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# Nourishing ten billion sustainably: resilient food production in a time of climate change


**In brief**

The global food system accounts for around one third of greenhouse gas (GHG) emissions generated by human activity[1]. It therefore offers a major opportunity for progress towards net zero if emissions can be reduced at the same time as delivering food security and building resilience to the inevitable impacts of climate change. Research shows how solutions can be found in diet change, respectfully approached, sustainable agricultural practices and harnessing the continuing wave of innovation in food biotechnology.


## INSIGHTS

- An opportunity exists for policy-makers, agricultural communities and scientists from many disciplines to work together to end hunger and to achieve food security and nutrition in a net zero context. This includes reducing emissions from the food system, increasing its resilience and protecting biodiversity.
- Research demonstrates the interconnectedness of climate impacts with food production and consumption. It indicates that food, agriculture and aquaculture policy should follow a strategic systems approach, involving all stakeholders, that will contribute to many of the UN Sustainable Development Goals.
- Given the environmental impact of many aspects of the food system, it is important for policy-makers to address the question of diet and its consequences for the climate, taking account of economic and social factors.
- Research and development is needed to support a sustainable, innovative, climate-smart global food production system; key areas range from agroforestry best practice and measures to reduce enteric fermentation to new breeds of crops that sustainably increase yields per hectare.
- Biotechnology is seeing a particularly rapid acceleration in the use of science and innovation to improve quality and yields as well as resistance to pests, diseases, heat and drought at a time of climate change.
- Progress towards a resilient, food system with low greenhouse gas (GHG) emissions requires science to be deployed from fundamental research and development through to demonstration and deployment of technologies and agricultural practices, working closely with the farming sector.

# 1. The food system and climate change – a four-way challenge

It has been estimated that between 21 to 37% of all human-generated, or anthropogenic, GHG emissions are directly or indirectly attributable to the food system.

This briefing focuses on the four-way challenge at the nexus of climate change and the food system. The tasks are: first, to nourish a world population projected to rise to nearly 10 billion by 2050[2]; second, to reduce GHG emissions from the food system; third, to make food production resilient to climate change; and fourth, to minimise biodiversity loss as well as other planetary concerns such as resource depletion and pollution arising from agricultural production. While the global population keeps rising, the world loses 23 hectares of arable land[3] to drought and desertification every minute.

### 1.1 Food security – the need to prevent millions going hungry

The challenge of creating a net-zero compliant and climate-resilient food system comes at a time when hunger is growing. While the proportion of undernourished people in developing regions has fallen by almost half since 1990[4], almost 700 million people went hungry in 2019, up by nearly 60 million in five years, and more than 1.5 billion experienced deficiencies in essential nutrients[5]. The UN Framework Convention on Climate Change (UNFCCC) has identified extreme weather events, conflict[6], land degradation, desertification, water scarcity and rising sea levels as particular drivers of hunger and food insecurity[7]. But, such is the imbalance in access to food that while millions go hungry, nearly two billion people are overweight[8]. On current trends the challenge will intensify as demand for food is projected to rise substantially by 2050, an increase that the FAO estimate at 50%[9].

### 1.2 Food for net-zero – the need to reduce the systems' carbon footprint

The global food system has itself become a major driver of climate change. Agriculture has become more intensive, expanding into forests, with livestock managed in high density feedlots and crops grown with high levels of fertiliser. 40% of land conversion to agriculture in human history has occurred in the past 100 years[10]. The mid-20th century 'green revolution', partly due to scientific advances such as crop research[11], boosted production, contributed to increased food security by saving an estimated billion people from starvation and prevented even more extensive farming[12]. However, the environmental impact was mixed. In particular, higher yields have reduced GHG emissions per hectare while greater use of fertiliser has increased them[13].

It has been estimated that between 21 to 37% of all human-generated, or anthropogenic, GHG emissions are directly or indirectly attributable to the food system, according to the Intergovernmental Panel on Climate Change (IPCC) 2019 report on Climate Change and Land (based on 2007 – 2016 data)[14]. This equates to around 11 – 19 billion tonnes of carbon dioxide equivalent per year ($GtCO_2e/yr$). A global food emissions database presented in 2021 reinforced and narrowed the estimate, indicating that in 2015, food-system emissions amounted to 18 $GtCO_2e/yr$, representing 34% of total GHG emissions[1]. Emissions from food production include methane, emitted from livestock and rice paddies, and nitrous oxide, largely created by fertiliser use, as well as $CO_2$ from land-use change and other sources.

The IPCC estimates that around 9-14% of all anthropogenic GHG emissions come from agricultural food production, while around 5-14% come from changes in land-use, including cutting down forests, draining peatlands and clearing grassland to meet society's needs for food. A further 5 – 10% of all emissions are estimated to come from the food supply chain including production, processing and distribution, as well as food waste[15]. Around 1.3 billion tonnes of food worth around $750 billion are wasted each year[16], with an estimated carbon footprint of 3.3 $GtCO_2e/yr$[17]. Around half of the wasted food is lost between harvest and distribution. Livestock alone, mainly ruminants, has been estimated to account for around 14.5% of total human-generated emissions when the whole life cycle is taken into account (7.5 $GtCO_2e/yr$ if applied to 2007 – 2016)[18].

Fishing vessels generate around 170 million tonnes of carbon dioxide ($MtCO_2$) per year, according to FAO figures, with aquaculture producing around 385 $MtCO_2$, together contributing around 1.5% of all anthropogenic $CO_2$ emissions[19].

A recent analysis estimated that even if all GHG emissions from fossil fuel use were halted immediately, current trends in global food systems would prevent the achievement of the 1.5°C target and, by the end of the century, threaten the achievement of the 2°C target[20].

### 1.3 Food resilience – the need to adapt to the impacts of climate change

As well as contributing to GHGs, the food production system is itself being affected by changing climate, with adverse impacts projected to outweigh gains. If no action is taken, climate change is currently projected to lead to a fall of 2% per decade in global agricultural production through to 2050, when global food demand will be increasing[21]. Crop yields are vulnerable to floods, heat, drought, climate unpredictability and newly emerging pests and pathogens[22]. Further, livestock production is affected by impacts on feedstock, forage, water and disease[23]. In the fisheries sector, climate change is expected to reduce the global catch level by up to 5% in a scenario of 2°C warming, further depleting overfished stocks and reversing successes in rebuilding some stocks in regions such as the US, Canada and Northern Europe[19]. In the aquaculture sector, while some fish will get larger, adverse impacts include weather damage to infrastructure such as cages and nets; increases in disease and parasites; and depletion of dissolved oxygen in water – hypoxia[19].

### 1.4 Biodiversity – the need to provide food without endangering species

The global food system includes thousands of species of plants, animals and fungi that form the food supply, as well as those that pollinate crops, control pests, create soil fertility and provide other services. However, as the recent UK Dasgupta Review on The Economics of Biodiversity notes, the food system is also the greatest driver of biodiversity loss[24], through damage to habitats, fragmentation and over-exploitation[10]. Of approximately 25,000 species identified as threatened with extinction, around 13,000 are threatened by agricultural land clearing and degradation, around 3,000 by hunting and fishing, and a further 3,000 by pollution from the food system[10]. The food system also creates pollution in the form of nitrogen and phosphorus from fertiliser that are not fully utilized by plants and instead affect the quality of air and water. The rock phosphate form of phosphorus used in fertilisers is also a finite resource with major reserves concentrated in a few countries. Estimates of how long the reserves can last range from 40 years to several centuries[25, 26].

In aquaculture, or fish farming, measures such as increasing efficiency, using renewable energy and improving feed conversion rates can reduce emissions[19].

# 2. What more do we need to know? How science can support low-carbon, climate-resilient food systems

Studies show that animal-based foods tend to have a much larger life-cycle carbon footprint than others, with beef, for example estimated at generating 15-50 times the greenhouse gas footprint of peas or pulses, depending on the regions and metrics analysed[27, 28, 29].

Policy-makers have an opportunity to build momentum in policy, innovation and investment in support of sustainable agriculture, food security and nutrition as part of the effort to achieve net zero and climate resilience. The complex challenge of meeting increasing demand for food while reducing its impacts on ecosystems, as well as its vulnerability to a changing climate, can be approached by many routes, including agronomy, soil science, social science, economics and political economy.

Here, we focus on the contribution of research in three important areas:

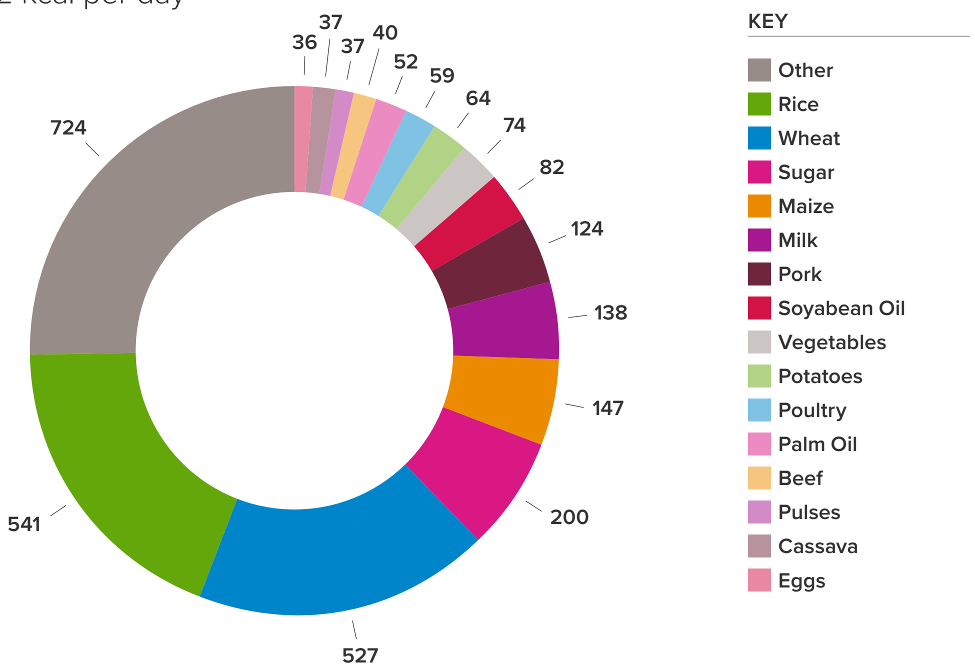
- First, sustainable food consumption – changes in demand and the composition of diets that release pressure on supply;
- Second, sustainable food production – producing more food with reduced carbon intensity and a lower environmental footprint; and
- Third, sustainable food technologies – improving both yields and resilience through breeding and genetic approaches, and other innovations.

### 2.1 Sustainable food consumption

In terms of food consumption, diets dominated by meat and dairy products have led to GHG-intensive farming. Studies show that animal-based foods tend to have a much larger life-cycle carbon footprint than others, with beef, for example estimated at generating 15 – 50 times the greenhouse gas footprint of peas or pulses, depending on the regions and metrics analysed[27, 28, 29].

**FIGURE 1**

A distribution of global average daily calorie intake per person from an estimated total of 2882 kcal per day*




* An estimated 75% of calories comes from twelve crops and five animal products. Figure 1 developed using data from FAOSTAT 2013[70, 71].

There is considerable evidence of the potential for diet change to reduce emissions, along with improvements in technologies and management, and reductions in food loss and waste[30]. The IPCC has analysed multiple studies on the technical mitigation potential of changed diets across the global population by 2050. It found that a diet with moderate meat but rich in fish and vegetables would reduce global GHG emissions (estimated at 59.1 $GtCO_2e$ in 2019[31]) by 3$GtCO_2e$/yr, a 'flexitarian' diet of limited meat and dairy by 5 $GtCO_2e$ /yr, a vegetarian option by 6 $GtCO_2e$ /yr and a fully vegan diet by nearly 8 $GtCO_2e$ /yr[32] (see Figure 2).

Diet choices are influenced by many factors, including social and cultural traditions. An opportunity now exists to create a global dialogue on the topic, where openness and respect are coupled with scientific evidence. Several studies have put forward models for sustainable diets that have benefits for the climate and for human health, typically high in plant-sourced foods[33, 34]. Global awareness of such diets does not prescribe that they should be followed, and in some places they may not currently be practical or affordable, but they provide terms of reference for public debate, nationally and globally.

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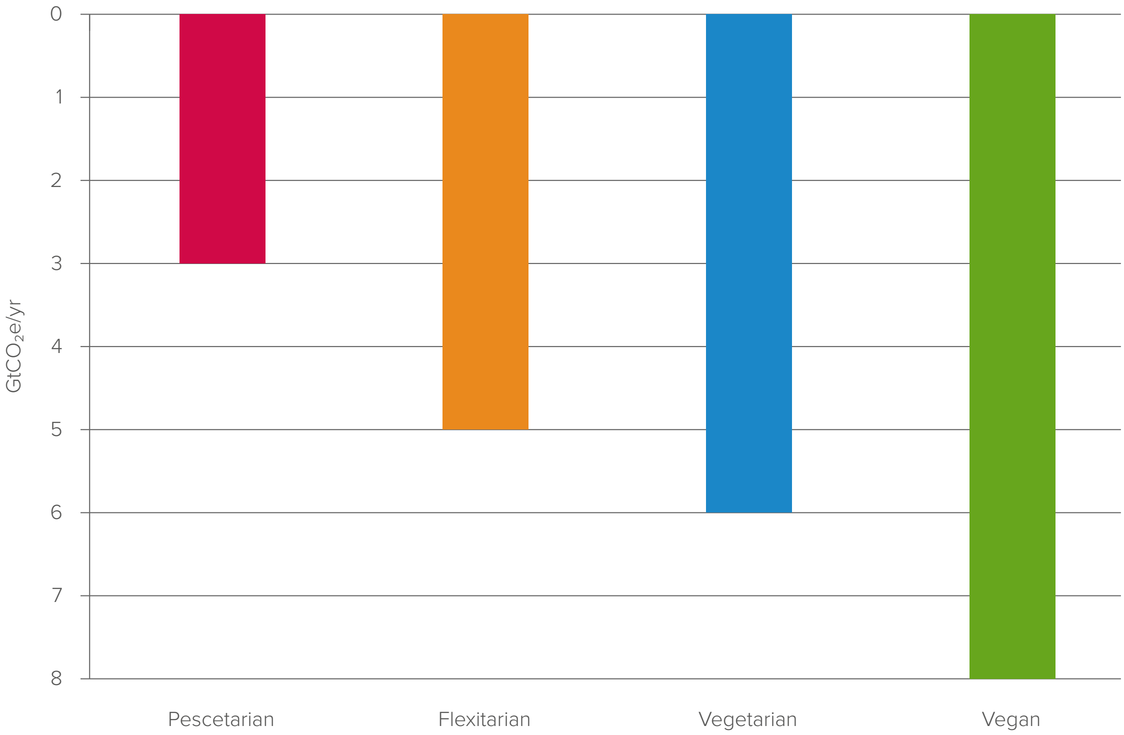
**FIGURE 2**

Demand side GHG mitigation potential



There is also potential to expand consumption of fish and seafood significantly with an increase in aquaculture productivity compensating for limitations on wild fisheries. However much current aquaculture is environmentally damaging and attention must be paid to ensure that any increases are sustainable[35]. One study indicated that policy measures and technology developments together could increase production of food from the sea, by as much as 75%, a level where it could replace around 25% of the projected increase in meat required to feed a population of 10 billion in 2050[36].

Other studies have examined the potential of so-called 'future foods' such as cultured meat, fungal protein, insect larvae and algae such as chlorella and spirulina. These require less land than traditional animal-sourced foods while providing a wider range of nutrients than plant-sourced ones. As with all aspects of dietary change uptake of these novel food types will be affected by deeply held social and cultural values as well as affordability and researchers recognise that greater understanding is required of ways to enable them to be acceptable and affordable[37].

While the growing and distribution of food are important, food loss and waste needs to be better understood, with various proposals that range from new approaches to measuring losses[38] to specific solutions such as a new approach to 'use by' and 'best by' labels[39].

### 2.2 Sustainable food production

On the supply side, in agriculture, research can support GHG reductions across the full range of farms and cropping systems, from industrial-scale operations to small-holdings that account for most of the world's farms[40].

Achieving both higher outputs and lower carbon footprints involves 'sustainable intensification': in which yields are increased without adverse environmental impact and without the cultivation of more land[41]. The process also releases land for rewilding or for farming for food and biodiversity.

Scientific innovation can support sustainable intensification in many ways. It can create new climate-resilient varieties of crops, which have higher yields and require less water, fertilisers and pesticides. Livestock farmers at all scales can benefit from research into reducing enteric fermentation in animals, for example, by manipulating silage composition[42] or novel feed additives such as '3 NOP' (3-Nitrooxypropanol). Agroforestry approaches that combine forestry with other forms of farming can be supported, for example, by research into outcomes of individual projects[43] or wider studies into issues such as potential certification programmes[44, 45, 46].

Fertiliser use generates emissions of nitrous oxide ($N_2O$), which is much more potent than carbon dioxide as a greenhouse gas[47]. With $N_2O$ emissions having risen 20% since pre-industrial times[48] the UN has launched a Global Campaign on Sustainable Nitrogen Management to halve waste and save $100 billion by 2030[47, 49]. Building on success in the US and Europe, work is needed to increase the efficiency of nitrogen use, for example, through precision delivery of fertiliser[49].

In capture fisheries – the harvesting of naturally occurring fish and seafood – it is estimated that emissions could be reduced by 10-30% through changes in machinery such as more efficient engines, larger propellers, and different vessel shapes[19]. In aquaculture, or fish farming, measures such as increasing efficiency, using renewable energy and improving feed conversion rates can reduce emissions[19].

One UK Government-commissioned analysis of 40 projects in 20 countries where sustainable intensification had been developed documented benefits for 10 million farmers and doubling of average yields. However, more appraisal is needed[50] (See section 3).

## 2.3 Sustainable food biotechnologies

Innovation is flourishing across food technologies, from food processing and biochemistry to nutritional sciences. Focusing here on one particularly fast-moving field of biotechnology, the discipline of genetic innovation is seeing a transformational step-change, unlocking data and knowledge that scientists and breeders can use to address some of the seemingly inseperable issues at the agriculture-environment interface.

Research has a particular role to play in providing new breeds and varieties that sustainably increase yields per hectare, and thus reduce emissions, as well as those that have greater resilience to the impacts of climate change.

The foundations of the latest breakthroughs lie in the genome sequencing of hundreds of varieties of crop species since the early 2000s, revealing hitherto-untapped variations that are being exploited to develop crops with sustainable properties. The rice genome was mapped in 2002 by an international consortium (See panel – Green Super Rice), followed by the genome of wheat, potatoes, tomatoes, strawberries, cocoa and many other plants[51].

Databases have been created, such as the International Rice Genebank, which holds more than 132,000 entries[52], providing resources to create new high-yield or low-vulnerability cultivars.

'Speed breeding' of new cultivars has become an established approach, with techniques that can achieve six generations per year for spring wheat, durum wheat, barley, chickpeas and peas[53].

Researchers are also studying possibilities for breeding livestock in ways that reduce emissions. For example, breeding for improved efficiency enables overall animal numbers to be reduced; one estimate suggested a fall of 8% in emissions might be achieved in this way[55].

**BOX 1**

### Green super rice

One of the world's foremost scientific efforts to create a climate-resilient, high quality crop is the project initiated in China to develop 'Green Super Rice' (GSR), so called because of its environmental and nutritional qualities[67]. The project emerged from a context in the 1990s where China was experiencing increasing environmental threats, particularly rain and pests, in its effort to feed and nourish more than 20% of the world's population with around 8% of its arable land[68]. The country formed a plan for a 'second Green Revolution' to create new varieties of rice. It took a leading role in the International Rice Genome Sequencing Project, along with Japan, Taiwan, Thailand, Korea, India, Brazil, France, Canada, the UK and US[69]. This provided the resource base for Chinese plant scientists to embark on a long-term plant breeding programme.

Genes and genetic processes were identified to improve rice in multiple, many climate-related, dimensions, not only increasing its yield, which was China's top priority at the start, but improving resistance to disease and drought, enhancing nutrient efficiency and thus reducing fertiliser, and making it tastier. The accumulation of the desired genes has resulted in progressive improvement of rice cultivars, and by 2018 over 40 new cultivars were designated as GSR. Farmers were set a 3x30 target – 30% less each of fertiliser, pesticides, water use and thus greenhouse gas emissions. The Chinese Academy of Agricultural Sciences is now working with international partners (the Bill and Melinda Gates Foundation) to share China's expertise in Sub-Saharan Africa and Asia[67].

Given that 75% of the world's food is generated from only 12 plants and five animal species[64], researchers have also been examining the scope for genetic improvements to so-called 'orphan' crops such as millet and grass pea which can provide highly resilient and nutritious protein, which are currently mainly restricted to certain regions[65].

Selective breeding also offers an adaptation strategy in aquaculture. For example, Sydney rock oysters that had been bred for fast growth and disease resistance were able to improve shell growth to overcome ocean acidification[54].

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Gene editing has also undergone a transformation in the last decade with the availability of the Nobel Prize winning CRISPR/Cas9 'genetic scissors'[56] that can enhance traits including pathogen resistance, abiotic tolerance, plant development and morphology[57]. New technologies based on CRISPR/Cas9, such as gene drive, which passes a modification through a population, offer novel prospects for pest control to replace broad-spectrum insecticides, provided their safety and acceptability to society can be demonstrated[58].

A number of scientists working in this area have proposed that genetic modifications to our food supply – whether by genome editing or by gene transfer – need to be regulated along the lines of the outcomes they produce and not the technology used to make the change[59, 60].

There are numerous examples where genetic modifications to crops have had environmental benefits. For example, more than 90% of cotton planted in the US, India, China, Australia and South Africa now consists of GM varieties with insect-resistant Bt toxin genes. Hawaii's papaya industry has been revitalised by adding a gene to the plant that enables it to resist the ringspot virus[61]. The use of GM has contributed to sustainable intensification and thus to reduced GHG emissions[62]. The opportunities to enhance crop resilience to environmental change and to reduce the impact of agriculture on the environment are substantial.

One active area of research is a programme to determine whether the capacity of legumes to take nitrogen from the air – nitrogen fixing – can be genetically transferred to cereals, averting the need for commercial nitrogen fertilisers among the world's many cereal farmers[63].

Given that 75% of the world's food is generated from only 12 plants and five animal species[64] (see Figure 1), researchers have also been examining the scope for genetic improvements to so-called 'orphan' crops such as millet and grass pea which can provide highly resilient and nutritious protein, which are currently mainly restricted to certain regions[65].

# 3. Priorities for research and development

This briefing has covered areas where research has already provided strong evidence to inform policy, such as on diet and waste, as well as others where further studies can play an important role in driving progress. In particular, crop science holds enormous potential for progress in climate-resistant, nutritious food that can also be applied within sustainable agriculture. Recent research has noted that while particular aspects of sustainable intensification (such as breeding or agroforestry) have been extensively studied, there has been little research on putting the components together in viable production systems, and developing robust metrics for environmental performance[66].

Recognising that national research budgets are limited, policy makers may want to take steps to foster more collaboration between countries and between public, private and non-profit / philanthropic sectors. Given the system-wide nature of the challenge there is also a case for policy-makers to support multi-disciplinary perspectives that take a joined-up, systems approach and in doing so put the drive for sustainable security in food at the heart of the wider programme to fulfil the UN Sustainable Development Goals.

# 4. In conclusion

Science has provided many advances and insights to support the goal of food security and align it with the journey to net zero emissions and climate resilience. Social science has a role to play alongside natural science and policy in widening public support for more sustainable diets and innovation in plant science, while progress in sustainable intensification of agriculture depends on action to disseminate the good practice identified in research.

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.

To view the whole series, visit **royalsociety.org/climate-science-solutions**
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# References


1. Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello FN, Leip A. 2021 *Food systems are responsible for a third of global anthropogenic GHG emissions.* Nat Food. (doi:10.1038/s43016-021-00225-9)
2. United Nations, Department of Economic and Social Affairs, Population Division. 2019 *World Population Prospects 2019: ten key findings.* See https://population.un.org/wpp/Publications/Files/WPP2019_10KeyFindings.pdf (accessed 10 March 2021).
3. United Nations Environment Programme. 2018 *#FridayFact: every minute, we lose 23 hectares of arable land worldwide to drought and desertification.* See https://www.unenvironment.org/news-and-stories/story/fridayfact-every-minute-we-lose-23-hectares-arable-land-worldwide-drought (accessed 10 March 2021).
4. United Nations Millennium Development Goals. 2015 *Goal 1: eradicate extreme poverty and hunger. We can end poverty: millennium development goals and beyond 2015.* See https://www.un.org/millenniumgoals/poverty.shtml (accessed 10 March 2021).
5. FAO, WHO, IFAD, WFP, UNICEF. 2020 *In Brief to The State of Food Security and Nutrition in the World: transforming food systems for affordable healthy diets.* (doi:10.4060/ca9699en)
6. Food and Agriculture Organisation of the United Nations, World Food Programme. 2020 *UN food agencies warn of rising levels of acute hunger with potential risk of famine in four hotspots.* See http://www.fao.org/news/story/en/item/1325054/icode/ (accessed 10 March 2021).
7. United Nations Framework Convention on Climate Change. 2018 *UN warns climate change is driving global hunger.* See https://unfccc.int/news/un-warns-climate-change-is-driving-global-hunger (accessed 10 March 2021).
8. World Health Organisation. 2020 *Obesity and overweight.* See https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight (accessed 10 March 2021).
9. Food and Agriculture Organisation of the United Nations. 2017 *The future of food and agriculture: trends and challenges.* See http://www.fao.org/3/a-i6583e.pdf (accessed 10 March 2021).
10. Tilman, D, Williams D. 2021 Preserving global biodiversity requires rapid agricultural improvements. *Reversing biodiversity loss: scientific essays about biodiversity.* See https://royalsociety.org/topics-policy/projects/biodiversity/preserving-global-biodiversity-agricultural-improvements/ (accessed 10 March 2021).
11. Pingali PL. 2012 *Green Revolution: impacts, limits, and the path ahead.* P. NATL. ACAD. SCI. USA 109, 12302–12308. (doi:10.1073/pnas.0912953109)
12. Stevenson JR, Villoria N, Byerlee D, Kelley T, Maredia M. 2013 *Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production.* P. NATL. ACAD. SCI. USA 110, 8363–8368. (doi:10.1073/pnas.1208065110)
13. Layman E. 2017 *Feeding global warming: assessing the impact of agriculture on climate change. The People, Ideas and Things Journal, cycle 6.* See https://pitjournal.unc.edu/article/feeding-global-warming-assessing-impact-agriculture-climate-change (accessed 10 March 2021).
14. IPCC. 2019 *Summary for Policymakers. In: Climate change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* Shukla PR *et al*. (eds). In press. See https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf (accessed 26 February 2021).
15. IPCC. 2019 *Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Shukla PR *et al*. (eds). In press. See https://www.ipcc.ch/srccl/ (accessed 29 March 2021).
16. Food and Agriculture Organisation of the United Nations. 2020 *Policy support and governance gateway: food loss and food waste.* See http://www.fao.org/policy-support/policy-themes/food-loss-food-waste/en/ (accessed 10 March 2021).
17. Food and Agriculture Organisation of the United Nations. 2013 *Food wastage: key facts and figures. In summary report. Food wastage footprint: impacts on natural resources.* See http://www.fao.org/news/story/en/item/196402/icode/ (accessed 10 March 2021).
18. Food and Agriculture Organisation of the United Nations. 2013 *Key facts and findings. In Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities.* See http://www.fao.org/news/story/en/item/197623/icode/ (accessed 10 March 2021).
19. Food and Agriculture Organisation of the United Nations. 2018 *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options.* FAO fisheries and aquaculture technical paper **627**. See http://www.fao.org/3/i9705en/i9705en.pdf (accessed 10 March 2021).
20. Clark MA *et al*. 2020 *Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets.* Science **370**, 705–708. (doi:10.1126/science.aba7357)
21. IPCC. 2014 *Future climate changes, risks and impacts. In: Climate Change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Pachauri RK, Meyer LA (eds). Geneva, Switzerland: IPCC. See https://ar5-syr.ipcc.ch/topic_futurechanges.php (accessed 26 February 2021).
22. Fahad S *et al.* 2017 *Crop production under drought and heat stress: plant responses and management options.* Front. Plant Sci. **8**. (doi:10.3389/fpls.2017.01147)
23. Rojas-Downing MM, Nejadhashemi AP, Harrigan T, Woznicki SA. 2017 *Climate change and livestock: impacts, adaptation, and mitigation.* Climate Risk Management **16**, 145–163. (doi:10.1016/j.crm.2017.02.001)
24. Dasgupta, P. 2021 *The economics of biodiversity: the Dasgupta review.* London: HM Treasury. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/957291/Dasgupta_Review_-_Full_Report.pdf (accessed 10 March 2021).
25. Cordell D, Drangert J-O, White S. 2009 *The story of phosphorus: Global food security and food for thought.* Global Environmental Change 19, 292–305. (doi:10.1016/j.gloenvcha.2008.10.009)

26. Cho R. 2013 *Phosphorus: essential to life – are we running out?* State of the Planet, Earth Institute, Columbia University. See https://blogs.ei.columbia.edu/2013/04/01/phosphorus-essential-to-life-are-we-running-out/ (accessed 18 March 2021).

27. Poore J, Nemecek T. 2018 *Reducing food's environmental impacts through producers and consumers.* Science **360**, 987–992. (doi:10.1126/science.aaq0216)

28. World Economic Forum. 2019 *Meat: the future series. Alternative proteins.* See http://www3.weforum.org/docs/WEF_White_Paper_Alternative_Proteins.pdf (accessed 10 March 2021).

29. Clune S, Crossin E, Verghese K. 2017 *Systematic review of greenhouse gas emissions for different fresh food categories.* Journal of Cleaner Production **140**, 766–783. (doi:10.1016/j.jclepro.2016.04.082)

30. Springmann M *et al.* 2018 *Options for keeping the food system within environmental limits.* Nature **562**, 519–525. (doi:10.1038/s41586-018-0594-0)

31. United Nations Environment Programme. 2020 *Emissions Gap Report 2020. Online introduction.* See https://www.unep.org/interactive/emissions-gap-report/2020/ (accessed 5 May 2021).

32. IPCC. 2019 *Food security. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* Shukla PR *et al*. (eds). In press. See https://www.ipcc.ch/srccl/chapter/chapter-5/ (accessed 10 March 2021).

33. Jarmul S, Dangour AD, Green R, Liew Z, Haines A, Scheelbeek PF. 2020 *Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of 'sustainable diets'.* Environ. Res. Lett. **15**, 123014. (doi:10.1088/1748-9326/abc2f7)

34. World Health Organisation. 2019 *Sustainable healthy diets: guiding principles.* See https://www.who.int/publications/i/item/9789241516648 (accessed 10 March 2021).

35. Martinez-Porchas M, Martinez-Cordova LR. 2012 *World aquaculture: environmental impacts and troubleshooting alternatives.* The Scientific World Journal 2012, 1–9. (doi:10.1100/2012/389623)

36. Costello C *et al*. 2020 *The future of food from the sea.* Nature **588**, 95–100. (doi:10.1038/s41586-020-2616-y)

37. Parodi A *et al*. 2018 *The potential of future foods for sustainable and healthy diets.* Nat Sustain **1**, 782–789. (doi:10.1038/s41893-018-0189-7)

38. Cattaneo A, Sánchez MV, Torero M, Vos R. 2021 *Reducing food loss and waste: five challenges for policy and research.* Food Policy **98**, 101974. (doi:10.1016/j.foodpol.2020.101974)

39. Patra D, Leisnham PT, Tanui CK, Pradhan AK. 2020 *Evaluation of global research trends in the area of food waste due to date labeling using a scientometrics approach.* Food Control **115**, 107307. (doi:10.1016/j.foodcont.2020.107307)

40. Lowder SK, Skoet J, Raney T. 2016 *The number, size, and distribution of farms, smallholder farms, and family farms worldwide.* World Development **87**, 16–29. (doi:10.1016/j.worlddev.2015.10.041)

41. The Royal Society. 2009 *Reaping the benefits: science and the sustainable intensification of global agriculture.* See https://royalsociety.org/-/media/Royal_Society_Content/policy/publications/2009/4294967719.pdf (accessed 11 March 2021).

42. Haque MN. 2018 *Dietary manipulation: a sustainable way to mitigate methane emissions from ruminants.* J Anim Sci Technol **60**. (doi:10.1186/s40781-018-0175-7)

43. Kiyani P, Andoh J, Lee Y, Lee DK. 2017 *Benefits and challenges of agroforestry adoption: a case of Musebeya sector, Nyamagabe District in southern province of Rwanda.* Forest Science and Technology **13**, 174–180. (doi:10.1080/21580103.2017.1392367)

44. Elevitch C, Mazaroli D, Ragone D. 2018 *Agroforestry standards for regenerative agriculture.* Sustainability **10**, 3337. (doi:10.3390/su10093337)

45. Jose S. 2019 *Environmental impacts and benefits of agroforestry. Oxford Research Encyclopedia of Environmental Science.* (doi:10.1093/acrefore/9780199389414.013.195)

46. University of Bristol Clinical Veterinary Science. 2021 *Towards BIOSmart livestock farming in Colombia: cultural landscapes, silvo-pastoral systems and biodiversity.* UK Research and Innovation. See https://gtr.ukri.org/projects?ref=BB%2FS018840%2F1#/tabOverview (accessed 11 March 2021).

47. Thompson RL *et al*. 2019 *Acceleration of global N2O emissions seen from two decades of atmospheric inversion.* Nat. Clim. Chang. **9**, 993–998. (doi:10.1038/s41558-019-0613-7)

48. Tian H *et al*. 2020 *A comprehensive quantification of global nitrous oxide sources and sinks.* Nature **586**, 248–256. (doi:10.1038/s41586-020-2780-0)

49. Agriculture Victoria. 2021 *Nitrogen fertilisers: improving efficiency and saving money. Victoria State Government of Australia.* See https://agriculture.vic.gov.au/climate-and-weather/understanding-carbon-and-emissions/nitrogen-fertilisers-improving-efficiency-and-saving-money (accessed 11 March 2021).

50. Pretty J, Toulmin C, Williams S. 2011 *Sustainable intensification in African agriculture.* International Journal of Agricultural Sustainability **9**, 5–24. (doi:10.3763/ijas.2010.0583)

51. Liu H *et al*. 2019 *Molecular digitization of a botanical garden: high-depth whole genome sequencing of 689 vascular plant species from the Ruili Botanical Garden.* GigaScience, **8**, giz007. (doi:10.1093/gigascience/giz007)

52. International Rice Research Institute. 2019 *International rice genebank.* See https://www.irri.org/international-rice-genebank (accessed 11 March 2021)

53. Watson A *et al*. 2018 *Speed breeding is a powerful tool to accelerate crop research and breeding.* Nature Plants **4**, 23–29. (doi:10.1038/s41477-017-0083-8)

54. Fitzer SC *et al*. 2019 *Selectively bred oysters can alter their biomineralization pathways, promoting resilience to environmental acidification.* Global Change Biology **25**, 4105-4115. (doi:10.1111/gcb.14818)

55. Cassandro M. 2020 *Animal breeding and climate change, mitigation and adaptation.* J Anim Breed Genet **137**, 121–122. (doi:10.1111/jbg.12469)

56. The Royal Swedish Academy of Sciences. 2020 *Press release: the Nobel Prize in Chemistry 2020.* See https://www.nobelprize.org/prizes/chemistry/2020/press-release/ (accessed 11 March 2021).

57. Zhang D, Zhang Z, Unver T, Zhang B. 2020 *CRISPR/Cas: a powerful tool for gene function study and crop improvement.* Journal of Advanced Research. (doi:10.1016/j.jare.2020.10.003)

58. Scudellari M. 2019 *Self-destructing mosquitoes and sterilized rodents: the promise of gene drives.* Nature. See https://www.nature.com/articles/d41586-019-02087-5 (accessed 11 March 2021).

59. The Royal Society. 2021 *Royal Society submission to the DEFRA consultation on the regulation of genetic technologies.* See https://scauthor.royalsociety.org/topics-policy/publications/2021/royal-society-submission-to-the-defra-consultation-on-genetic-technologies (accessed 25 March 2021).

60. European Academies Science Advisory Council. 2020 *The regulation of genome-edited plants in the European Union.* EASAC Commentary. See https://easac.eu/fileadmin/PDF_s/reports_statements/Genome_Editing/EASAC_Genome-Edited_Plants_Web.pdf (accessed 18 March 2021).

61. The Royal Society. 2016 *Which genes have been introduced into gm crops so far and why? In Genetically modified (GM) plants: questions and answers.* See https://royalsociety.org/topics-policy/projects/gm-plants/which-genes-have-been-introduced-into-gm-crops-so-far-and-why/ (accessed 11 March 2021).

62. Kovak E, Qaim M, Blaustein-Rejto D. 2021 *The climate benefits of yield increases in genetically engineered crops.* bioRxiv. (doi:10.1101/2021.02.10.430488)

63. Agri-TechE. 2020 *Nitrogen fixation for cereals to sustainably increase yields in Africa.* See https://www.agri-tech-e.co.uk/nitrogen-fixation-for-cereals-to-sustainably-increase-yields-in-africa/ (accessed 11 March 2021).

64. Food and Agriculture Organisation of the United Nations. 2000 *What is happening to agrobiodiversity?* See http://www.fao.org/3/y5609e/y5609e02.htm (accessed 11 March 2021).

65. Kamenya SN, Mikwa EO, Song B, Odeny DA. 2021 *Genetics and breeding for climate change in Orphan crops.* Theor Appl Genet (doi:10.1007/s00122-020-03755-1)

66. Cassman K, Grassini P. 2020 *A global perspective on sustainable intensification research.* Nat Sustain **3**, 262-268. (doi:10.1038/s41893-020-0507-8)

67. Zhang Q. 2007 *Strategies for developing Green Super Rice. Special series of Inaugural Articles.* P. NATL. ACAD. SCI. USA. See https://www.pnas.org/content/pnas/104/42/16402.full.pdf (accessed 11 March 2021).

68. Chung CT. 2020 *Is paying for fertilizer the answer to advancing African agribusiness? Lessons from China. Development Reimagined.* See https://developmentreimagined.com/2020/09/01/is-paying-for-fertilizer-the-answer-to-advancing-african-agribusiness/ (accessed 11 March 2021).

69. Eckardt NA. 2000 *Sequencing the Rice Genome.* Plant Cell **12**, 2011–2017. (doi:10.1105/tpc.12.11.2011)

70. Food and Agriculture Organisation of the United Nations. FAOSTAT. *2013 Food Supply - Crops Primary Equivalent.* See http://www.fao.org/faostat/en/#data/CC (accessed 22 March 2021).

71. Food and Agriculture Organisation of the United Nations. FAOSTAT. *2013 Food Supply - Livestock and Fish Primary Equivalent.* See http://www.fao.org/faostat/en/#data/CL (accessed 22 March 2021).