implement. On a global

On the ground, emerging evidence suggests that solutions that protect ecosystems from destruction or degradation should be a priority as they have very high mitigation potential. This is because the loss of a forest, peatland, grassland or mangrove not only releases stored carbon as it is cut down, but also prevents years or decades of future carbon sequestration.

scale, dietary shifts and reduced food waste are often prioritised as they release pressure on land and enable other actions to be taken.

On the ground, emerging evidence suggests that solutions that protect ecosystems from destruction or degradation should be a priority as they have very high mitigation potential[40]. This is because the loss of a forest, peatland, grassland or mangrove not only releases stored carbon as it is cut down, but also prevents years or decades of future carbon sequestration[41, 42]. Such protection-based measures are accompanied by restoration and management, where different types of solutions can have different potentials. In the roadmap covered above (see figure 2), for example, reducing emissions from deforestation and degradation of coastal wetlands and peatlands accounts for the highest potential mitigation (4.6 $GtCO_2e/yr$), followed by reforestation (3.6 $GtCO_2e/yr$) and then improved forest management (1.6 $GtCO_2e/yr$)[1].

In practice, many of the pledges made by governments relate to forests and in particular to afforestation. For example, more than 40 countries have committed to bringing together 350 million hectares of deforested and degraded land into restoration by 2030 as part of the Bonn Challenge[43, 44]. Researchers have raised concerns that tree-planting is distracting from the need to rapidly phase out use of fossil fuels[45]. As well as the issues regarding monoculture plantations discussed above, there are also concerns that forestry expansion presented as a climate solution is taking precedence over options for other native ecosystems. Specialists have urged policymakers to consider the wide range of ecosystems beyond forests, such as grasslands, coastal wetlands and peatlands[45].

3.5 Unlocking investment

Land-based solutions have been supported by governments, banks, international financial institutions, private companies and funds such as the Green Climate Fund (GCF)[46]; Adaptation Fund (AF)[47]; Climate Investment Funds (CIF)[48]; and Global Environment Facility (GEF)[49].

Although such options have struggled to attract funding compared to low-carbon energy over the past two decades, there are some signs that investment may be on the rise.

Momentum is building in the business community, with around 25% of Fortune 500 businesses committed to carbon neutrality by 2030[50]. While such sustainable investments are needed, investors and others are also urging companies to commit to feasible reductions in their life cycle fossil fuel footprints[51].

Science-informed monitoring, reporting and verification tools are developing rapidly. For example, in June 2020, the International Union for the Conservation of Nature (IUCN) launched a Global Standard to help ensure that activities described as nature-based solutions deliver benefits such as economic development, health, biodiversity, food and water security[52, 53]. Such tools help create the enabling environment for large-scale investments to go ahead sustainably.

3.6 Still much to learn

Research into land-based mitigation has grown very rapidly in recent years. A search of science databases found that articles and reviews using the term ‘nature-based solutions’ grew from around 100 up to 2018, to around 650 by 2020[45]. However, with nature-based solutions being characterised by multiple benefits, wider research is important to determine and measure the positive – or negative – outcomes that land-based activities demonstrate. For example, ongoing research is needed to determine how the potential of land-based options may be affected by the impacts of climate change itself. At a more detailed level, studies can demonstrate how some options have both mitigation and adaptation benefits – such as restoration of mangroves or woodlands that enhances carbon sequestration as well as providing flood and erosion protection.

Research can also maximise the biodiversity benefits of activities, for example by integrating biodiverse habitats into connected networks that allow species to shift their ranges in response to climate change[54].

4. Taking care of nature

In the 2020 documentary *David Attenborough: A Life on our Planet*, the naturalist and broadcaster Sir David Attenborough has said that "nature is our greatest ally"[55] in overcoming climate change, but its allegiance is not unconditional. The land, with the ocean, has effectively soaked up more than half of the greenhouse gases humans have put into the atmosphere since the Industrial Revolution.

But climate change may itself reduce the land's sink capacity if energy emissions are not reduced rapidly. However, if fossil fuel emissions are cut, land-based climate mitigation options can still play an important part[56]. As Attenborough goes on to say, "If we take care of nature, nature will take care of us"[57].

This briefing is one of a series looking at how science and technology can support the global effort to achieve net zero emissions and adapt to climate change. The series aims to inform policymakers around the world on 12 issues where science can inform understanding and action as each country creates its own road map to net zero by 2050.

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