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Foreword

The future of food and agriculture will be challenging

Our food system – the way we grow, process, transport, retail and consume food – and its impacts on prosperity, people (through nutrition) and the environment is, rightly, a focus of research and debate. This is principally because our current food system is unsustainable in a multitude of ways.

Firstly, it is environmentally unsustainable, accounting for about 50 per cent of total global land use, a third of anthropogenic greenhouse gas emissions, it is a major user (and polluter) of water and it is arguably the greatest overall threat to biodiversity. Secondly, it is socially unsustainable, particularly through the restricted availability and access to nutritious food, leading to a global epidemic of illness associated with poor diets. Lastly, it is fragile, so increasingly politically unsustainable: disruption of globalised supply chains in a more contested and conflicted world is leading to volatility in prices and access to food. This creates a growing problem for food security (in the sense of national security) and makes it more difficult for economically marginalised populations to access a healthy diet. Farmers also are under pressure, facing market and climate volatility on tight, and unsustainable, margins.

There has been growing discourse – and literature – on the need for food system transformation in the last decade, but little actual progress other than incremental improvements in the productivity and efficiency of commodity-based agriculture. Part of this arises from the fact that our current food system is locked in, in ways that makes it politically, economically and socially difficult to change.

In part it is also due to a lack of common vision for what a transformed food system would be like.

As the world is changing rapidly through increasingly contested geopolitics and growing climate impacts, it is also *certain* that food and agriculture will have to change. Such change will be driven by market forces in a world in which commodities trading becomes increasingly unreliable and disrupted, alongside the growing need to adapt to cope with the effects of climate change and increasingly extreme weather. Mitigation will also need to become a larger driver of change: unless we reduce emissions, we store up greater problems for the future.

Looking ahead, many plausible futures have shorter supply chains, more domestic production for domestic consumption, the need to build more agro-ecological processes into farm management and more on-farm production diversity – all with less reliance on the large-scale, intensive production of today's major commodity crops.

This provides an enormous research agenda: how do we do what we do but better, but also changing what we grow and how, and what and how we consume food? This is not simply a technically led agenda. It requires change in market drivers, political spaces and the social norms within which people interact with the challenges of living and consuming more sustainably.

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Cover design: Harold Roth has been making art since the 70s, when he spent some time at the School of the Art Institute of Chicago. Lately his work has featured Surrealist landscapes involving the use of Automatism, where the artist doesn't choose the focus of the painting but instead allows it to arise from their subconscious. **haroldroth.com**

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Agricultural revolutions and revelations

Nicola Cannon chronicles the history of agriculture and its effects on humanity and the planet.

The development of agriculture is often attributed to three agricultural revolutions in which transformational change happened in how we grow food (see **Figure 1**). The first agricultural revolution occurred around the Neolithic Revolution, at approximately 10,000 BCE when humans shifted from hunting and gathering to farming and domesticating plants and animals. The development of farming systems allowed humans to move towards a more staple supply of food. The production, harvesting and storage of food has enabled human populations to expand and civilisations to develop by trading surplus food and generating wealth, which led to trade between regions, the development of markets and, ultimately, systems of governance, taxation, defence and infrastructure.

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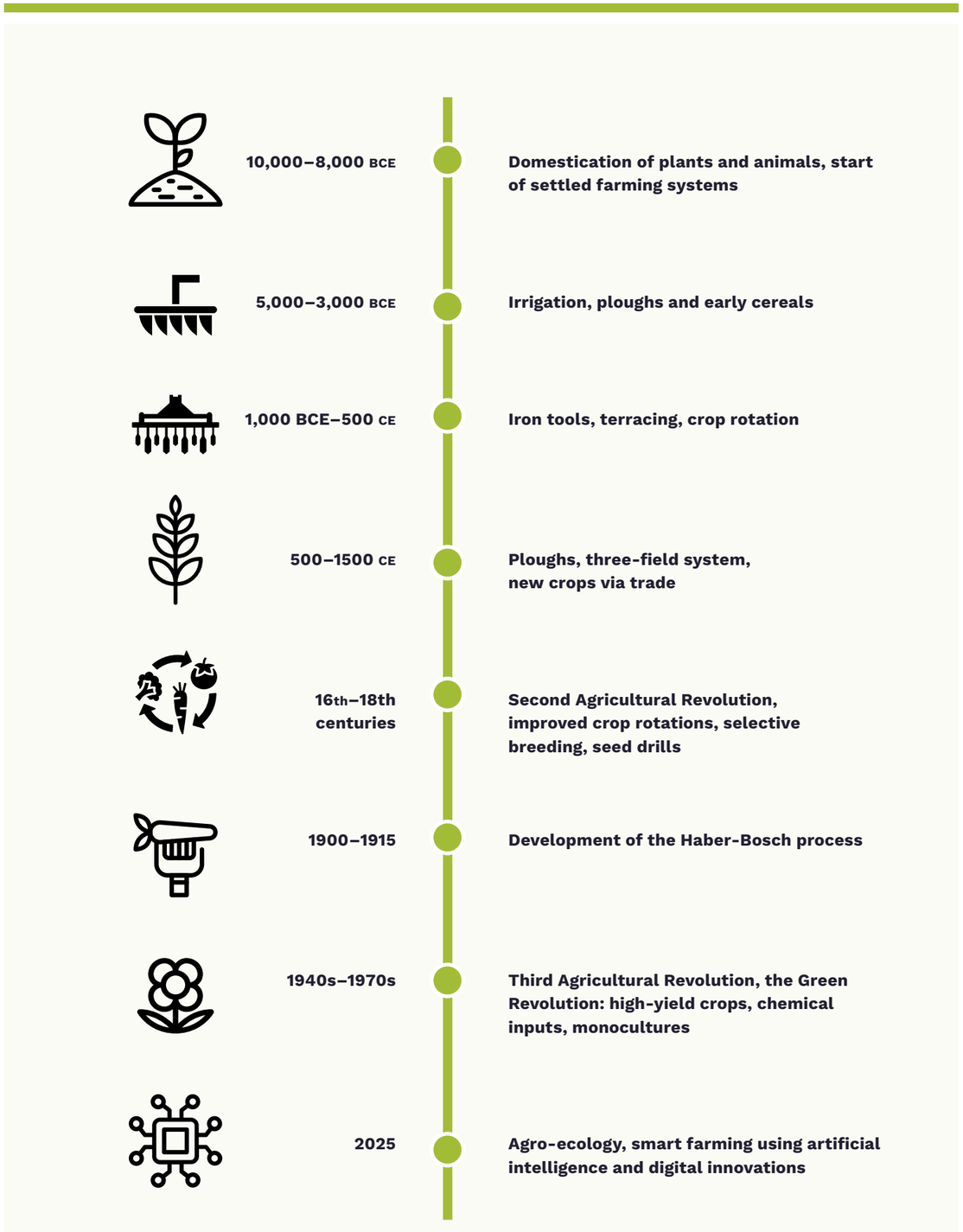

▲ **Figure 1. A timeline of agricultural development.**

The second agricultural revolution occurred between the 17th and 19th centuries, mainly in Europe and particularly in Britain. Farms became enclosed, crop rotation was adopted, livestock was bred for enhanced size, strength and productivity, and equipment was developed to improve land cultivation, crop planting and threshing. Agricultural productivity soared, enabling a rapid population growth and the freeing up of labour for factories, leading to a shift from rural to urban living and fuelling the Industrial Revolution.

The third agricultural revolution occurred in the mid-20th century and is often referred to as the Green Revolution. A gene called Norin 10, discovered in Japan, reduced the height of wheat crops. US scientists crossed this gene with commonly grown varieties to produce semi-dwarf, high-yielding wheat. The shorter plants helped reduce the incidence of lodging, which is where crops collapse when grown under fertile conditions, making them difficult to harvest and lowering recoverable yield and reducing crop quality. After the introduction of this gene, wheat plants were almost half the height, which increased the proportion of grain to straw and enabled the application of fertiliser to improve crop productivity.

The developments in plant breeding happened after scientists in the early 1900s determined that nitrogen was essential for plant growth; but natural sources like guano and Chilean saltpetre were limited. Between 1905 and 1909, Fritz Haber discovered he could generate continuous ammonia gas in a laboratory by taking atmospheric nitrogen and adding hydrogen gas, high pressure (150–200 atmospheres), high temperature (400–500C) and an iron-based catalyst. Carl Bosch then immediately started working to overcome enormous engineering challenges to enable factory production by building a reactor that could withstand the high temperatures and pressures required to enable the process. By 1913, the first industrial Haber–Bosch plant was operating in Germany, making ammonia-based fertilisers widely available.

▲ **Diseased wheat plants. © Aleksa | Adobe Stock**


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Norman Borlaug transformed crop improvements by creating high-yielding wheat and rice varieties using the Norin 10 gene, further incorporating multiple disease-resistance genes to overcome devastating plant diseases, especially stem rust. He also developed shuttle breeding techniques where wheat was grown in two different locations (north and south), doubling the speed of genetic improvement. The wheat varieties developed were adaptable to multiple climates and day lengths, making them suitable for countries as diverse as India, Pakistan and Turkey. Cereal crops could now be reliably grown in a wider range of environments and enriched with ammonia-based fertilisers, enabling a doubling or even tripling of cereal yields in many regions of the world. These developments helped many farmers produce surplus grain and assisted in reducing global hunger, saving millions from starvation. The improved income for farmers led to investment in mechanisation, irrigation and agricultural inputs. The third agricultural revolution was initially seen as a major success and Borlaug won a Nobel prize.

“While the Green Revolution averted famine, we are paying the price of adopting high-input, resource-intensive production systems.”

It can be argued that while the Green Revolution averted famine, we are paying the price of adopting high-input, resource-intensive production systems that can be viewed today as unsustainable and lacking resilience (see **Table 1**). Growers now have to adopt farming systems to adapt to the changing climate, extreme weather events and feeding a growing global population with higher dietary expectations.

Many see that agriculture needs a fourth agricultural revolution – sometimes referred to as Agriculture 4.0[1] – to adapt and to find solutions to our unsustainable farming techniques. Some believe this will be technologically driven through artificial intelligence, the Internet of Things, robotics and sensors leading to data-driven, resource-efficient farming. Others see an environmental revolution where agriculture becomes more aligned to the environment and works in greater harmony with nature, often referred to as agro-ecological solutions.

Prior to the second agricultural revolution, farms tended to be mixed and subsistence-based, growing a variety of crops and keeping livestock to meet household needs. Specialisation was rare and usually tied to unique environments – for example, vineyards in southern Europe or rice paddies in Asia. Farms became more specialised in the 17th–18th centuries with the rise of market-oriented agriculture and international trade – such as wool and, later, grain markets in

TABLE 1. CAUSES, RESPONSES AND ENVIRONMENTAL CONSEQUENCES BROUGHT ABOUT BY THE GREEN REVOLUTION

CAUSE	MAIN EFFECTS AND RESPONSES	ENVIRONMENTAL CONSEQUENCES
Greater yield potential, which required additional macro and micro elements to realise the majority of enhanced yield	Increased use of nitrogenous fertilisers manufactured using the energy-intensive Haber–Bosch process	Increased emissions in manufacturing, nitrate leaching and nitrous oxide emissions from inefficient use in the field
	A surge in demand for phosphorus fertiliser involving extensive mining and transport	Higher phosphorus levels in agricultural soils, which leads to eutrophication when run-off occurs from fields
Increased yields for wheat and rice crops	Further specialisation into higher-yielding crops	Lower biodiversity on the farm
	More frequent and intensive cultivation of cereals	Increased soil cultivation and soil degradation
	Increased pressure from weeds that flourish in arable crops and enhanced fertility levels in soils supporting greater weed competition	Increased use of herbicides to reduce weed competition, which has escalated the loss of biodiversity and caused pollution
	Greater disease risk in cereal crops due to increased crop density	Wide-scale adoption of fungicides to reduce disease incidence but impacting soil health
	Increased pest incidence due to tighter crop rotations	Use of more insecticides and other pest controls
	Investment in bigger farm machinery for specialised arable crop production	Increased compaction of soils, reducing soil health
	Fewer other plant species grown for human consumption	Loss of traditional, diverse diets; high carbohydrate intake; biodiversity loss
	Increased growing costs due to greater reliance on external inputs; inaccessible finance for smaller farmers leading to unviable production	Increased inequality between rich and poor; loss of food security; displacement of rural labour
	Small genetic pool of improved varieties	Reduction in genetic diversity and increased risk of plant breakdown due to disease
Extension of growing areas of major cereal crops	Semi-dwarf wheats grown in many drier environments requiring regular irrigation to meet growing crop demands	Water scarcity and salinity

Britain, wine from France and grains from eastern to western Europe. The process of farm specialisation dramatically accelerated in the 19th century, linked to industrialisation. Innovation in transport systems such as railways, canals and shipping allowed farmers to sell their products further afield and was the beginning of farms producing for markets rather than for survival. Farmers increasingly started to focus on producing one or two commodities, which was then further enhanced by the improvements of the Green Revolution's crop yields.

The changes to the agricultural sector resulting from the Green Revolution in cropping systems enabled the move from small, mixed farms to highly specialised, industrial-scale livestock operations with large amounts of grain available to feed intensive livestock enterprises. The separation of cropping and livestock systems on a farm scale has led to tighter, less-diverse crop rotations and poorer nutrient recycling, as livestock manure is bulky and therefore expensive to transport.

TABLE 2. CHALLENGES OF THE GREEN REVOLUTION AND PATHWAYS TO AGRO-ECOLOGICAL SOLUTIONS

CHALLENGES RESULTING FROM THE GREEN REVOLUTION	POTENTIAL AGRO-ECOLOGICAL SOLUTIONS
Soil degradation from intensive fertiliser use and monocropping	Wider crop rotation, intercropping, compost and green manures to restore soil fertility and organic matter
Water scarcity and salinisation due to irrigation in low rainfall areas	Rainwater harvesting, drip irrigation, agroforestry, watershed management to conserve and regulate water use
Loss of biodiversity from monocultures and reliance on a few high-yielding varieties	Bi-cropping or polycultures, agroforestry, seed diversity, habitat creation to enhance resilience and ecosystem services
Pollution from pesticides (i.e. herbicides, fungicides, insecticides, nematicides etc.) contaminating soil and water	Biological pest control, integrated pest management, nature-based fertilisers, fertility-building crops and biostimulants to reduce chemical dependency
Greenhouse gas emissions from fertiliser production and mechanised farming	Carbon sequestration through cover crops, agroforestry, and reduced or conservation tillage to mitigate climate change impacts
Rural inequality as wealthier farmers were able to invest in high-input systems	Farmer-led innovation, participatory research and local seed systems to empower smallholders and maintain biodiversity
Dependency on external inputs (seeds, fertilisers, machinery)	Self-sufficiency through local seed saving, nature-based inputs and community-based farming systems
Health risks from exposure to agrochemicals	Organic farming, reduced chemical use and nature-based solutions to improve food safety and farmer health

WHAT DOES THE FUTURE HOLD?

For many years it has been difficult to secure funding for agro-ecological solutions because most public and private investment still prioritises industrial, high-input farming models, while agro-ecology requires long-term, locally tailored and participatory approaches that do not fit easily into conventional funding structures. Securing commercial partners has been challenging, as the shift away from high-input systems often reduces sales and revenue for these companies. However, this is beginning to change as evolving policies and legislation increasingly mandate or financially incentivise more sustainable practices, leading to potential agro-ecological solutions to some of the problems created by the Green Revolution becoming available (see **Table 2**).

If the fourth agricultural revolution embraces agro-ecology (rather than digitisation), for many the changes will depend on reintegrating livestock into arable systems to restore soil health, fertility and resilience. Yet this shift faces resistance, with many advocating reducing livestock numbers and animal-based diets, while many farmers hesitate to reintroduce livestock due to the major changes required in infrastructure, management, labour, biosecurity and markets that have long supported specialised systems. For mixed farming to succeed, it must diversify crop rotations and recycle nutrients and organic matter from livestock efficiently while upholding high standards of animal welfare.

The rapid changes of the Green Revolution brought major gains but also left lasting harm to society, biodiversity and economies. Banned agrochemicals such as DDT, aldrin, chlorpyrifos and neonicotinoids illustrate the problematic legacy of innovations once hailed as revolutionary. Industrial agriculture advanced so quickly that pesticide and antibiotic resistance, soil degradation and environmental damage soon followed. Today, with climate change, resource depletion, pollution and the biodiversity crisis intensifying, we may not have the luxury of slow reflection as we shape the next agricultural revolution. The fourth agricultural evolution remains some way off; digital tools have yet to reliably guide and revolutionise most farm operations. Agro-ecological approaches, combined with carefully applied digital innovations, appear the most responsible path forward, but urgent global action is needed to prevent further instability and hunger.

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Agriculture is as important today as it ever has been, affecting everyone's food security, availability and health. The products of agricultural production form the basis of international trade including staples such as wheat, coffee and cocoa. The development of agricultural systems over millennia has led to landscape changes through land clearance, terracing and irrigation, thereby shaping and characterising much of our planet. Today, most calories consumed globally are from wheat, rice and maize, or from livestock that feed on these crops. What will diets look like in 100 years' time? Indeed, what will our planet look like?

Over the next 20 years, agriculture is expected to see deeper integration of smart technologies, with artificial intelligence and robotics finally becoming practical tools for decision-making and farm management. Advances are already reducing pesticide use, both through lower application rates and the substitution of synthetic chemicals with biologically derived alternatives. Improving nutrient efficiency will be critical, with research shifting towards circular systems that recycle waste from one enterprise into inputs for another, as well as towards precision, sensor-driven irrigation systems. Plant breeding will continue to shape what farmers grow, but the focus is moving from yield and quality towards resilience, nutrient efficiency and compatibility with regenerative practices, thereby helping farms adapt to climate extremes. At the same time, consumer demand for transparency, traceability and ethical sourcing will pressure supply chains to evolve – although price sensitivity and economic conditions will remain powerful influences. However, land use will be subject to mounting tensions as the need for food production competes with the drive to grow crops for energy generation while also providing space for nature.

Fifty years from now, agriculture may look very different. Cellular agriculture and lab-grown meat are likely to be mainstream, reducing reliance on livestock and cutting methane emissions. Farms will operate as highly efficient closed-loop systems, recycling water and nutrients with the help of advanced sensors and automation. In 100 years, traditional farming could be largely replaced by synthetic food production, with diets tailored to individual genetic and health profiles. Yet land management will remain vital for climate regulation, and it is highly unlikely that humanity will completely abandon land-based food systems within this timeframe.

Put simply, the first agricultural revolution made civilisation possible; the second fuelled industrialisation; the third fed a booming global population; and the fourth may determine whether we can sustainably feed 9–10 billion people in the future. ES

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The social and environmental cost of coffee

Jack Bridger examines some of the key impacts of coffee cultivation.

Regular coffee drinkers may have noticed a dramatic increase in coffee prices in recent years, partly driven by climate-induced weather anomalies disrupting coffee production and contributing to the volatility of coffee commodity prices. The impact of climate change on coffee farming is severe, with approximately 50 per cent of the land that supports coffee growing expected to be lost by 2050.[1] However, what is less well-known is the impact coffee cultivation has on climate – it is the sixth largest driver of deforestation – on nature and on smallholder farmers and farm workers, many of whom are trapped in extreme poverty and subject to human rights abuses including forced and child labour and human trafficking.[2]

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Similar to other commodities such as cocoa, coffee supply chains have deeply entrenched systems of environmental destruction and worker exploitation.[3] In recent years, non-governmental and news organisations have exposed egregious human rights abuses, cases of modern slavery, and farm workers subjected to degrading living conditions, low pay and dangerous working conditions. Reports published by numerous non-profit organisations document such findings on farms, many of which were certified through programmes like Rainforest Alliance or 4C, and linked to well-known brands including Starbucks, Nestlé, and McDonald's.[4,5]

Research gathered from sustainability reports, policies and supplier codes of conduct from 19 of the largest North American, Asian and European coffee companies, conducted in collaboration with the industry watchdog Coffee Watch during 2025, as well as students and faculty from Australia's Wollongong and Macquarie universities, examined how the social and environmental costs of coffee are being addressed.

LIVING INCOME AND LIVING WAGE

Smallholder farmers and farm workers are the backbone of coffee cultivation, but many live in extreme poverty due to a lack of a living income price (for farmers) or living wage (for farm workers), which are necessary for a basic standard of living.

Coffee company environmental, social and governance reporting neglects to properly examine what a living income price would be for smallholder farmers, and farm workers' livelihoods are rarely mentioned. Where livelihoods are discussed, the focus is on improving agricultural practices, increasing productivity and yield, or on income diversification. While these are important drivers of living income for impoverished smallholder farmers, there is little to no evidence of companies paying a living income price for their coffee or even accepting a specific calculation of a Living Income Reference Price, which is what a farmer needs to be paid for their crop in order to earn a living income.[6] This indicates a reluctance by most coffee companies to address a key dimension of their responsible purchasing practices. Incorporating a living income and living wage into these practices is especially important given that certifications, which are prominent in coffee growing (e.g. organic, Fairtrade, Rainforest Alliance) do not guarantee a living income price for farmers or provide a living wage for farm workers.[7]

HUMAN RIGHTS AND GENDER INEQUALITY

Reports from the last 10 years, compiled by Coffee Watch, have documented multiple cases of child and forced labour, debt bondage, human trafficking and modern slavery in coffee supply chains, largely in Brazil and to a lesser extent in India and other countries.[8] While there are many contributing factors to the use of child labour, it often exists because smallholder farmers are paid so little they cannot afford to hire seasonal farm workers and must rely on their children to work instead of sending them to school.

Most companies examined have policies and codes of conduct prohibiting labour abuses such as the use of child and forced labour and a commitment to respect human rights. However, commitments to end human rights abuses are almost completely absent. Only one company had a goal to eliminate child and forced labour from its supply chain.

Women are also responsible for much of the labour in coffee farming, but only 20–30 per cent of coffee farms globally are run by women.[9] Women are typically less likely than men to have land tenure, access to financing, loans, proper contracts and coffee knowledge, and be able to make decisions; they also often work under particularly precarious conditions and earn less than their male counterparts (many of whom are already in poverty or extreme poverty).

Cultural norms also often deny women access to many of these crucial resources. Women in coffee farming also have less access to public services, such as training and extension programmes, which provide advice to farmers on agricultural practices and are crucial for improving productivity and economic resilience. A lack of access to financial services further compounds their challenges, making it difficult for women to invest in better farming techniques.

"Few coffee companies have meaningful commitments, policies and practices to crack down on gender inequality and discrimination within their supply chain."

Most of the companies examined have policies promoting equality and empowerment among their staff and prohibiting gender discrimination and harassment, but the women most affected by these issues are more likely to be working in their supply chains. Few coffee companies have meaningful commitments, policies and practices to crack down on gender inequality and discrimination within their supply chain – let alone to foster equality and women's empowerment. Only four companies examined specifically refer to risks of sexual or gender-based violence in coffee supply chains.

CLIMATE AND DEFORESTATION

Carbon emissions are an area in which coffee companies are more consistently setting targets and commitments. Almost all the coffee companies examined have set scope 1 and 2 emissions reductions targets, with some validated by the Science Based Targets initiative. (Scope 1 refers to sources of greenhouse gas emissions directly owned or controlled by the company, such as business vehicles using fuel; and scope 2 covers indirect emissions from energy purchased by the company, such as electricity.) Only 12 of the companies have set some kind of scope 3 target, which is where the majority of their emissions occur. (Scope 3 covers all other indirect emissions associated with a company's upstream and downstream value chain, such as business travel and purchased goods and services.) Scope 3 targets are often determined according to whether emissions are related to forests, land or agriculture, including those associated with deforestation, which is often driven by expansion for more coffee cultivation or by environmentally detrimental agricultural practices.

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Eleven of the companies examined have some partial or total commitment to end deforestation, particularly where they are in scope of the EU's Deforestation-free Regulation (EUDR) but many make little to no reference to deforestation or fail to set time-bound commitments to end it in their supply chains. The EUDR applies to cattle, wood, coffee, cocoa, palm oil, rubber and soy, and in-scope companies must prove that their products are not linked to deforestation, are traceable to the farm level and comply with laws of origin countries. Few coffee companies appear to consider forest degradation in their sustainability reporting and commitments, and fewer still mention the conversion of peatland or other ecosystems into coffee plantations.

CHEMICALS AND PESTICIDE USE

The use of pesticides and other chemicals is also widely practised in coffee cultivation and poses significant short- and long-term health risks to coffee farmers, farm workers and nature. Research demonstrates that growing coffee in major producing countries such as Brazil is connected to significant worker mortality and morbidity.[10] Top producers such as Brazil and Vietnam often lack effective laws and their enforcement for governing or restricting highly hazardous pesticides.

For most of the companies examined the risks of hazardous agrochemicals like pesticides, herbicides or fungicides in coffee supply chains are rarely acknowledged, and there is little to no evidence of meaningful targets for ending their use in coffee cultivation. There is also little discussion of the impacts these agrochemicals have on the health of farmers or farm workers, or on how to ensure proper protections are in place. Some coffee companies are working to phase out the use of the most harmful agrochemicals or to prohibit the use of banned pesticides. Few major coffee companies advocate for their elimination altogether or their replacement with less-harmful methods such as integrated pest management, which can involve a variety of techniques to sustainably manage pests and reduce reliance on pesticides. In coffee cultivation this can include better pest monitoring, boosting natural pest predators and using pest-resistant bean varieties.

AGROFORESTRY VERSUS MONOCULTURES

More commonly known as shade-grown coffee, agroforestry is a system in which coffee shrubs are combined with trees or animal grazing, rather than monoculture systems in which a single crop is cultivated. One study has shown that agroforestry coffee can have up to 19 times more biodiversity than monocultures and can capture double the amount of carbon – and more under the best systems.[11,12] In comparison, monocultures negatively impact biodiversity by reducing the quantity of other plants and habitats for different species, creating greater vulnerability to pests and diseases and further dependence on pesticides. With agroforestry there is an opportunity for coffee to be regenerative and offer protection from climate change, as trees cool coffee plants during heat dome events, maintain soil moisture in droughts and absorb water during intense rainfall.

Of the companies examined, agroforestry or monocultures are often not discussed and many companies lack commitments to promote agroforestry or end monoculture in their supply chains despite the benefits to coffee crops. However, seven companies do refer to agroforestry or regenerative agriculture initiatives, or even to tree planting objectives or targets for sourcing a certain amount of coffee via agroforestry systems. Others are either only at pilot stage or intend to engage in agroforestry in the future.

TRACEABILITY AND TRANSPARENCY

If coffee companies do not know where their coffee comes from, they cannot effectively address human rights or environmental risks in their supply chain. Despite coffee supply chains often being less complex than other commodities (such as palm oil), a lack of traceability and opacity appear to be the norm. This has allowed many coffee supply chain risks to be out of sight and out of mind and has fostered a lack of accountability.

Twelve of the companies examined have some degree of traceability, and many are adopting systems to comply with the EUDR, setting time-bound targets either to meet the December 2025 deadline or a later date if not in scope of the EUDR. For the companies examined, clear commitments to full traceability of their coffee supply chains are lacking, and only a few state whether they are tracing coffee to the farm level.

SUPPORT FOR REGULATION

A reliance on voluntary efforts has failed to adequately address the systemic environmental

◀ **An area of land deforested for coffee growing, between Tolima and Quindío, Colombia. © GiorgioMorara | Adobe Stock**

and human rights problems in the coffee sector. While regulation is not the answer to every problem of coffee's sustainability, regulations like the EUDR can address both human rights abuses and deforestation, raise standards across the industry and create a more level playing field for businesses.[13]

Many of the companies in this study are clearly demonstrating the efforts and resources they have invested to comply with EUDR, and many have actively supported the regulation. However, despite having sufficient time and the estimated low compliance cost, many parts of the coffee sector have been slow to prepare.[13,14] Furthermore, research by Coffee Watch revealed that many coffee corporates have lobbied hard to slow or derail the EUDR and very few coffee companies have supported regulation in the UK, USA or elsewhere to curb deforestation and rights abuses across high-risk commodities including coffee.[15]

Legislation such as the EUDR concerns wealthier countries regulating how developing nations should behave. Unfortunately, in many jurisdictions where coffee is grown the rule of law is different to what we expect in more developed countries, and corruption is rampant with many producing countries ranking low on the Global Corruption Index. The effect is a lack of legal and political infrastructure in many jurisdictions to support imposed regulation. Worse yet, the costs of complying with regulation are often pushed on to farmers who are already impoverished and cannot afford to implement the practices needed to comply.

KEY FINDINGS

There is a noticeable gap between the efforts of European and non-European companies, driven in part by a stronger regulatory environment. It can be said that European companies appear to perform better than their peers elsewhere, especially on traceability and deforestation issues, indicating that the EUDR may have had an impact even before coming into force.

Yet despite efforts by many companies, there is still much that goes unsaid about coffee's environmental and social impacts in their sustainability reports. This could be attributed to 'greenhushing' in order not to attract the ire of politicians who do not approve of efforts around diversity, poverty alleviation or climate action. But it may also suggest that companies do not properly recognise the issues or lack understanding of the scale of the problems, such as the true prevalence of child labour in coffee supply chains and how deforestation or monocultures affect coffee yields, particularly in the face of worsening climate impacts.

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WHAT THIS MEANS FOR CONSUMERS

Given the complexity and depth of issues within coffee supply chains, it is not easy for consumers to make sense of these problems when buying coffee, especially given the promises of responsibly sourced coffee by many companies and the limitations of certifications.

Coffee Watch provides useful guidance for consumers and in 2026 will publish a Coffee Scorecard providing a more comprehensive benchmark of many of the world's largest coffee companies, scoring them on these key issues.[7] Taking a similar approach to the well-established Chocolate Scorecard, the Coffee Scorecard aims to engage in collaborative dialogue with participating companies to help them learn and improve, and to drive the coffee industry towards a more equitable and less-exploitative system for people and planet, creating greater resilience for the sector amid increasing uncertainty.[16] ES

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The role of digital technology in delivering agricultural sustainability

Kit Franklin sets out how technology can enable a better farming future.

In common with all commercial sectors, agriculture is developing and adapting in the digital age. Agricultural engineers are using digital technologies in farm machinery to advance the established evolutionary development of mechanisation, reducing physical human interaction during field tasks.[1] Meanwhile, layers of digital information are driving management decisions on farms in the form of precision agriculture. These development streams will not only enhance farm business finances but can also play a pivotal role in improving the farmed environment, helping to drive agriculture towards climate and biodiversity goals.

The International Society of Precision Agriculture defines precision agriculture as 'a management strategy that takes account of temporal and spatial variability to improve sustainability of agricultural production'.[2] The practice drives increased attention to detail and although it is a management approach rather than any specific technology (e.g. hand weeding could be part of a precision agriculture approach), geospatial information and geographical information systems (GIS) often direct decision-making.

In precision crop production, management of the farmed environment is broken down virtually beyond physical field divisions and in some instances precision at an individual plant level can be achieved. The process of precision crop production is to observe, measure and understand in-field spatial variation and to synergise this insight with external factors (e.g. market conditions, weather predictions) to make crop management decisions to optimise for business and environmental sustainability.

Ultimately, it is neither financially nor ecologically worthwhile to apply inputs – such as seed, fertiliser, irrigation, crop protection or manure – to crops that have already reached their yield potential. However, it is important to understand the root causes of any crop performance variation, rather than focus solely on the symptoms, in order to target efforts effectively. This is where integrating multiple layers of data, both source and year, becomes essential.

PRECISION CROP PRODUCTION TECHNIQUES

An early example of spatial data used in precision crop production is yield mapping, developed in the early 1990s. Harvesters record yield in real time during harvest operations, logging each measurement to its precise location using global navigation satellite system (GNSS) coordinates.[3] The data are then displayed and interrogated as maps with the intention of improving decision-making in subsequent seasons.

Multiple years of yield maps can be directly compared, with reference to temporal conditions such as annual weather records and underlying field soil texture maps to guide farm strategies for cropping and environmental initiatives. Areas which regularly produce unprofitable yields become clear candidates to remove from future cash crop production to be used instead for initiatives such as tree planting, mixed species meadow conversion, and legume or pollinator mixes. Such initiatives have been grant funded in recent years to help meet government biodiversity and carbon capture aims.

There is a range of digital technologies that can be used for precision crop production during the growing season to target the optimum application of crop inputs. Technology as ubiquitous as RGB [red, green and blue] digital cameras can provide data that add value to the farmers' in-season decision-making. For example, high-resolution aerial imagery can visually guide farmers to areas of concern in a field, such as standing water and reduced crop coverage.

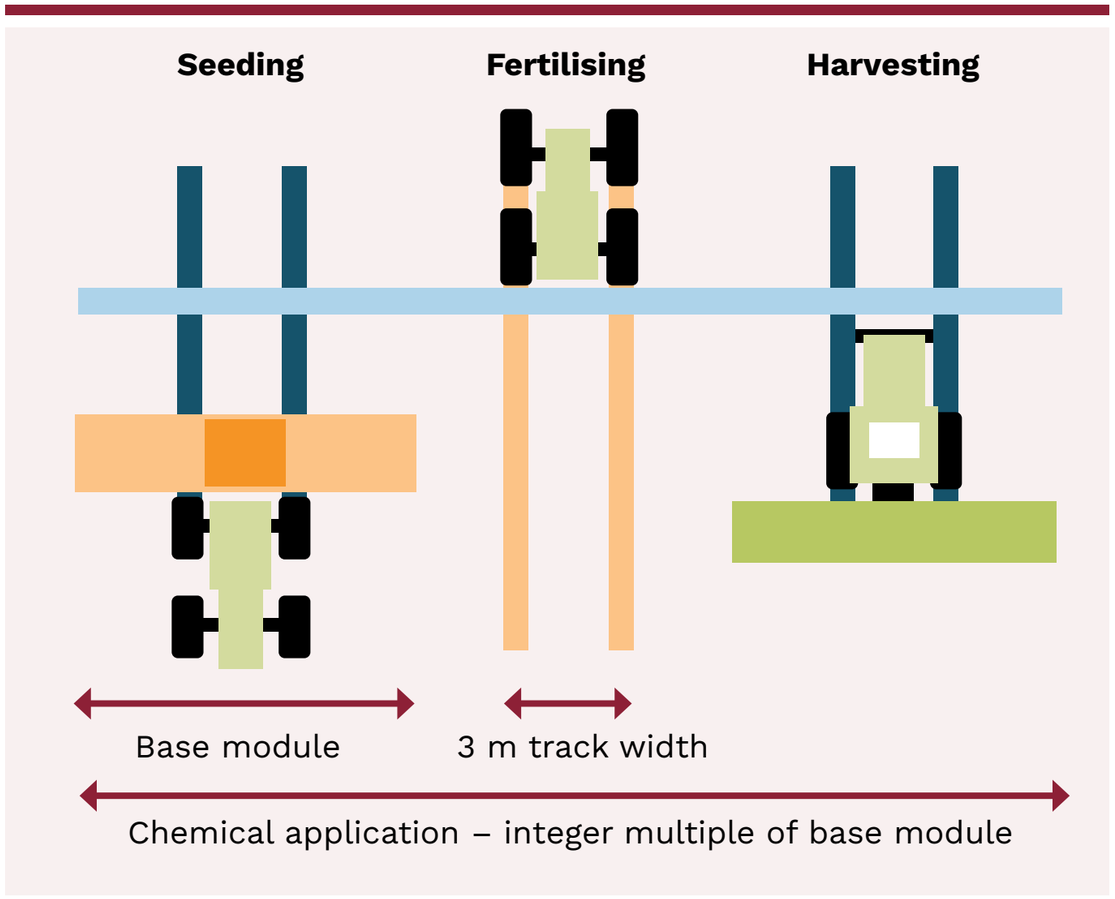
Quantitative analysis of crops also be achieved by using basic analysis of aerial RGB images. GIS techniques such as image segmentation by shape and colour can identify discrete plants and then automate population counts, which can in turn determine fertiliser or irrigation application rates.[2] In relatively low-population, broad-acre crops such as maize (corn) or fresh produce such as lettuce, the loss of one or two plants per square metre could represent a 10–20 per cent population reduction. These areas can accept significantly reduced inputs with no effect on yield, while reducing production cost and preventing the environmental impacts of over-application.

Another ubiquitous image analysis index used for crop health and performance assessment is the normalised difference vegetation index (NDVI), which requires the addition of multispectral imaging (specifically, near-infrared) to enable calculation of the index. The NDVI calculation gives a value from zero to 1: lower numbers indicate a stressed plant or a ripening crop, while higher numbers indicate vigorous plants that are photosynthesising and growing. The results of NDVI analysis are often plotted as maps in false colour scale for visual inspection: generally, reds are assigned to low values and greens to high ones. Threshold NDVI values can be set during analysis to identify precision crop production management boundaries for variable fertiliser application rates – again, only putting the right amount into the field to ensure a crop meets its potential without wastage.

AERIAL IMAGING IN PRACTICE

These imaging techniques can be implemented via various technology assets available to farmers, each with its own benefits and weaknesses. The first technique, using a pair of European Sentinel-2 program satellites, has provided high-quality multispectral imagery to environmentalists and agriculturalists every five days for the last decade.[4] With visible and near-infrared data being captured, NDVI data have been openly available; however, even when offering images every five days, it is not unusual for UK farmers to be deprived of data for several weeks when considering the frequent cloud cover, which is not ideal for timely precision crop production decisions. The ground resolution on offer from Sentinel-2 is 10 m x 10 m, which is limiting if plant-by-plant-level data are required, and it can lead to trees and hedgerows influencing the data at field edges.

Alternatively, unmanned aerial vehicle (i.e. drone) platforms can be used, opening the possibility for far greater ground resolution (reaching square-centimetre level) and the option to fly below cloud level ensures high image quality. However, with the sensors, flight platform, training, licensing and analysis software required, there are considerable financial and time barriers for farmers to gather the data by these means.



▲ **Figure 1. The controlled traffic farming method.**

In both these two approaches, data must be analysed and decisions made prior to the field work being conducted. A third option is tractor-or implement-mounted systems that can capture and act on gathered crop insights in real time to allow inputs to be adjusted while traversing the field. These systems are favourable in terms of limiting additional workload; however, the sampling can be imperfect because the area measured beneath or alongside the machine often only covers part of the working width, potentially leading to poor assumptions about crop uniformity when adjusting application rates. Farmers must, therefore, strike a balance when deciding on an image capture technology.

GUIDANCE AND AUTOMATION

When considering the mechanical application of agricultural inputs, GNSS control of modern tractors and implements ensures that application is highly precise to the location where it is required. Firstly, auto steering on tractors ensures that the working width is optimised, guiding the tractor straight up and down the field to within 2 cm accuracy – meaning that no area of the field is either missed (causing reduced output) or overlapped (wasting resources and effort). Using automatic over manual steering reduces field inputs by 5–10 per cent. With GNSS control, some farmers choose to follow the controlled traffic farming method, whereby all implements must match a base working width or multiple of it (e.g. 8 m for planting with 24 m for fertilising) (see **Figure 1**).

The permanent controlled traffic farming driving routes across fields minimise soil compaction from wheel traffic to the least possible surface area (<20 per cent is possible) improving soil health, yield and water infiltration and reduce

▲ **Figure 2. An example of small-scale automation on the Hands Free Farm. © Kit Franklin**

future tillage efforts across the majority of the field 'meaning a win–win scenario for farmers and the environment'.[5] Further GNSS control over the application implements allows for individual outlet control (e.g. seeding coulter – a disc or tine that opens the soil to place the seed or liquid fertiliser nozzle), so that even with irregularly shaped fields no area has unnecessary double or even triple application, leading to a potential further 5–10 per cent input saving on a typical UK farm.[6]

Despite the opportunities presented to the farmer and the environment through precision crop production there is an issue with the precision that is truly on offer. Since the conception of precision agriculture, expanding farms, reducing labour availability and a continued efficiency drive mean machinery working widths have increased considerably, with a large combine harvester in the 1990s having a 6 m work width versus a more than 13 m width today, therefore reducing the resolution when collecting data and applying inputs. A 1961 article set out a future where it was possible for farms to be run largely by automated machines and that this change would be important to the development of agriculture.[7] The technology barriers to this future were stated as field machinery guidance and decision-making; however, the availability of GNSS and artificial intelligence means technology is no longer a barrier and that fully autonomous farming is possible (see **Figure 2**).[8]

THE POTENTIAL OF AUTOMATION

Autonomous technologies can fulfil the needs of precision agriculture for both farmers and the environment in a new robotic paradigm. With autonomous control the trend for bigger machines can be reversed, as multiple small autonomous machines operating in swarms can offer the same output of a single large machine that is limited by operator availability. This size reduction will enable droplet-level application resolution and reduced machinery weight – dramatically lowering input volumes and improving soil health, respectively.

The smaller form factor that agricultural robots are likely to take will enable further potential environmental improvements. For example, taking the option of using advanced battery technology to replace diesel engines with electric power, electrifying a typical 170-horsepower UK tractor would roughly double its weight if equipped with enough battery capacity to operate for a modest eight-hour field day.[9] In contrast, a single robot from a swarm manages only a fraction of the total farm area and, with no onboard operator, can work more slowly. This slower pace makes battery power practical and even opens up the possibility of energy independence through onboard solar generation. This is already being demonstrated in several commercial agricultural robots that are implementing environmentally friendly mechanical weed control (see **Figure 3**).

"Autonomous technologies can fulfil the needs of precision agriculture for both farmers and the environment in a new robotic paradigm."

Another potential opportunity is to consider the layout and composition of cropping. Current mechanisation has driven the expansion of field size to the detriment of biodiversity. Smaller autonomous machines have been shown in economic analysis to be viable in smaller field sizes, meaning that reinstating hedgerows and field trees that have previously been removed to accommodate the efficient movement of large machinery is a realistic possibility.[10]

Furthermore, multi-cropping becomes a viable option instead of whole fields being dedicated to single crops. The hands-free autonomous system at Harper Adams University has already demonstrated strip cropping, growing and harvesting three combinable crops (wheat, barley and field beans) in 2 m strips (see **Figure 4**).[11]

As well as improving biodiversity of the farmed environment there are synergistic benefits, such as leguminous crops securing natural nitrogen for use by their neighbouring crops and the natural phasing of crops making better use of water and light resources.[12] In time, these multi-cropping robotic systems may develop into pixel-grid layouts incorporating more diverse crop types.

When it comes to the adoption of these emerging technologies and farming methods there are many things to consider. For instance, business models for autonomous farm machines vary widely, with some manufacturers pursuing a 'robots as a service' option, while others pursue conventional sales models. Some companies are offering autonomous tractors much like conventional machines, while others like FarmDroid represent

▲ **Figure 3. A FarmDroid commercial solar powered agricultural robot controlling weeds. © S. Leitenberger | Adobe Stock | Editorial use only**

▲ **Figure 4. Strip cropping, growing and harvesting. © Harper Adams University**

new ‘agbots’ concepts. As a result, the current market has significant price disparities, ranging from £50,000–£300,000. Simultaneously, farmers will consider adopting novel farming practices based on the perceived profitability of cropping changes and the availability of incentives such as government environmental grants or opportunities to engage in carbon and biodiversity markets.

The future path of mechanisation incorporating digital technology has the potential to not only maintain the agricultural output society requires but also to benefit the farmed environment and wider drive for global sustainability. Whether it is improving attention to detail with precision crop production to drive down waste and optimise land use or harnessing the potential for robotics to move towards renewable energy sources, agri-tech and agricultural engineering will be integral to the farming transition. ES

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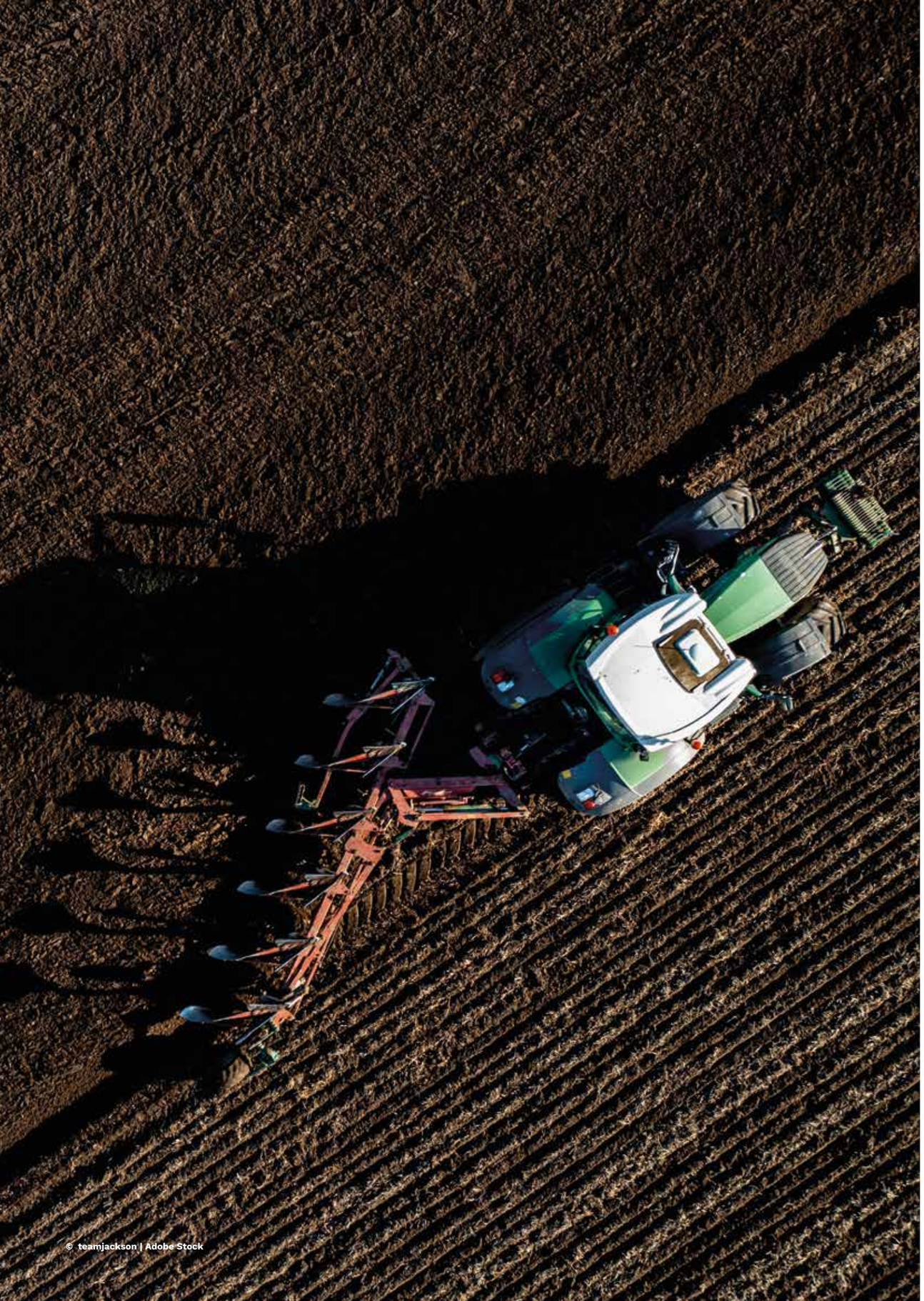

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Digging into the detail: the changing landscape of soils assessment

Matthew Orman explores how new stakeholders, policies and priorities are influencing the way UK soils are assessed.

A BRIEF HISTORY OF SOILS ASSESSMENT

Farmers have assessed the state of their soils in an informal capacity since the dawn of agriculture, mainly via visual observation – soil colour and texture – and the health of the plants growing in it. The process of collecting data using more scientific methods began in the 19th century following advances in chemistry and geology, while more formal soil testing methods have been widely available to farmers since the 1950s.

In the last few decades, soil assessment by farmers has evolved rapidly. While the main objective continues to be informing land management decisions, these changes also reflect trends in science and government policy and a growing understanding of the varied services soils provide – and the threats they face. These trends include:

Soil chemistry, traditionally used to inform farmers' decision-making on the appropriate application of chemical fertilisers, became regulated in 2018 in response to EU clean water legislation.[1] English farmers must test soil chemistry at least once every five years on land where organic manure or manufactured fertiliser is applied.

Carbon and organic matter are well-established as proxy measures for overall soil health but have grown in significance over the last decade to reflect awareness of farming's role in climate change mitigation (carbon loss, sequestration and storage) and the regenerative farming movement. In England, the government-funded Sustainable Farming Incentive pays farmers to measure their soils' organic matter content.


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Earthworm counting has always been a mainstay of soil assessment. Earthworms are a biological indicator and a proxy of wider soil health, since their number is affected by pH, waterlogging, compaction and organic matter management. Otherwise, the systematic inclusion of biological activity (microbial biomass and soil respiration) in soil quality assessments is relatively recent – and still too expensive to be included in standard assessments.

Soil structure – the arrangement of solids and pore spaces in a given soil – is an important indicator of its water-holding capacity, and therefore its resilience in the face of extreme weather. High-carbon soils with good structure are more flood- and drought-resistant. Measurement techniques range from low-tech options, especially visual soil assessments, through to the use of soil remote sensing and modelling.

GOVERNMENT INITIATIVES

As on-farm testing has evolved, so has soil data collection at a national level by UK governments – again driven by different policy and environmental motivations. Since 2024, England's Natural Capital and Ecosystem Assessment programme has incorporated farming and non-farming soils' physical, biological and chemical properties. The data collected will show how different soils contribute to ecosystem services and will underpin the establishment of a nationwide indicator for soil health that will help map change over time.

Meanwhile, Northern Ireland is rolling out a government-funded £37 million Soil Health Nutrient Scheme, including the sampling of every field, to create a detailed baseline. One objective is to help farmers target fertiliser more efficiently and reduce the phosphorus surplus in the soil – one of the causes of the blue-green algae that has blighted Lough Neagh, the UK's largest freshwater lake.

NEW STAKEHOLDERS

Alongside farmers and governments, a third stakeholder has emerged as an increasingly critical assessor of – and investor in – the country's soils: the private sector. This interest started with food and drink businesses that have a vested interest in the state of the asset on which a reliable, healthy, nutritious supply depends but has expanded to include businesses with a far less obvious connection to land use and management.

This interest has been accelerated by the recognition that soils are at the front line of extreme weather – the intense rainfall, prolonged droughts and heatwaves caused by climate change. Extreme weather impacts UK soils by increasing erosion and nutrient loss, altering soil moisture and structure, and affecting microbial communities that are vital for nutrient cycling and carbon storage.

This in turn undermines the soil's ability to carry out the vital 'business-material' ecosystem services required of it and, as a result, soil now features on the agendas, sustainability accounts and strategies of a variety of sectors, including:

- Food and drink – to ensure long-term resilient production, report nature and climate impact (e.g. removals in scope 3 emissions) and provide evidence for regenerative claims;
- Transport infrastructure and insurance – to increase water storage capacity and reduce the likelihood and severity of flood incidents;
- Water companies – to increase water storage and filtration capacity and reduce the need for investment in downstream infrastructure;
- Financial institutions – as part of regulatory compliance (international and national), to understand their nature-related risk exposure and to improve the financial resilience of their lendees; and
- Technology – to increase water storage in the landscape and offset large amounts of water used by data centres, both directly for cooling and indirectly to generate the electricity they need.

FILLING THE GAP: FINANCE AND DATA

This newfound interest and potential investment in soils is extremely timely. UK farmers are being

hit by two major uncertainties in the form of (1) unpredictable climate and weather, and (2) mixed messages from the Government about the future of farm support schemes (i.e. its willingness to pay for public goods, including soils), at what rate and for what outcomes.

The Government hopes that business will fill any gaps left by reductions in public subsidies and is actively encouraging private investment to support nature-recovery projects, setting a target in 2023 of raising at least £500 million a year by 2027 and of over £1 billion a year by 2030.[2] To unlock this potential investment, data are needed – and increasingly high-integrity, transparent and scalable data that will justify any investment and enable businesses to report on their climate, biodiversity, and risk exposure and impact.

At the forefront of these reporting requirements are carbon and climate, and a complex matrix of policy instruments is emerging at UK, EU and international level to regulate soil-carbon removal. These include the BSI 700 series of standards for nature markets, including BSI Flex 703 (nature-based carbon) in the UK, the EU's Carbon Removals Certification framework, the Draft Greenhouse Gas Protocol Land Sector Removals Guidance, the Science Based Targets initiative and Improved Agricultural Land Management.[3-7]

Soil's place in nature and biodiversity – and in schemes such as biodiversity net gain – is less well-researched, but likely to become more significant as its role as an ecosystem in and of itself, and fundamental for above-ground biodiversity, becomes better understood.

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The same appetite for reporting-grade data can be seen among policy-makers – especially in HM Treasury – who require that any public expenditure is evidence-based, provides taxpayer value for money, and contributes clearly and measurably to the achievement of national targets – all of which are data dependent.

This is already changing the type and way in which soils are being assessed – a transition from the largely informal, citizen science approach designed to inform behaviour change on the ground towards an increasingly complex, data-driven and technology-enabled process to justify the exchange of increasingly large sums of money.

THE CHALLENGE

This raises a new challenge, however. As we have seen, different businesses have different expectations of the soils in their sphere of influence and the services that they expect of them: productivity, carbon storage and sequestration, biodiversity uplift, water storage and filtration, nutrient neutrality, climate resilience or risk mitigation.

This is reflected in the various metrics used to measure and report on status and effect – on organic matter, chemistry and physical structure – and is exacerbated by the suite of novel technologies and data platforms helping farmers and corporations to keep track of this process. This leads to inconsistent (and, arguably, inefficient) data collection, duplication and confusion for farmers, as well as to concerns about data ownership. These bring added – and sometimes unnecessary – cost to projects, as well as uncertainty. End users are unsure which technology to trust with the data and the decision-making support they need.

THE NEED FOR STANDARDISATION

There is a clear need for investment in soil health at scale, a tangible opportunity in the form of significant amounts of pent-up private sector investment in soils, and a barrier in the lack of standardised, universal, data-driven methodology for assessing soil health and evidencing impact.

Such a standard will provide a thread of soils knowledge and understanding between all stakeholders juggling different outcomes and priorities – from the farmer who decides how to manage their land to the board of directors that bears ultimate responsibility for deciding how and where to invest sometimes limited budgets for maximum business impact. It will bring soils into line with other critical pillars of the environment – air, water and biodiversity – and bridge the gap between the critical drivers of corporate behaviour: biodiversity, climate change mitigation and water resilience. Without such a standard, there is a risk that the current momentum behind soil assessment and data collection will be lost. ES

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Developing climate-resilient vegetable varieties

Ashley Garrison, **Lauren Chappell**, **Rosemary Collier**, **Andrew Beacham** and **Jim Monaghan**

explore the benefits of the Vegetable Genetic Improvement Network to ensure the future of agriculture.

CLIMATE CHANGE AND FOOD PRODUCTION

Spring of 2025 was exceptionally dry across much of the UK and Europe, and summer offered little respite, bringing multiple heatwaves.[1,2,3] While holidaymakers welcomed soaring temperatures, farmers anxiously awaited for rainfall to keep their crops alive. Prolonged drought and excessive heat can severely affect crop growth, resulting in lower yields, reduced quality and supply shortages in supermarkets.

Extreme weather events are occurring more frequently as a result of climate change. Alongside worsening droughts, winter floods are becoming increasingly common and threaten the growth of overwintering crops. In addition to these abiotic (non-living) stresses, changing weather

patterns can drive surges in pest and pathogen populations, exposing crops to biotic (living) pressures, exacerbating production challenges. It is evident that climate change poses a serious threat to long-term food security and farmer livelihoods, so we must turn our attention to how agriculture can adapt to ensure crop production is sustainable in a changing climate.

IMPROVING CROP RESILIENCE

To strengthen crop resilience against climate change, new varieties are needed that can better withstand extreme conditions. This requires the identification of stress-resilience traits within collections of genetically diverse crop varieties, a stage known as pre-breeding. This process involves exposing crop varieties to various stress conditions, such as drought or waterlogging, and monitoring traits that can act as indicators of plant health and productivity such as shoot and root biomass, leaf colouration and nutrient use efficiency.

Plants that demonstrate beneficial traits can subsequently be used in breeding programmes to combine their stress resilience with other beneficial agronomic characteristics, such as yield and flavour, to develop crops that are better equipped to handle future environmental conditions. In turn, more reliable yields could ease the financial pressures faced by farmers, further safeguarding food production, while also reducing reliance on crop imports, which are at risk from global supply chain disruptions due to factors such as extreme weather, global conflict, cyberattacks and pandemics. In 2024, domestic production made up 53 per cent of the UK's total supply of fresh vegetables.[4] Developing climate-resilient varieties will help to maximise domestic production and improve supply stability.

DIVERSITY SETS: A BLAST FROM THE PAST

To tackle the climate challenges affecting vegetable production, the Defra-funded Vegetable Genetic Improvement Network (VeGIN) has been set up as a collaborative research effort across Harper Adams University, the University of Warwick, the UK Vegetable Genebank and the Met Office. VeGIN research aims to provide a pre-breeding pipeline to identify climate-resilience traits for many important vegetable crops grown in the UK, including brassica (e.g. cabbage), lettuce, carrot and onion crops – all of which hold substantial economic value.

When commercial vegetables falter under climate stress, where can we turn to find climate-resilient varieties? The answer may lie in the past. Throughout the processes of crop domestication and commercial breeding of modern varieties, yield, appearance and taste have been prioritised. Generations of selective breeding have acted as a bottleneck, allowing only the highest-yielding and most appealing varieties to pass through. However, stress-resilience traits may have been overlooked or even lost in this process.[5] This means that today's commercial varieties perform well under optimal growing conditions but can struggle to cope with extreme weather events, increased pest or pathogen exposure, and longer-term changes to water availability. This is where ancestral varieties and closely related wild species left behind during domestication and commercial breeding processes could become significant again.

Many wild relatives of crops evolved across diverse ecological niches, sometimes thriving in environments with limited water, high salinity or extreme temperatures. These adaptations can provide valuable genetic traits for improving resilience to modern climate stresses. Similarly, early domesticated crops, which were not subject to intensive selective breeding programmes, may retain greater tolerance to drought, flooding or pest outbreaks – traits that were often lost as breeding efforts focused on yield under more stable growing conditions.[5,6,7] As a result, revisiting these left-behind accessions could help to recover stress resilience in modern crop varieties.

A wealth of genetic and morphological variation in vegetable crops and their wild relatives is available for researchers to investigate. For brassica, lettuce, carrot and onion varieties, the UK Vegetable Genebank has collections of diverse ancestral accessions originating from all over the globe. VeGIN has curated these accessions into representative collections called diversity fixed foundation sets (or diversity sets for short) (see **Figure 1**).

Plants within these collections are genetically fixed, meaning their traits remain stable. This allows seeds to be bulked up and reused by growing plants to maturity and making the collections a sustainable, long-term resource (see **Figure 2**). For each diversity set, plants can be grown under various abiotic and biotic stress conditions to determine which lines maintain their health and productivity and, therefore, could have improved climate and pest resilience.

▲ **Figure 1. A selection of varieties within the lettuce diversity set, highlighting genetic and morphological diversity. © Ashley Garrison**

However, growers and consumers still want the attractive appearance and taste of modern crop varieties, traits that are less favourable in the left-behind varieties. This is where breeding programmes or gene editing come into play. Once a climate-resilient variety has been identified within the diversity sets, genetic analysis is carried out to determine specific gene variants (alleles) or genomic regions that confer beneficial traits. By harnessing this knowledge, the variety can be used in precision breeding programmes to combine its climate-resilience traits with other commercially important ones, like taste and appearance, obtained from a different variety, thus creating a new commercially viable variety with improved climate resilience.

This could also potentially be achieved via CRISPR [clustered regular interspaced short palindromic repeat] gene editing to introduce small mutations similar to those that can occur naturally; this technique was recently legalised for use in the development of commercial crops in England.[8] Small DNA mutations arise frequently in nature, which act as a key driving force behind evolution, particularly when these genetic changes lead to an advantageous trait. Using CRISPR technology, an enzyme can be targeted to make precise

▲ **Figure 2. Lettuce diversity set plants being grown to maturity in a polytunnel to restock seeds. © Ashley Garrison**

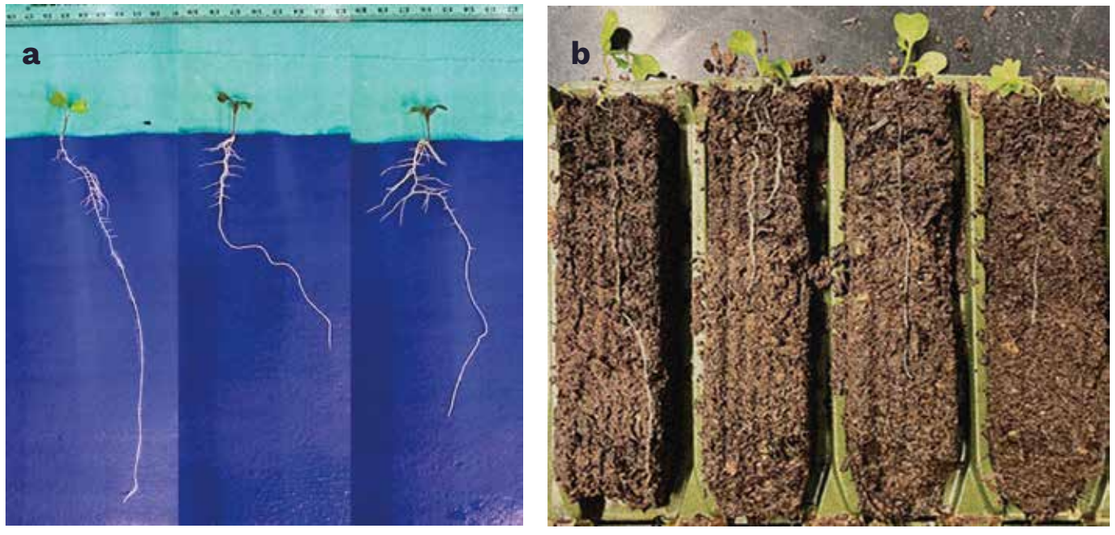
changes to a DNA sequence, which can be used to introduce beneficial traits to commercial crop varieties.[9] In recent years, many countries have begun to ease regulations surrounding gene-edited crops. While numerous such crops have received approval for commercial application in countries such as Japan, Brazil and the USA, these products are not yet widely available in supermarkets.[10] However, as the demand for climate-resilient crop varieties continues to rise, gene editing could become an integral tool for incorporating beneficial traits into commercial crops.

SCREENING FOR ABIOTIC STRESS RESILIENCE

At Harper Adams University, pre-breeding research is focused on uncovering abiotic stress-resilience traits within brassica, lettuce, carrot and onion diversity sets. Early VeGIN research identified a number of lines with improved drought and flood resilience compared to commercial varieties.[7] These lines can act as valuable resources for breeding programmes that are developing climate-resilient crops.

Ongoing research is exploring the importance of root systems in facilitating improved climate resilience. Roots are integral to plant survival because they take up water and nutrients from the surrounding soil. A faster-growing, more extensive or more efficient root system could aid crop performance under challenging environmental conditions. For crops such as brassica and lettuce, root function can significantly influence the morphology of the above-ground part of the crop that is harvested.[11] And for root crops such as carrots, root development directly determines yield and quality, as the harvested organ is the root itself. These developmental roles make it essential that root systems are considered when attempting to develop climate-resilient crops. However, roots are inherently difficult to analyse due to their hidden nature, which means that below-ground traits are far less studied than above-ground ones.

To uncover root development traits, 54 accessions from the brassica diversity set and two commercial brassica varieties were grown in a paper-based hydroponic assay. In this system, seedlings are placed between sheets of tissue paper that hang above a container of liquid nutrients. The paper absorbs the liquid, providing suitable conditions for root growth, while also blocking out light. The plant shoot grows out the top of the paper pouch. The two layers of paper can later be separated to reveal the developing root system. This assay was used to identify plants with beneficial rooting traits, such as rapid growth (see **Figure 3a**), in a high-throughput manner, before moving on to soil experiments, which can be more time-consuming.



▲ **Figure 3. Brassica diversity set varieties were grown in (a) a high-throughput paper-based hydroponic assay and (b) in soil in root-trainers to reveal root systems. © Ashley Garrison**

Analysing primary root length and overall root biomass for each of the lines enabled the identification of rapid-rooting brassica varieties. Rapid rooting enables plants to reach deeper soil layers, where moisture remains more readily available while the surface dries out during drought conditions. Therefore, brassica varieties exhibiting this trait could have improved drought resilience. Furthermore, many farmers are required to reduce fertiliser application to limit potential environmental damage and greenhouse gas emissions. Larger root systems and more efficient nutrient uptake may reduce the fertiliser application rates necessary for plant growth, further highlighting how rapid rooting can improve the climate resilience of crops and agricultural sustainability.

Once the paper assay had been employed, varieties of interest were grown in soil in root-trainers, which are plastic growing containers that can be opened like a book to observe the root system (see **Figure 3b**).[12] These experiments confirmed that most of the selected varieties also demonstrate rapid-rooting traits in a more natural soil system. Genetic analysis will be carried out in the next phase to determine alleles and genomic regions that contribute to rapid rooting. To assess the extent to which rapid rooting could benefit abiotic stress resilience, further experiments are exploring brassica growth in nutrient-deficient conditions. If rapid rooting does indeed confer stress resilience, incorporating this trait into commercial varieties could be key to combatting pressures on brassica production caused by climate change. Exploring climate-resilient brassica varieties is just one of the ongoing VeGIN projects among many at Harper Adams University.

SCREENING FOR BIOTIC STRESS RESILIENCE

Managing crop pests and pathogens remains an ongoing challenge, compounded by factors such as climate stress and the withdrawal of synthetic chemical pesticides. At the University of Warwick, research is focused on identifying traits conferring pest or disease resistance within a range of vegetable crops including brassica, lettuce, carrots, onions, celery, wild rocket, parsnips and coriander.

▲ **Figure 4. Screening for resistance to cavity spot caused by *Pythium violae*, and willow-carrot aphid (*Cavariella aegopodii*) in the VeGIN carrot diversity set: (a) cavity spot symptoms in carrot; (b) VeGIN macrocosm screening experiment; (c) carrot red leaf virus symptoms transmitted by willow-carrot aphid; and (d) VeGIN carrot diversity set field screen for willow-carrot aphid resistance. © Lauren Chappell and Nicole Pereira, VeGIN project**

Climate change is altering the dynamics of pest and pathogen populations. Overwintering survival, population growth rates and the number of generations within a season are all influenced by weather conditions, principally temperature and precipitation.[13] Understanding the underlying impact of climate change on an individual pest or pathogen is essential for developing techniques to identify plant resistance and deploying it as part of an integrated pest and pathogen management system.

Two key crop protection challenges for carrot growers are cavity spot, caused by the oomycete *Pythium violae*, and infestation by the willow-carrot aphid (*Cavariella aegopodii*). Cavity spot causes small black lesions on mature carrot roots (see **Figure 4a**), rendering them unmarketable, with estimated crop losses of £3–5 million per season.[14] Within VeGIN, *Pythium violae*-inoculated compost and soil methods have been developed for both pot-based glasshouse trials and in-field macrocosms (see **Figure 4b**).

These have allowed the carrot diversity set to be screened for resistance to cavity spot in both controlled and field environments, and a number of lines from the set have shown good levels of resistance compared with more susceptible commercial cultivars.[14] Carrot crops are usually overwintered in the soil, with a straw layer added to prevent frost damage. Cavity spot incidence is greater in overwintered crops, and with increasingly warm winters it is likely this incidence will increase further. Additional screening is now being undertaken in an inoculated open-field trial, before resistant lines will be handed over to breeding companies for incorporation into commercial breeding programmes.

Willow-carrot aphid is a major pest of apiaceous crops, including carrot. Winged aphids migrate from willow, their overwintering host, in April–June and may lead to large infestations on carrot, their primary summer host, which is an abundant food source that supports rapid asexual reproduction. Of greatest significance is the role of willow-carrot aphid as a vector, transmitting several plant viruses, including the carrot red leaf virus (CtRLV), part of the carrot motley dwarf complex.

CtRLV symptoms include reddening leaves and stunting (see **Figure 4c**), resulting in severe yield reductions and crop losses. As part of the VeGIN project, 85 accessions from the carrot diversity set were screened in a field trial, sown to coincide with the aphid migration. Several accessions supported lower numbers of aphids compared with current commercial cultivars, indicating potential sources of resistance (see **Figure 4d**). An assay for CtRLV is now being developed to identify accessions that might be resistant to the virus.

FUTURE FARMING

As global climate targets look increasingly likely to be missed, including that of limiting global temperature rise to 1.5C above pre-industrial levels (as set out in the 2015 Paris Agreement), it is inevitable that extreme weather and pest and pathogen pressures will continue to challenge food production.[16] As these impacts intensify, our current vegetable varieties could become less and less viable, leading to food shortages and quality issues. Innovation in the agricultural sector will be essential to combat the impacts of climate change. Developing new climate-resilient varieties is one way in which agriculture can be adapted to improve the sustainability of food production. And the vast array of genetic diversity that exists within left-behind crop accessions could act as the toolkit needed to achieve this.

Pre-breeding research to identify beneficial traits is the critical first step for improving crops. And as DNA and RNA sequencing technologies continue to advance and become more accessible, it is becoming increasingly feasible to identify specific genes that contribute to resilience traits. This knowledge will improve the efficiency of breeding programmes, allowing desirable alleles to be selected with greater precision. Furthermore, gene editing technologies could provide a more direct and timely approach for incorporating resilience traits into commercial vegetable varieties, which may be necessary if the frequency and intensity of climate stresses continue to rise rapidly. Together, advances in pre-breeding research, sequencing and gene editing will drive the development of climate-resilient vegetable varieties for future farming. ES

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Rosemary Collier focuses on development and application of integrated pest management strategies for horticultural crops. Components include novel pesticides and biopesticides, biological control, host-plant resistance (VeGIN project), monitoring and forecasting, and approaches that influence pests through increased plant diversity in the cropping system (e.g. companion planting, intercropping, trap crops and conservation biocontrol).

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Ammonia: the invisible farming by-product

Claire Holman and **Kieran Laxen**

contextualise the climate impacts of agricultural emissions and what the necessary changes are to reduce them.

If you live or spend time in the countryside you may have experienced rather unpleasant smells from manure or sludge spreading or from a poultry shed but, while that is annoying, you might not be aware that these activities can cause air pollution far away. Farming is a significant source of air pollution, especially of ammonia, which is an important contributor to that unpleasant pong.

Agriculture contributes to both air pollution and climate change. Globally, over 80 per cent of ammonia emissions are from agriculture, while in the UK farming contributed 87 per cent of the emissions in 2023 (see **Table 1**).[1,2] In the same year, agriculture contributed 12 per cent of the UK's greenhouse gas emissions (in terms of carbon dioxide equivalent). Approximately 30 per cent of the UK's total nitrous oxide emissions and 49 per cent of methane emissions are due to farming activities.

TABLE 1. AGRICULTURE AS A PERCENTAGE OF TOTAL AMMONIA EMISSIONS IN 2023

NATION	Agriculture (%)	Total (kilotonnes)
England	84	174
Northern Ireland	97	32
Scotland	92	31
Wales	93	23
UK	**87**	**259**

Note: Totals may differ from sum of components due to rounding.
(Source: National Atmospheric Emissions Inventory, 2025[3])

The environmental impacts of atmospheric ammonia are well recognised, resulting primarily from the acidification and eutrophication (due to over-fertilisation) of ecosystems, causing changes in species diversity, particularly in sensitive habitats, and ecosystem resilience. In rural areas ammonia emissions from livestock production are the primary contributor to nitrogen deposition (see **Box 1**).[4]

Ammonia is also a significant source of fine particulate matter ($PM_{2.5}$), which is known to have a wide range of adverse health effects, and a significant reduction in $PM_{2.5}$ will only be possible if ammonia is reduced. Originally thought to be a cause of cardiovascular disease, $PM_{2.5}$ is now recognised as affecting organs throughout the body, including being associated with dementia. There has, however, been relatively little research on the potential, direct impact that ammonia may have on human health at ambient levels.

Ammonia is very reactive in the atmosphere and has a short lifetime of just a few hours. The particulate matter it forms can travel across country boundaries. Most ammonia will be deposited close to where it is emitted (within a few kilometres) and therefore will have the greatest impact on nature conservation sites near to sources. Dry deposition of ammonia shows strong local-scale variability and is closely correlated to emissions from livestock. Ammonia also contributes to the wet deposition of ammonium salts. These components have a relatively long atmospheric residence time, up to two weeks, and when removed by precipitation contribute to nitrogen deposition in remote ecosystems after being transported long distances. Together, ammonia and ammonium are known as reactive reduced nitrogen.

BOX 1. CRITICAL LOAD & LEVEL EXCEEDANCES

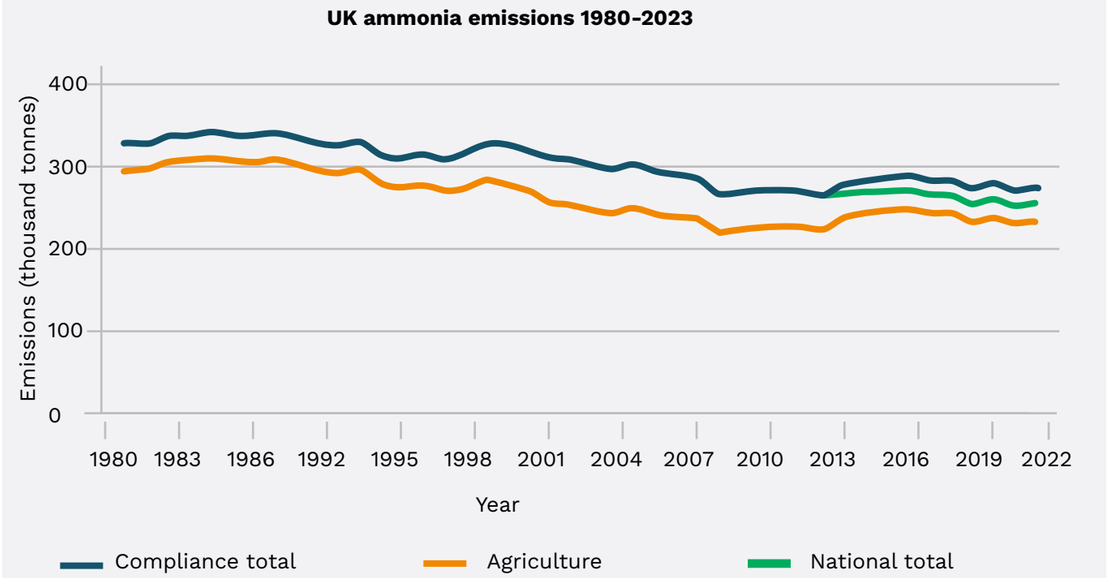
Critical levels and critical loads are used to indicate whether an ecosystem is at risk from air pollution, although effects are known below these levels. When pollution decreases there can be a delay in recovery, but the risk of harm is reduced.

The most recent assessment shows that in 2021 about 2 per cent of the UK's land area was exposed to ammonia concentrations above the critical level set to protect higher plants (3 µg/m³), and 55 per cent were exposed to ammonia at concentrations above the critical level set to protect lichens and mosses (1 µg/m³). The area where the critical level for lichens and mosses is exceeded has decreased by just 2 per cent of UK land area since 2003.

Of the total acidifying pollution on UK woodland in 2021, 62 per cent was reduced nitrogen (ammonia and ammonium).

The area of nitrogen-sensitive habitats with exceedance of nutrient nitrogen critical loads fell from 94 per cent (87,954 km²) in 2003 to 84 per cent (78,687 km²) in 2021. This decline was largely driven by changes in Scotland; in England, Wales and Northern Ireland there was relatively little change in area experiencing exceedance over this period.[5]

Emissions of ammonia in the UK peaked in the 1980s and have since decreased by about 20 per cent, although that reduction stopped around 2008. Despite the damage ammonia causes to semi-natural habitats and its contribution to $PM_{2.5}$, emissions have changed little over the last 15 years – standing at 265 kilotonnes (kt) in 2023 compared to 257 kt in 2008 (see **Figure 1**). The UK has obligations under EU law and international



▲ **Figure 1. UK ammonia emissions 1980-2023 (Source: Defra, 2025[2])**

treaties to reduce ammonia emissions. By 2030, the UK must reduce its ammonia emissions by 16 per cent compared to 2005 levels. Emissions dropped 11 per cent by 2023, but the lack of significant progress since 2008 puts achieving the 2030 target into some doubt. One mitigating factor is the long-term decline in livestock numbers as people eat less meat. As an illustration, between 2021 and 2025, the female cattle breeding herd in England dropped by 7 per cent, breeding pigs by 24 per cent, sheep by 10 per cent and poultry (breeding and laying birds) by 10 per cent.[6]

Agriculture is an essential economic activity, but despite being responsible for the majority of ammonia emissions, it contributes less than 1 per cent to the UK economy.[7] It is, of course, an important producer of food, and vital for withstanding disruption to international supply chains. The challenges farmers experience – especially related to increasingly uncertain weather conditions due to climate change, and to reliance on government support – should not be underestimated. Many may consider over-fertilising to be the safer option compared to poor crop yield and reduced income in such an uncertain world.

SOURCES OF AGRICULTURAL AMMONIA

Emissions occur due to the use of nitrogen-based fertilisers and from livestock farming, and more than half of the agricultural sector emissions are related to cattle, mainly when they are kept inside sheds (see **Table 2**). Most of the urine that is excreted on to the floor of animal housing is either mineralised to ammonium or transformed to ammonia. However, this urine can also combine with faeces in animal houses such as those with slat-based or solid-floor systems to produce slurry. The resulting slurry can release gaseous emissions by bacterial degradation and enzymatic reactions, resulting in the release of nitrogen, nitrous oxide and ammonia.[8]

Many different factors can influence gas formation and volatilisation, in turn affecting both the emissions from animal houses and the resulting atmospheric concentrations in the surrounding area. These factors are related to the animals (e.g. type, genetics, diet, number, weight, activity and behaviour), wastes (e.g. handling, treatment, pH, temperature and surface area), environment (e.g. indoor and outdoor temperature, ventilation flow rate and air velocity over the manure surface) and other site-specific factors, such as the presence and type of bedding materials.[9] As a result, it is

TABLE 2. ESTIMATES OF AMMONIA EMISSIONS FROM UK AGRICULTURE (2023)

SOURCE	Ammonia (kilotonnes)	Percentage of total ammonia[a]
By livestock category		**73.3**
Dairy cows	56.9	24.6
Beef cattle and non-lactating dairy cattle	56.3	24.4
Sheep	11.7	5.1
Pigs	14.8	6.4
Poultry	28.2	12.2
Minor livestock (horses, goats and deer on agricultural holdings)	1.2	0.5
Manure emission by management category		**73.3**
Grazing/outdoors	18.5	8.0
Housing	57.6	25.0
Hard standing	13.9	6.0
Manure storage	19.2	8.3
Manure application	55.4	24.0
Manure digestate storage	0.4	0.2
Manure digestate application to soil	4.1	1.8
Other sources		
Urea/UAG fertiliser application	30.2	13.1
Other nitrogen fertiliser applications[b]	10.8	4.7
Sewage sludge application	4.8	2.1
Non-manure digestate application	15.8	6.9

Notes: a. Totals may differ from sum of components due to rounding.
b. Other nitrogen fertilisers include ammonium nitrate, calcium ammonium nitrate, ammonium sulphate, diammonium phosphate and other nitrogen fertilisers (including compound blends).
(Source: Carswell *et al.*, 2025[9])

difficult to develop robust emission factors for use in emissions inventories and dispersion modelling.

Cattle and pig housing can use either slatted floors with slurry collection beneath or solid scraped floors. Cattle can also be housed in naturally ventilated buildings, either year-round or over the winter period with an outdoor grazing period in summer. Poultry production units can have various housing styles, including high-rise, cage-based systems with manure stored beneath the cages, manure belt systems, cage-free housing or be free-range. Changes to housing, including ventilation rates, bedding, flooring, temperature and manure storage, can all reduce emissions. For livestock buildings, air treatment systems (e.g. biofilters, bio-scrubbers, activated carbon filters) are considered to be best available techniques by the EU but, in reality, such measures are often considered too expensive.

EMISSIONS REDUCTION STRATEGIES

Ammonia is regulated to some extent by EU law including by:

- The National Emissions Ceilings Directive (2016/2284), which requires the reporting of ammonia emissions and meeting of national emissions limits (ceilings);
- The Habitats Directive (92/43/EEC), which requires plans and projects to be put into place to limit damage to sensitive habitats; and
- The Industrial Emissions Directive (2010/75/EU), which controls emissions from certain agricultural facilities.

As stated, cattle are responsible for about half the ammonia emissions, yet these emissions are largely unregulated. In its Clean Air Strategy 2019 (for England), Defra announced a number of measures to reduce ammonia emissions by requiring the adoption of low-emissions farming techniques and extending the environmental permitting regime to dairy and intensive beef farms. Intensive poultry (more than 40,000 places) and pig farms (more than 2,000 places for production pigs, 750 places for sows) are already part of the permitting system under the Environmental Permitting Regulations 2016, which transposed the Industrial Emissions Directive into UK law, but cattle have yet to be included.

Instead, the Government has opted for a combination of voluntary measures and fiscal incentives. The Code of Good Agricultural Practice (COGAP) for Reducing Ammonia Emissions includes advice on reducing ammonia emissions, particularly from the application of livestock manures to land, the storage of manures and management of waste from livestock housing.[10] It also includes advice on livestock diet, as this can affect the nitrogen levels in manure (see **Box 2**). In addition, how farmers are financially supported has changed since the UK left the EU and now includes targeted action to protect habitats affected by ammonia. Grant funding for slurry store covers and other infrastructure is available for farmers.

In general, nitrogen-sensitive designated sites located near intensive agricultural land use, such as lowland bogs, respond well to geographical targeting, as dry-deposited ammonia from local sources will be the predominant form of atmospheric nitrogen input to these sites. The targeting of reduction strategies in the vicinity of these types of sites will significantly reduce these local sources.

For nitrogen-sensitive designated sites further away from intensive agricultural land use, such as upland moor or mountainous sites, geographical targeting of reduction strategies is less effective, as nitrogen deposition at these sites is generally dominated by longer-range or background nitrogen sources including wet-deposited ammonium. Significantly reducing these longer-range inputs requires a regional approach to tackle regionally elevated concentrations and for some sites will require transboundary measures.

This is supported by modelling undertaken for the Joint Nature Conservation Committee (JNCC).[11] This shows that, per unit of ammonia emissions abated, measures targeted within 1 km of designated sites are on average 4.6–5.8 times more effective at reducing ammonia concentrations in the air. In Northern Ireland, on average, they are also approximately four times more effective at reducing dry deposition of ammonia at designated sites when compared to applying enhanced measures across the whole country.[12] Therefore, the closer enhanced mitigation measures are

BOX 2. REDUCING AMMONIA EMISSIONS

The Code of Good Agricultural Practice states the following for reducing ammonia emissions:[10]

'Nitrogen, in the form of ammonia, is lost from organic manures (such as slurry, solid manure and litter, digestate, sludge and compost) when they come into contact with air, particularly on warm or windy days. Nitrogen is also lost from manufactured fertilisers during spreading. The more that this occurs, the more nitrogen is lost as ammonia, meaning the material is a less effective fertiliser and loses value. Therefore, measures to reduce ammonia emissions and improve overall nutrient management practices could reduce the amount of manufactured fertiliser that farmers need.'

'Ideally, measures to reduce ammonia emissions should be applied to all stages of the farming process, from livestock diet and housing to manure storage and spreading. Otherwise, nitrogen retained at one stage could be lost at the next stage as ammonia.'

'Your aim should be to integrate and balance all nutrient sources to improve crop nitrogen use efficiency. Fertiliser should be applied in the right amount, at the right time and in the right place. If too much fertiliser, either organic or manufactured, is applied to land, or it is applied in inappropriate weather conditions, the soil and crops can't use the nitrogen quickly enough and a percentage is lost from the farming system as ammonia or nitrous oxide to air and nitrate to water. This pollution could be substantially reduced and savings made through consistent use of good nitrogen management practices.'

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applied to designated sites, the greater effect these have at reducing ammonia.

Maximising the effectiveness of ammonia-reduction measures will require an approach that combines (a) country-wide measures to decrease ammonia concentrations region-wide from a high baseline and (b) selective local targeting of measures to decrease ammonia concentrations and local nitrogen deposition at nitrogen-sensitive sites where there are high emissions densities in close proximity.

SUMMARY

While providing good advice on reducing ammonia emissions from agriculture and offering some fiscal support will help the transition to low-ammonia farming, it is likely to take many years before such practices are widespread.

Meanwhile, the UK edges closer to failing its 2030 emissions target and continues to damage valuable semi-natural habitats. Recovery could take decades; therefore, the sooner ammonia emissions are reduced, the better, and it is likely that inclusion of intensive cattle facilities in the environmental permitting regime will prove necessary. It is important to ensure that the transition is managed by supporting farmers appropriately, in recognition of the vital role they play in food production and the need for security of supply in these turbulent times.

The Government committed to introducing clear, proportionate regulations to reduce ammonia emissions in the Clean Air Strategy 2019, but little has been done to date. It is understood that a draft of the Government's Environmental Improvement Plan 2025, written before the latest Cabinet reshuffle, mentioned agricultural emissions. The final version may, however, change and not commit to regulation. While the solution to minimising emissions may be either regulation or voluntary measures, supported by the COGAP and grant schemes, any solution requires monitoring and measurement systems to be put into place to understand the progress and effectiveness of new policies.
It is, therefore, important that the information gap on ammonia emissions from different agricultural activities is filled. This is also vital for assessing the impacts of new intensive livestock farming facilities for planning and environmental permitting. Local planning authorities need to have greater awareness of the issues associated with intensive livestock facilities. ES

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Farming at the sweet spot for nature and food

Vicki Hird examines how farming for biodiversity recovery could benefit everyone.

The UK is one of the most nature-depleted countries in the world, with increasingly fragmented remnants of isolated habitat across our land and seas.[1] Data suggest that across the UK, species studied have declined on average by 19 per cent since the 1970s, and that 16 per cent of our species are threatened with extinction. Invertebrates such as insects, spiders and millipedes have been found, on average, in 13 per cent fewer places now than in 1970.[2]

Given that around 70 per cent of UK land is farmed, any nature restoration strategy must have a strong focus on farming. To recover, restore and connect wildlife, all opportunities need to be taken to examine not only how but what is farmed and why.

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WHY MORE FARMERS CARE ABOUT BIODIVERSITY

Looking at the value of biodiversity to both the farmer and society in general, there is significant evidence showing why restoring nature matters, from global assessments on the value of biodiversity down to national research.[3] The Office for National Statistics suggests the total asset value of ecosystem services alone in England was £5.431 billion for agriculture in 2020, but even that does not cover all the assets related to food production.[4] The evidence base used to develop new farm support provision in England shows just how far government now recognises the role of nature in farming.[5]

Farmers too have begun to recognise what they have always known but forgotten with the advent of technology, genetics and chemicals: that at the heart of most farms, fully functioning ecosystems are vital. Accessing ecosystem-focused tools, which organic and permaculture farmers have used for decades, is a core emphasis at many farmers events, organisations and in the farming press; one of the farming magazines, *Farmers Weekly*, even runs regular sustainability events. However, the food industry beyond the farm gate, which dictates largely what and how farmers grow food, is less focused on biodiversity than it is on carbon, although it does recognise its importance.[6]

With climate change creating rapid and more unpredictable changes in temperature, precipitation and natural cycles that are becoming more obvious than ever, farmer awareness is not surprising. Alongside growing input costs, with food, feed, fuel and fibre resilience under threat, farmers recognised the potential for nature to provide answers. The number of organisations like the Nature Friendly Farming Network (NFFN) is growing, reflecting the interest in nature-friendly farming in both a practical and economically beneficial way.[7]

More biodiversity can also deliver for farmers more diverse food markets, provide options for nature finance, offer better local adaptation to climate, flood and drought changes, provide economic resilience, and create greater well-being for them and for rural communities.[8] Specific agronomic examples of how biodiversity can boost these outcomes on farms include:

- Pollination services by invertebrates and small mammals transferring pollen from male to female crop flower parts, allowing fertilisation and seed production. Invertebrates are encouraged to do this by plants through visual and chemical cues and the provision of nectar. Studies show that natural pollination can increase product yields, stability and quality;[9]
- Natural pest predation reducing loss and disease risks;[10]
- Building soil health, fertility and organic content;[11]
- Natural flood management; and
- Trees and shrubs in and around fields providing soil and water management, biodiversity and income.

When lost, these essential services can be extremely expensive to replace and have potentially disastrous consequences. Alongside climate change risks, it clearly makes increasing sense for farmers to use biodiversity services.[12] To illustrate, we look in more detail at some of these systems.

TREES ON FARMS: 3D FARMING

It is clear that addressing individual issues on farms – through policy or industry attention – tends not to deliver the long-term solutions and resilience needed. Much private finance, for instance, has focused on carbon storage through trees without considering how to incorporate that well into a farm system.

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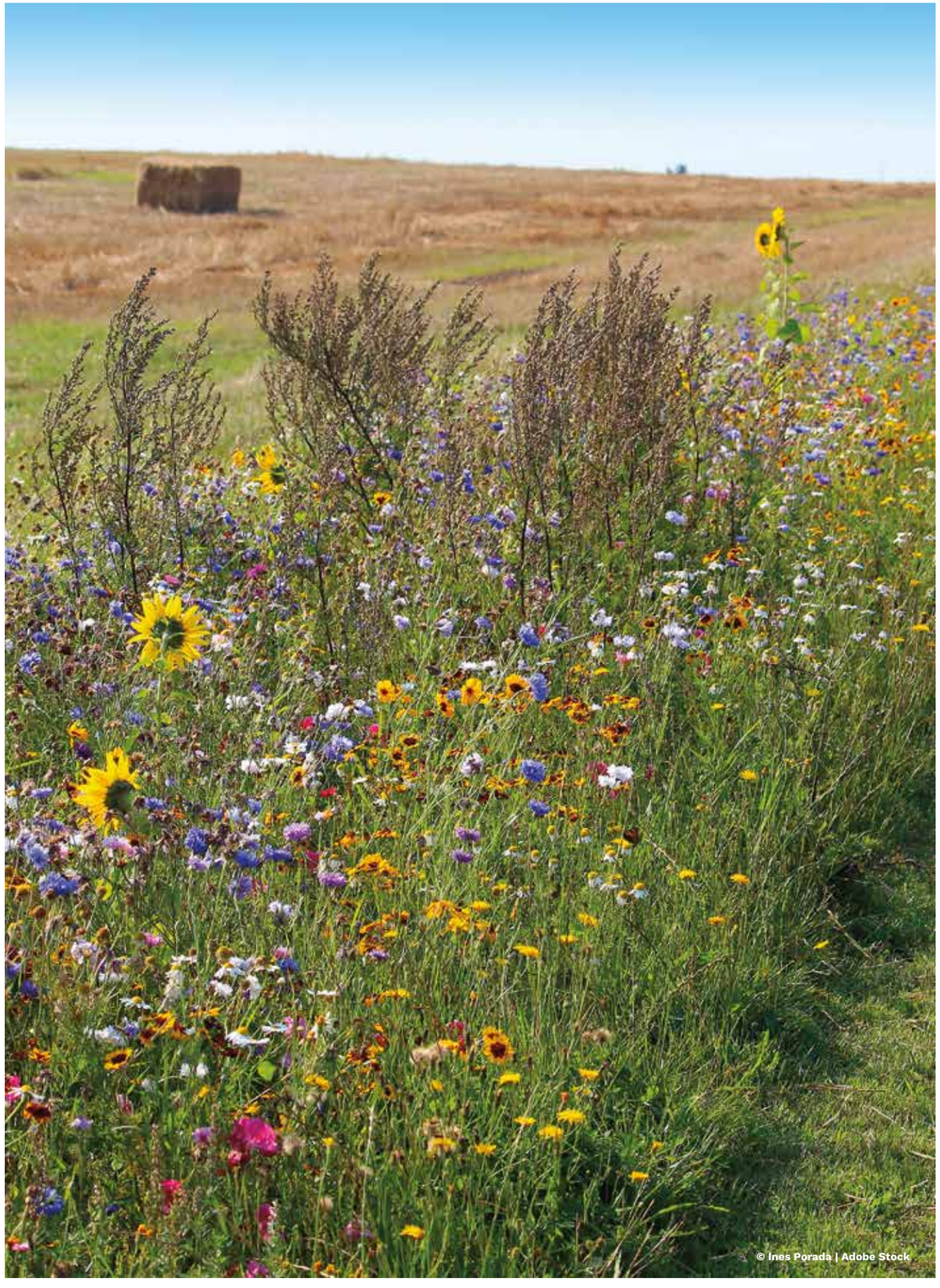
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Yet that mindset is shifting and the growth of agroforestry in the UK – integrating trees and shrubs into arable, horticulture and livestock systems – is growing from its low base of 3 per cent to reach a government target of 10 per cent.[13] This will give a major boost to wildlife on and around farms and provide much-needed green corridors to reduce the fragmentation of key habitats. It will also provide farmers with healthier livestock and crops, better soil health, improved water management, new income sources from fruit, nuts and timber, and new investment and financing avenues.

The availability of public support through capital and maintenance grants, training, skills and applied research are all vital to delivering greater agroforestry on UK farms. Numerous centres now provide courses in agroforestry, and organisations such as the Soil Association, Woodland Trust and Organic Research Centre offer many useful tools to develop agroforestry and farm woodlands.[14] These include a biannual Agroforestry Show with practical demonstrations, peer-to-peer learning networks, farm walks and technical advice; online videos, case studies and a digital e-learning course; plus funding advice, low-cost trees and financing. There is now even a distance-learning Master of Science course in Agroforestry and Food Security at Bangor University.[15]

BIODIVERSITY AND THE NUTRIENT CYCLE

The evidence also indicates some key areas for action to deliver both biodiversity benefits and food production resilience: smarter use of nutrients and chemicals, greater diversity of production, and improved soil and wider habitat management.

Looking at nutrients, there is a long way to go given the significant level of farm-based nutrient pollution in soils, rivers and marine habitats. We need a systems approach to farming, looking at how changes across the whole farm – and by definition the whole-food system – can create a more circular approach using naturally created nutrients on or around the farm and reducing the overload that comes from farming too many animals that are highly concentrated in specific areas. This needs more mixed farm planning (via subsidies, farmer collaboration and food system change), where animals are an integral part of the whole farm system, and within a river catchment or landscape so the nutrients produced by the livestock are in balance with the needs of the system. Ideally all farmers would be incentivised to use nutrient-balanced approaches on-farm so nothing is wasted and causing pollution.

It also means reducing the use of artificial fertiliser, using it in a more precise way to build in cover crops and nutrient-beneficial crops such as legumes, which host nitrogen-fixing bacteria. Several farmers are trialling intercropping legumes with cereals, which is an ancient farm practice where two or more plant species are grown simultaneously in the same field. This provides greater opportunities for pest control (compared to monocropping), an option to add free nitrates to soils when legumes such as beans are one of the crops, and less risk with two marketable crops rather than one. Yet despite its environmental and economic benefits, intercropping is still a niche practice. Barriers include lost skills, a lack of advice, seed and the necessary machinery for harvesting, and poor market development.[16] That the farming sector is running major trials, however, shows the level of interest and it is hoped that more intercropping will follow given the benefits for nature from fewer chemical inputs and greater crop diversity.

INVERTEBRATES MATTER

Looking at invertebrates is particularly important given their crucial role in healthy ecosystems, natural food cycles, and for farm services above and below ground and in water. Invertebrates are an integral part of the natural food cycle and there has been highly worrying evidence of their decline in all areas, but particularly in the rural environment. Research in 2022 found a 60 per cent decline in UK flying insects over the past two decades.[17] Global studies are showing similar patterns.

Pesticide use, habitat fragmentation and loss, pollution and climate change are key factors in this decline. UK farmers are being encouraged through new payment schemes and private financing to reduce pesticide use and to build habitat corridors and refuges. Wildflower margins or in-field strips, for instance, planted on farmland support invertebrate populations, which enhances the area's biodiversity. This practice can also benefit the farmer through positive effects on pest management, soil health and pollination.

When it comes to pesticides, there is copious evidence of harm from their use, the interactions between different pesticides, and the impact of non-active ingredients such as surfactants. The UK has recently confirmed a permanent ban on the use of one of the most toxic insecticides –

neonicotinoids – alongside delivering a long-awaited Pesticides National Action Plan, with the UK's first ever pesticide reduction target of 10 per cent.[18,19] There is also a significant payment option available to farmers who agree to drop all insecticide use in England.[20] But much more is needed to support all farmers in using fewer pesticides and more nature-based and cultural tools.

THE BUSINESS DIVIDEND

One meta-analysis suggests that ecological practices (specifically, increasing crop diversity and adding fertility crops and organic matter) have generally positive effects on the yield of staple crops.[21]

The pioneers of the maximum sustainable output (MSO) or 'sweet spot' model, Nethergill Associates, are seeing an ever-increasing number of farms using their tool.[22] The approach involves analysing the farm's financial operations and inputs and shows the point at which the business becomes more profitable and nature is at an optimum balance. Their work shows that when farming at the MSO level, the staged reduction of costly inputs – such as artificial fertiliser, pesticides, veterinary care and imported feed concentrate – makes farmers significantly better off across all the farm systems studied.

MSO research for The Wildlife Trusts and NFFN on 165 farm business accounts showed that reducing input costs can deliver both better incomes and reduced environmental harm.[23] The predicted commercial returns, before farm support payments, saw an average income increase of 10–45 per cent. By farming sector, the commercial return was 45.3 per cent for lowland livestock, 39.1 per cent for upland livestock, 32.7 per cent for dairy systems and 9.5 per cent for lowland arable farms.

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IS REGENERATIVE FARMING THE ANSWER?

Regenerative farming is an increasingly dominant approach and is even being used in food marketing, However, as yet, it has no legal definition. The core approaches vary – including minimal soil disturbance, keeping soil covered, maintaining living roots in soil for as long as possible (which keeps the underground ecosystem functioning), and creating crop diversity and more mixed farming – but all will help both farmers and nature if done well. Evidence of the environmental and socio-economic impacts of regenerative farming across different systems and climates remains limited, with few studies measuring multiple outcomes following whole farming system transition.[24]

A NATURE-FRIENDLY, RESILIENT FUTURE

Short, medium and long-term plans for the whole-food system could deliver a vision for resilient farming, where biodiversity and ecosystem restoration and recovery are at the heart of the changes. This should fit with the national environmental targets, as outlined in the 30 by 30 biodiversity commitment, Environment Act 2021, and current climate adaptation and mitigation targets such as on natural flood management and tree planting.[25-27]

This would ensure that nature is in recovery with abundant, diverse wildlife and with natural processes creating wilder land and green connectivity where people and nature can thrive.

But it would also help deliver on a food strategy, where a 'good food cycle' for all ensures far fewer unhealthy foods (which rely on unsustainable supplies of cheap raw materials), more sustainable diets, better climate mitigation and adaptation, and fair supply networks. For all this to happen, sustained and effective global, national, regional and local policies need to be directed to encourage nature-based solutions on farms and within food systems, including crop diversity and agroforestry, but also to replace some harmful agricultural technologies, including overuse and misuse of fertilisers, pesticides and antimicrobials.

Incentives will be essential for farmers to deliver public goods that are not supported by the market. Critical too is the role of food traders, supply chains and consumers on farmer treatment, prices, promotion of unsustainable foods and diets, and food waste – all of which must change. Without that, farmers will be unable to change their practices in a sustained way, and the major shifts, particularly around livestock farming, will be impossible. As noted in a recent EAT–*Lancet* report, this will inevitably mean eating more plants and less grain-reared meat to reduce the unnecessary land (and water) requirements associated with industrially reared livestock.[28] The role of livestock will be more in the form of mixed cropping, building in soil fertility and carbon in well-managed pastures, and in converting waste food to protein.

Advice, guidance, online resources, traditional extension services and farmer-to-farmer exchanges are also crucial, as are putting a stronger agro-ecological focus into agricultural education provision. Farmers and growers need access to better information and knowledge-exchange networks to develop their skills and to deliver on agro-ecological and systems approaches. The market is unlikely to pay for the research and knowledge exchange, or for farmers' time in accessing and disseminating changes, so public investment and ongoing financial support will be necessary. ES

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Can technological advances solve abiotic stresses in wheat?

Melissa Fitzgerald examines how technology can address the challenges facing a global food staple.

Wheat is one of the world's most important crops and the staple food for approximately 35 per cent of the global population. It is also the primary ingredient in many carbohydrate-rich foods consumed worldwide.[1] Over the past decade, however, wheat production has become increasingly vulnerable to global uncertainty and climate change.[2] The international wheat supply chain has faced significant strain, with major shocks such as the Covid-19 pandemic and the war in Ukraine disrupting production, transport and trade flows.[3,4] These disruptions have exposed the risks of depending on a small number of key wheat-producing regions and prompted many countries to revisit their food security strategies. As a result, global wheat cultivation is beginning to shift, with production expanding into new and sometimes unconventional environments, such as Sharjah in the United Arab Emirates (UAE).[5,6]

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At the same time, climate change – driven largely by global warming – is reshaping agricultural systems globally. Rising temperatures, more frequent heatwaves, shifting rainfall patterns and more frequent climate extremes are changing where and how crops can be grown.[4] Many staple crops, including wheat, maize and rice, are becoming more vulnerable to heat stress, which can shorten growth cycles, reduce grain filling (the process that determines the development of grains) and ultimately lower yields.[7]

As wheat cultivation expands into hotter and drier regions, robust scientific research becomes essential to mitigate the abiotic stresses that limit productivity. Strengthening our understanding of how to reduce the impacts of drought and heat stress will be critical for maintaining stable yields, supporting these emerging production systems and safeguarding global food security against future shocks.

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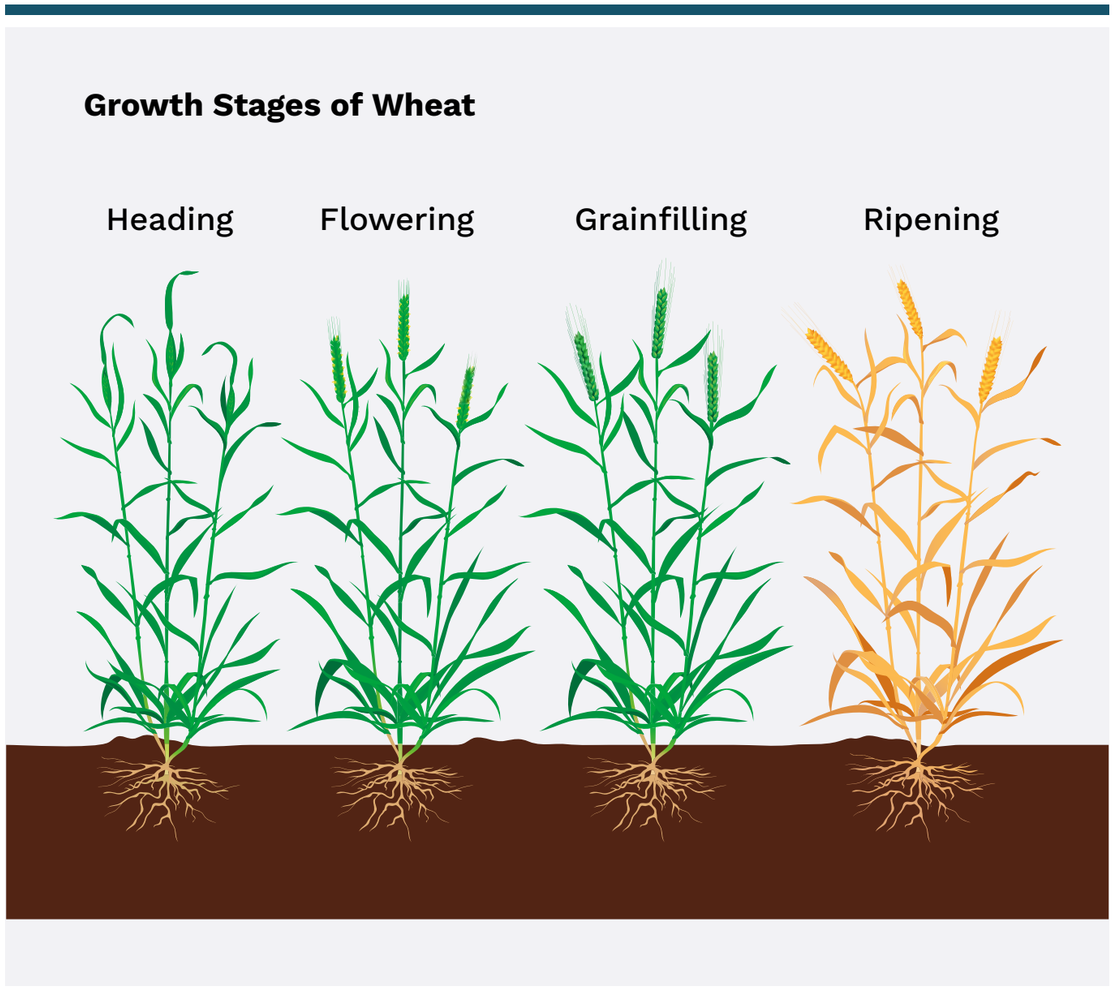
HIGH TEMPERATURES

The impact of high temperatures on wheat yield has been a topic of research for decades in every wheat-growing area in the world. High temperatures have the greatest impact during the reproductive and grain-filling phases.[8] The optimal temperature for grain filing in wheat ranges from 12–22C. When the temperature significantly exceeds this threshold – for example, by 10C during the day – the effects on wheat plants are a decrease in chlorophyll in leaves, lower assimilation of carbon dioxide, increased photorespiration and a shorter grain-development duration.[9] If temperatures rise by 8–10C during flowering and grain filling, the yield is affected due to a decrease in pollen viability, and the grains that do develop are likely to be of low quality.[10]

When grains are defined as low quality, their functionality is lost due to changes in the amount or composition of proteins and to the starch structure. The types of proteins in wheat grains



▲ **Figure 1. The growth stages of wheat. © Vector Tradition | Adobe Stock**

determine the end use of the grain, such as for bread, pasta, cakes or noodles.[11] The structure of the starch and the ratio of amylose and amylopectin also affect several of the grain's cooking qualities.[12] Proteins and starch are each synthesised by processes that involve an interplay of several enzymes. Some of these enzymes are sensitive to high temperatures during grain filling, which then affect the composition and structure of both proteins and starches.

It is not simple to determine the genetics of heat tolerance in wheat, as there are many different phenotypic impacts of high temperature on both the plant and the grain. Furthermore, the timing of the high-temperature interval has a strong effect on the response in the plant. For example, high temperature at flowering decreases pollen viability and, therefore, decreases yield.[10] A high-temperature interval during grain filling impacts the starch-synthesising process and leads to less starch in the grain, which means smaller grains and lower yields.

In one study, wheat was exposed to heat stress for periods of three days between one and 33 days after flowering.[13] Heat applied early during grain filling (i.e. around 6–8 days after flowering) had a much stronger effect on yield and quality than heat applied later (i.e. at 36–38 days after flowering) (see **Figure 1**). That study also found that heat stress applied early during grain filling

reduced both types of starch (amylose and amylopectin), with amylopectin synthesis being particularly sensitive. This aligns with broader evidence that heat stress disrupts the expression of key starch-biosynthesis genes. For example, ADP-glucose pyrophosphorylase – an important enzyme in starch synthesis – is downregulated under heat stress, along with several related genes, contributing directly to reduced starch accumulation and, therefore, yield.[14]

Given that heat stress affects wheat differently relative to the amount of heat, its interval and its timing, it is challenging to identify causal relationships between genes and the phenotypes of heat response, since there are likely to be different genes for different effects. A recent review of the research on heat-response genes reported 134 genetic regions, or loci, across the A, B and D genomes that correlated with a phenotype of heat impact.[15] The large number of loci, and their small effect, makes it difficult to apply the results of this mapping to wheat breeding.[16] However, the rapid development of both genetic understanding and phenotyping technologies suggests that scientific research could soon deliver new selection tools to breeding programmes.

DROUGHT

The availability of water is the most important factor influencing yield.[16] There is no single, universal definition of drought, but for agriculture the most relevant form is meteorological drought, which is typically defined through precipitation and temperature patterns to estimate potential evapotranspiration.[17] In wheat systems, drought stress occurs when potential evapotranspiration becomes high for a given production environment. The severity of drought ultimately depends on how vulnerable the production system is, the magnitude of the water deficit, and the duration and extent of elevated temperatures. The timing of the stress is equally critical with wheat being particularly sensitive during flowering.[16] Early-season drought can lower establishment and cause total crop loss, while drought during grain filling can sharply decrease harvest index and lower overall yield.[18]

Many genetic regions have been associated with anatomic and physiological traits associated with drought tolerance such as root architecture, plant biomass, water-soluble carbohydrates and grain yield.[19] As with genetic and phenotypic associations with high temperature, the large number of these traits for drought tolerance makes it difficult to apply the results to wheat breeding.

There is a clear and well-established relationship between heat and drought, and numerous studies have shown that when these stresses occur together – as they often do in many wheat-growing regions – their combined effects can be far more damaging to yield than either stress alone.[20,21] It is therefore critical for future wheat production that science delivers useful selection tools to wheat breeding programmes.

TECHNOLOGIES TO TRANSFORM BREEDING

Looking ahead, progress in crop improvement will increasingly rely on the convergence of several rapidly advancing technologies. Breakthroughs in genetic understanding – ranging from high-resolution analyses of gene expression to detailed mapping of biochemical pathways

BOX 1. FUTURE ADVANCEMENTS

The future of crop breeding will be defined by powerful advances in artificial intelligence (ai) and precision genetic technologies. AI will transform data analysis by integrating genomic, phenotypic, environmental and sensor-derived data to identify complex trait relationships with unprecedented speed and accuracy. This will enable breeders to predict performance under climate stress and select superior lines earlier in the breeding cycle.

At the same time, next-generation gene-editing tools – capable of modifying large genomic regions with high precision – will allow targeted upgrades to plant stress-response pathways. Genes that regulate drought tolerance, heat resilience, salinity management and nutrient efficiency can be fine-tuned, while resistance traits against pests and pathogens can be stacked without compromising yield.

Emerging technologies such as CRISPR-based multiplex editing, epigenome engineering and high-throughput phenotyping platforms will work together to accelerate the development of robust, climate-adapted crops. This integrated approach promises resilient varieties that maintain productivity across diverse and challenging environments.

Imagine a future of completely organically grown, high-quality, high-yield crops.

◀ **Al Wathba Wetland Reserve, Abu Dhabi, UAE. © Makaty | Adobe Stock**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through metabolomics technologies[22]—are now being paired with sophisticated imaging and sensing technologies capable of capturing canopy temperature, soil temperature and soil moisture with remarkable precision.[23] Together, these technological advances allow researchers to generate extremely rich phenotypic datasets and link them more effectively to underlying genetic variation, which will ultimately feed into more powerful and targeted breeding tools.

Future developments are expected to focus on increasing the throughput and efficiency of genome editing, including the ability to edit large DNA segments at the megabase scale and beyond. As artificial intelligence capabilities expand, tools for protein design and automated platforms such as CRISPR-GPT (a large language model for designing and streamlining gene-editing experiments) are likely to become transformative in directing crop improvement.[24] Alongside these technological gains, deeper insights into gene function, regulatory networks and the development of robust methods for directed phenotyping will be essential for unlocking the full potential of these innovations.

The integration of advanced editing platforms, enhanced phenotyping and expanding biological knowledge promises to accelerate crop improvement dramatically, allowing new, genetically upgraded crops able to produce high yields and high-quality grain independently of environmental challenges. In turn, this will enable new varieties of wheat to flourish in hot and dry environments, such as in the UAE. ES

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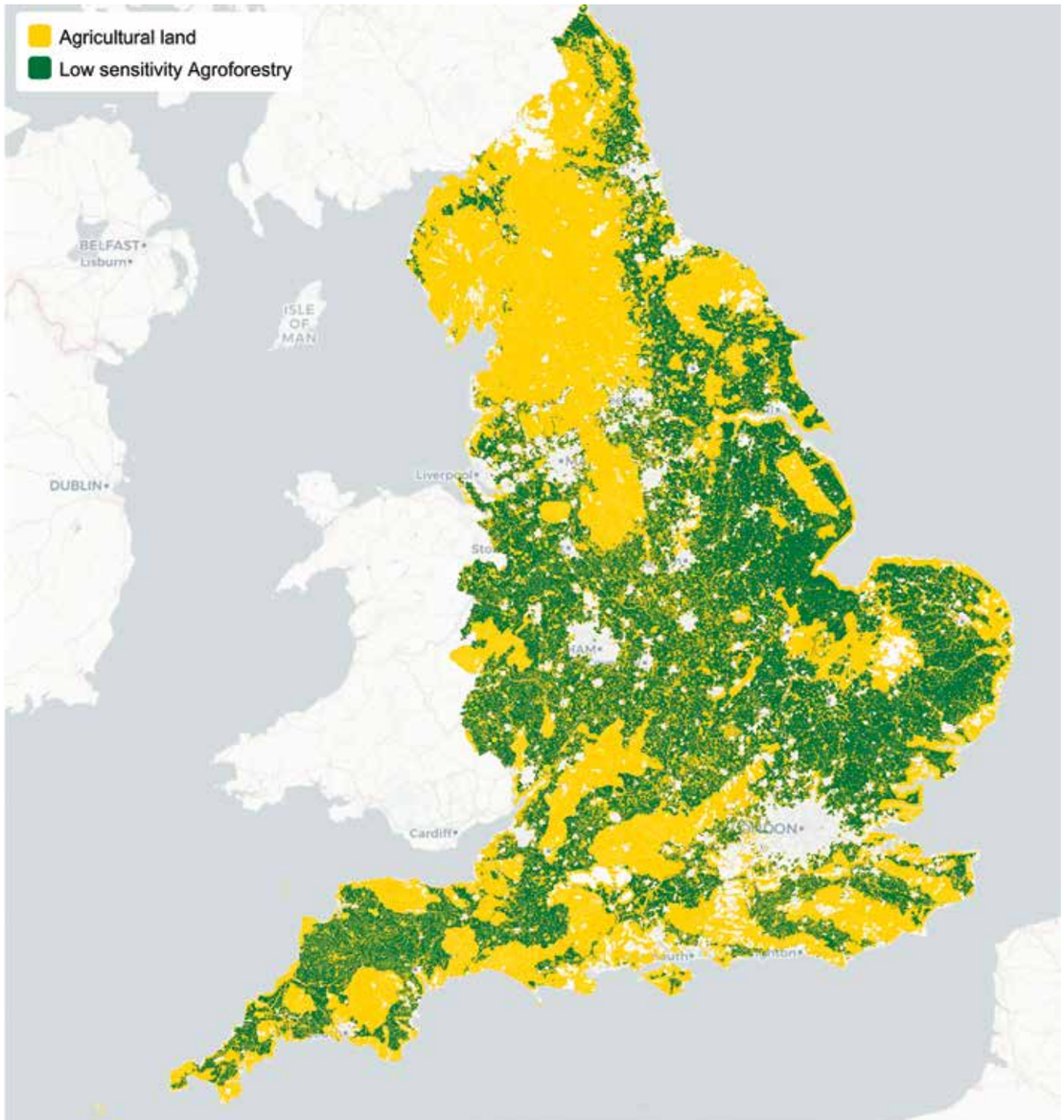
Is agroforestry the answer to making agriculture sustainable?

Blaise Kelly explores whether a return to combining forestry and crops could solve some of the problems in modern food systems.

According to the Food and Agriculture Organization (FAO), the hidden cost of our food system on health, nature and human suffering exceeds US$10 trillion a year – 10 per cent of global gross domestic product. It also states that one-third of the world's population cannot afford a healthy diet, while one-third of the world's food is wasted.[1] Some estimate that there are fewer than 60 harvests left, unless urgent action is taken, because of depleted soils and extreme weather.[2] In some parts of the world the soil is already beyond repair: land is so degraded that it can no longer sustain any crops.[3]

Industrial farming has given us abundance, but it has not automatically given all of us better health. Levels of obesity and type 2 diabetes are soaring, yet so is nutrient deficiency; farmers are abandoning the profession in droves, but supermarkets are making enormous profits.[4,5] According to the United Nations 'the global food system is broken and billions of people are paying the price'.[6] Yet when farming is discussed in policy and the media it ends up as numbers – prices and yields, with the wider costs to the environment and, particularly, human health mostly ignored.

Nitrogen pollution from farming is an increasing problem.[7] In the Netherlands, desperation to meet legally binding nitrogen limits, has forced farms to close and caused significant political unrest, leading to a government that is sceptical of environmental policy.[8,9] Dutch legislation requires that farms are more than a certain distance from Natura 2000 areas because of the risk of nitrogen pollution.[10] This puts farms into similar categories as other polluting industries.



▲ **Figure 1. Total class 1–5 agricultural land in England overlaid with the Forestry Commission's assessment of land with low sensitivity to agroforestry. (Adapted from: Forestry Commission, 2025; Kelly, no date; Natural England, 2025[18,19,22])**

But does it have to be a choice between nature and food production? What if farms could improve biodiversity and absorb nitrogen and carbon from the atmosphere while simultaneously produce food, thereby addressing some of the biggest health issues of our time?

AGROFORESTRY: A POSITIVE SOLUTION?

The FAO's 10 elements of agro-ecology lay out the ambition for farming in a way that improves the natural environment, provides stable, healthy work for local people and, most importantly, can transform human health.[11] One way to apply these principles is by using agroforestry: essentially, adding trees to farmland.

Growing crops in a forest might not seem logical, but until the mid-20th century most farms were like this.[12] In the UK it is estimated that the proportion of land devoted to agroforestry has remained stable at 1 per cent from 2014 to the present day.[13,14] In 2022, Greece led the way with an estimated 23 per cent of all land under some form of agroforestry. However, the trend across the EU between 2012 and 2022 has unfortunately been a downward one.[15] The Climate Change Committee estimates that between 3.2 and 6 million tonnes of carbon dioxide equivalent ($MtCO_2e$) annually could be sequestered by converting 10 per cent of permanent pasture and rough grazing and 10 per cent of arable and temporary grassland to agroforestry.[14,16]

This is quite a small figure given the Forestry Commission's assessment of areas in England that would be suitable for agroforestry.[17] Overlaying the Forestry Commission data on Natural England's agriculture map, it is estimated that 41 per cent of class 1–5 total agricultural land in England (4.7 million hectares) could be suitable for reforesting to some degree (see **Figure 1**). Under the Government's grant scheme, farmers embarking on low-density agroforestry (i.e. 50–130 trees per hectare) do not need to submit an agroforestry plan to qualify.[18] This means that making the switch could be quick and easy for motivated farmers. If all farmland highlighted by the Forestry Commission was converted in this way, the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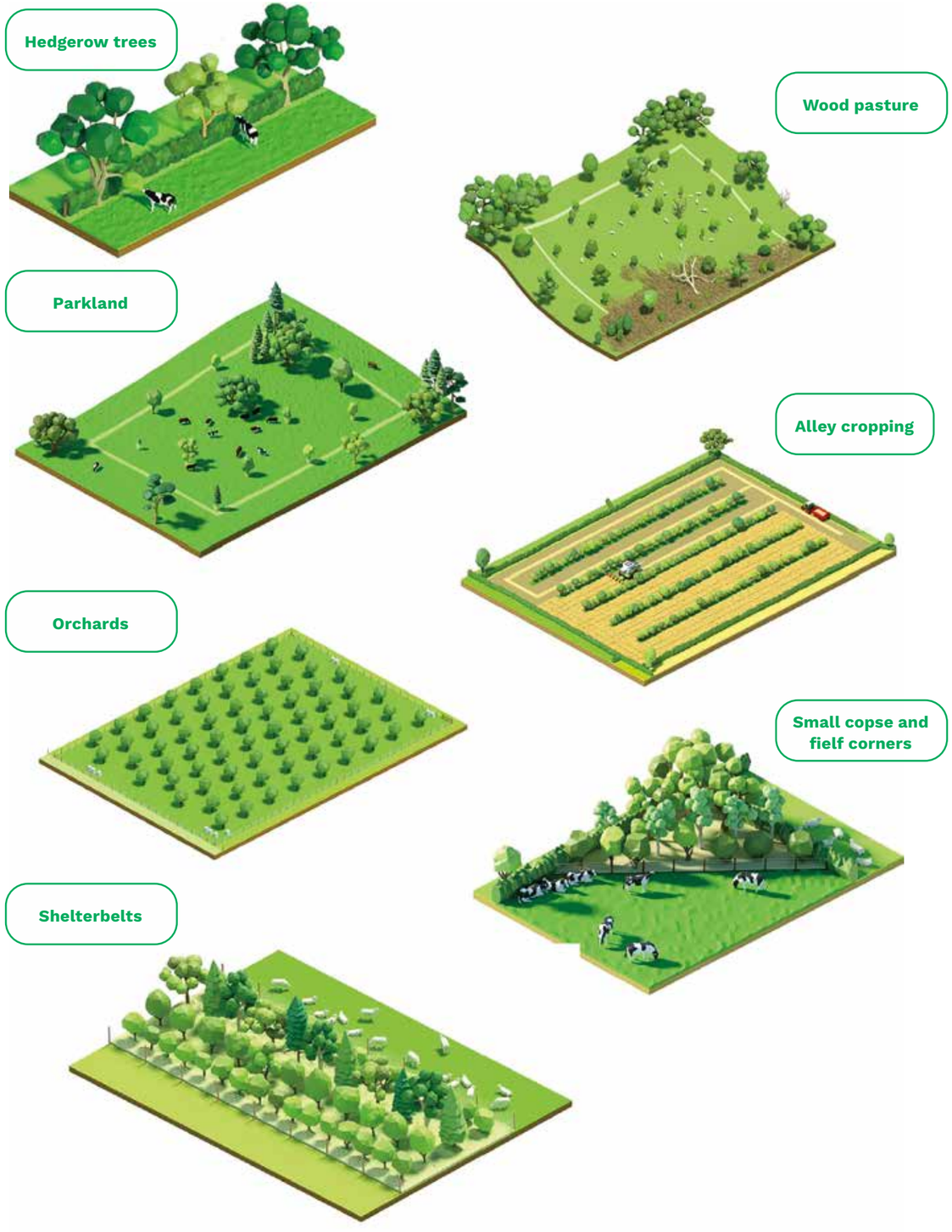
237–616 million trees it would introduce could sequester between 2 and 29 $MtCO_2e$ (assuming an annual sequestration of 10–48 kg of carbon dioxide per year per tree).[19,20] For context, the total agricultural emissions for England in 2020 were estimated at 32 $MtCO_2e$, showing the significant potential of such a system.[21]

The Tree Council has published recommended agroforestry layouts (see **Figure 2**).[23] In most configurations, except perhaps for orchards, other plants and shrubs can grow among the trees. For example, the Tree Council encourages alley-cropping systems to have wildflowers in between the trees, with clusters of trees naturally developing foliage between them.[24] The right trees can significantly increase carbon uptake, not just in the tree itself but also in the soil. Their sturdy roots can reduce soil erosion, improve water management by holding water in the soil, and access the water table down to around 10 m, which can also support plant water needs during dry periods.[25-27] These benefits, along with the earning potential from possible tree crops themselves, can make such systems very attractive for farmers.[28]

While agroforestry systems are not intrinsically organic (e.g. no use of artificial fertilisers, herbicides or pesticides), the additional trees and plants support healthier root systems, which improves soil health.[29] The rhizosphere is the region of soil where the roots connect with microorganisms, fungi and bacteria. One of the key discoveries of recent years is the density of fungal filaments, known as hyphae. The system as a whole is known as the mycorrhizal network or 'the wood wide web', and it allows plants and trees to interact, sharing information as well as nutrients, notably nitrogen.[30]

Nitrogen deposition on leaves can be transferred into the soil, either directly through the roots or through leaf litter. One of the ironies of synthetic nitrogen application is that it actually reduces the ability of crops to access nitrogen due to the



▲ **Figure 2. Typical agroforestry layouts as illustrated by Stuart Jackson-Carter (SJC Illustration) in *Agroforestry. An Illustrated Guide*. Created by the Trees Outside Woodland programme.**[23]

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damage it causes to these delicate soil systems, meaning increasing amounts have to be added.[31] A significant proportion of nitrogen fertiliser is not absorbed by crops and is lost by volatilisation (becoming a gas), run-off (staying on the surface and being washed away) or leaching (soaking in but not absorbed fully and ending up somewhere else). But when the rhizosphere is in good health, the utilisation of nitrogen is far more efficient.[32] It has also been found that crops under an agroforestry system have similar levels of biomass (i.e. leaf and crop amount) to those exposed to full sun, despite being shaded by the trees, thanks to the more efficient use of soil nitrogen.[25] Instead of being a significant nitrogen emitter, agroforestry can turn farms into sinks, using excess nitrogen from the surroundings and making the adoption of chemical-free, organic farming much easier.[33,34]

PESTS, NUTRIENTS AND EMISSIONS REDUCTION

Over millennia, farmers have developed an understanding of how plants work together to ward off predators, known as companion planting. Introducing the right plants can actually bring predatory insects in, keeping damaging pests at bay. Agroforestry by its nature is not just about dropping some trees in but about creating natural areas where fauna and flora can thrive; this increases biodiversity and reduces the risk of pest invasions that are common on monocultures, which create the need to apply pesticides.

The debate over pesticide safety has raged ever since their introduction. However, what is becoming clearer is just how important those ‘nuisance’ pests are and how the environment a plant is raised in affects its nutritional properties.[35] Plants that do not have fertiliser applied have higher levels of vitamins and nutrients, while those that are exposed to pests have significantly higher levels of polyphenols.[32,36] It has also been shown that plants and trees that are attacked or eaten by insects and animals can communicate and tell neighbouring plants to release protective chemicals.[37]

The role of these protective chemicals in the human body is becoming increasingly apparent.[38-40] Additionally, certain antioxidants released into the soil unlock nitrogen and other nutrients, enabling absorption. When big shiny fruits and vegetables have easy access to copious amounts of fertiliser and breed in lifeless environments, they are depleted of nutrients and these essential chemicals: industrially farmed crops are deficient in many essential nutrients that large proportions of the population are also chronically deficient in.[41]

Polyphenols also play a key role in how the human body uses nitric oxide, which is essential to the health of our vascular system and has been positively correlated with lower instances of dementia.[42,43] Nitric oxide is produced in the body from nitrites, which are formed when we eat nitrates in food, yet synthetic nitrites added to processed food (e.g. used to make grey meat look red) are considered a type 1 carcinogen.[44] Consuming nitrates with vegetables is considered to be a safe way to improve nitric oxide production in the body. Industrial produce results in higher levels of nitrates from fertiliser and was thought to be beneficial to human health, as the resulting produce has higher nitrate. However, recent research shows it is more complex than this and it is vegetables that contain a balanced level, with more polyphenols, that have the most useful and beneficial nitrate for the body.[45]

Another significant contributing factor to chronic disease in the population is the imbalance in omega 3 and 6.[46] Humans evolved eating less than a 1:4 ratio, but this has shifted as far as 1:20 in favour of omega 6, which is resulting in inflammation, a decline in intelligence and higher instances of type 2 diabetes.[47-49] Omega 3 is often associated with fish, but historically beef and other animal meat was also high in the essential fat. Grass-fed cows produce milk with a 1:1 ratio, whereas in grain-fed cattle the ratio is 1:10.[50] It is a similar story with eggs and meat from poultry fed on foliage and manure larvae versus grain.[51-54] Like with all nutrients, the combinations they have existed in throughout human evolution is important, and omega 3 supplements have been linked to poor health outcomes.[55]

It is not just crops and humans that benefit from forests. Agroforestry systems also support livestock, providing shelter and shade. Studies have shown a 20–30 per cent reduction in temperature extremes under agroforestry systems compared to monocultures.[56] Poultry such as chickens, ducks and geese also provide symbiotic benefits and can get into more intricate forest areas to clean up unwanted weeds or plants. When farmed closely with livestock, chickens also peck through manure, eating fly larvae, parasites and maggots, reducing the number of flies (which are often controlled using sprays) and helping to work the manure into the soil to improve carbon and nitrogen sequestration.[57,58]

We think of cows and sheep grazing open fields, but their original natural environment was silvopasture (the integration of trees, pasture and livestock) and has been shown to have significant benefits on their well-being and diet.[59] Zoopharmacognosy is the behaviour shown by animals of ingesting or applying plants, soils and insects to self-medicate. Eating leaf matter reduces parasites and worms in cows, lowering the need for chemical treatment.[60] Endectocides, used in the treatment of parasites on livestock, are a significant cause of dung beetle species decline.[61] Dung beetles perform a vital role in breaking down manure, reducing emissions of methane and ammonia.[62,63] Eating forest plants has also been shown to further reduce methane


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emissions from the rumen (stomach) in cattle, in some cases by nearly one-third.[64,65]

Methane from livestock manure comes, by and large, from anaerobic breakdown in lagoons or tanks in intensively farmed sheds. In contrast, when manure lands on soils and breaks down aerobically, little to no methane is produced.[66] Animals moving around means less mixing of urine and manure, reducing ammonia emissions. Overall, agroforestry has the potential to transform farming systems into net carbon sinks, while still enabling meat and dairy production.[67]

FARMING IS MORE THAN PRODUCING FOOD

Micheal Fakhris, speaking at the FAO food systems conference in 2024, described what good food is:

'Good food is not charity, not the right to be fed, not a commodity like a car that is bought and sold for profit and not a technological advancement. Good food is food that makes communities stronger and healthier and makes the environment more biodiverse[,] more resilient. Food is life, food is pleasure, it is how we define our culture, who we are and connects us with our past and has a profound sense of meaning.'[68]

Fakhris says that one approach that has been most effective time and again for providing good food at affordable prices to the public is local markets selling to consumers directly; for example, a system where people shop at local food specialists, who are passionate and knowledgeable about the food they sell.[68]

Agroforestry and support for a more integrated approach to farming will only happen if there is public demand for it. It is no use providing nutrient- and antioxidant-rich produce if people do not appreciate or understand the difference. Agroforestry has the potential to not only sequester large amounts of carbon dioxide in trees and soils but to unlock essential nutrients like nitrogen that are abundant in our modern environments, displacing the need for synthetic fertilisers and improving biodiversity – thereby reducing the need for pesticides. These changes, along with improvements in animal diets, can both have a positive impact on health and address some of the most pressing environmental problems facing modern society.

ES

Blaise Kelly, MIEnvSc, MIAQM, has 15 years' experience in working in building, environmental and transport modelling. Blaise has a strong research interest in understanding how these systems interconnect and influence one another and how they relate to human health.

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Integrated water resources management and the water–energy–food–ecosystems nexus

Kiran Tota-Maharaj explores how the application of two simple frameworks can cultivate agricultural resilience.

Water resources are critical for supporting sustainable agricultural practices and ensuring the viability of UK farming. Yet this vital resource is currently under significant pressure from the combined effects of climate change, a growing population and the degradation of existing water infrastructure (e.g. pipes and canals), rendering standard management approaches inadequate.

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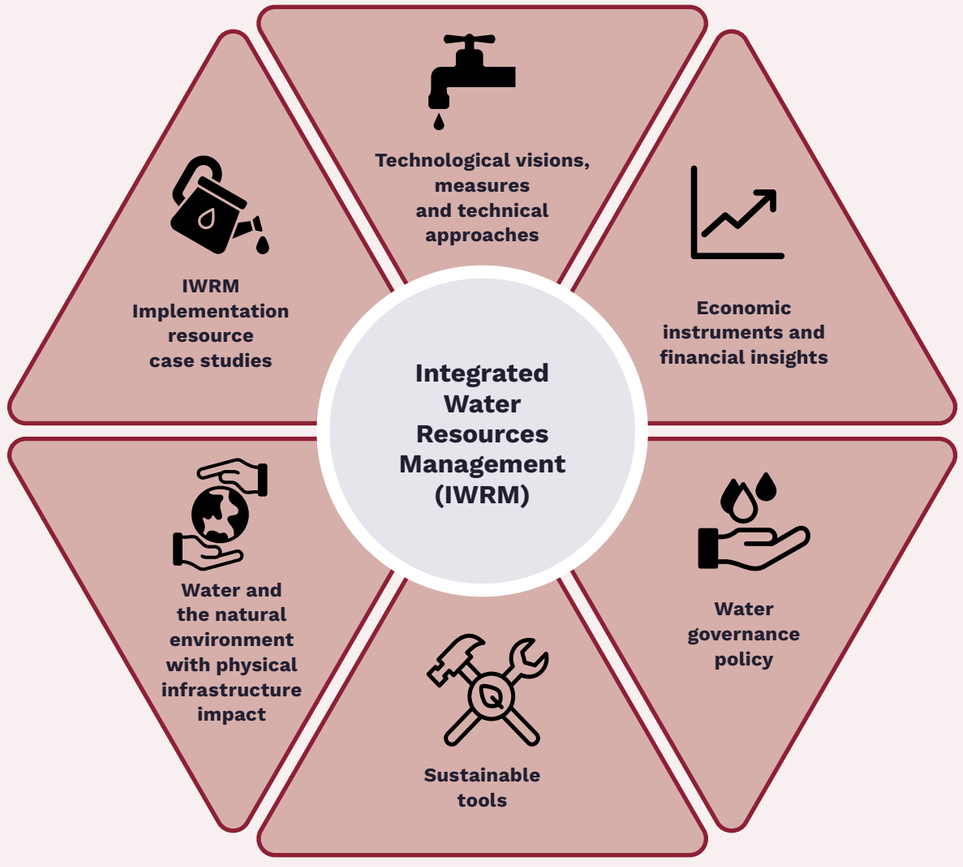
This is why frameworks like integrated water resources management (IWRM) and the water–energy–food–ecosystems (WEFE) nexus are essential, encouraging a holistic, big-picture approach that connects the dots between water, energy and food security to promote smarter, more efficient resource utilisation. The practical application of IWRM and the WEFE nexus within UK agriculture can ultimately bolster the resilience and future viability of UK farming – especially in response to increasingly frequent droughts, in examining farmer initiatives (e.g. investing in on-farm reservoirs for storage), and in exploring the crucial roles that supporting policy changes and adopting new technologies play in ensuring these efforts succeed.

The UK agricultural sector and its farmers face significant challenges stemming from climate change, diminishing resources and environmental strain. Water, which is vital for food production, is increasingly difficult to manage due to recurring droughts and rising demand.

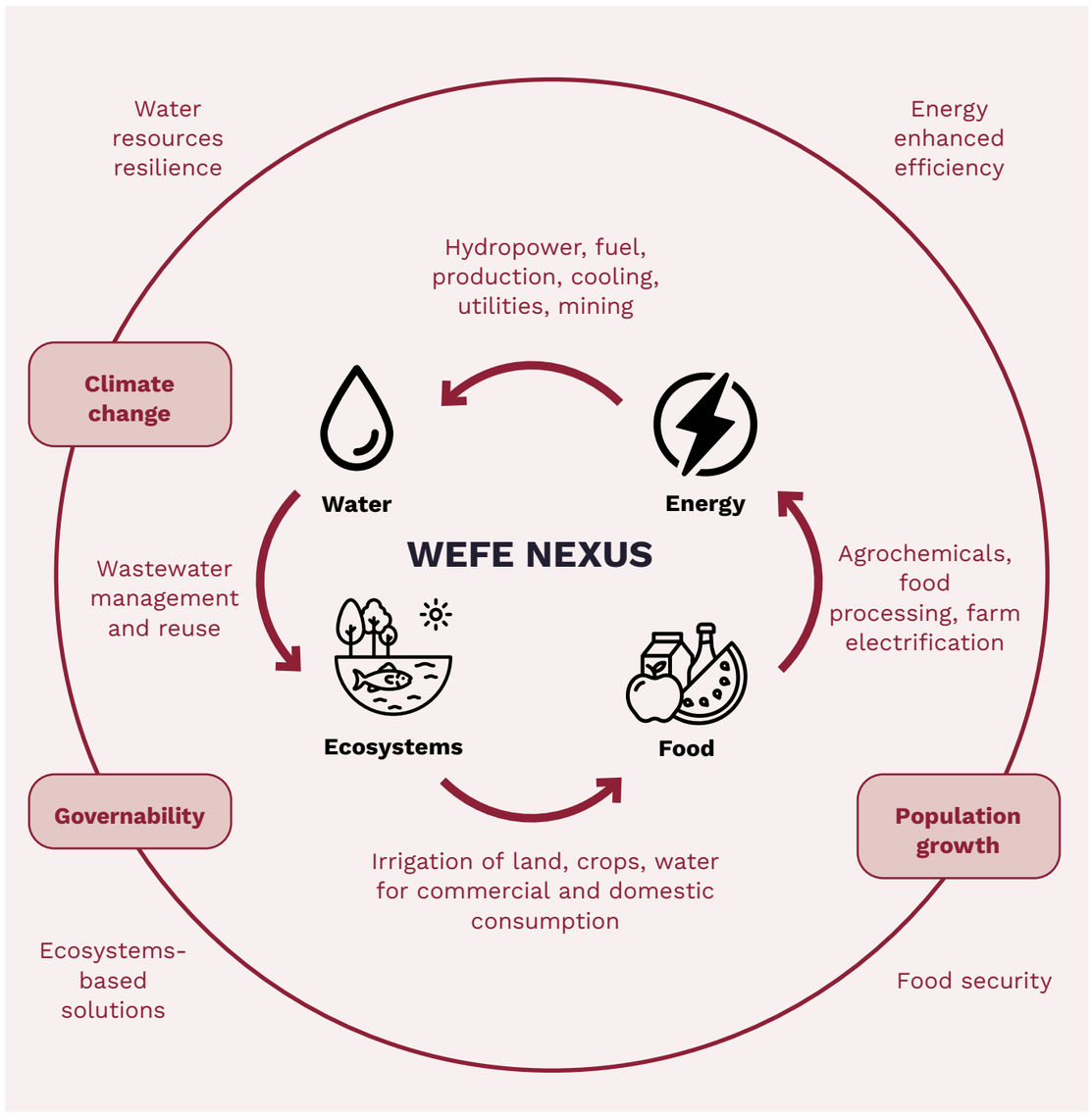
UNDERSTANDING THE TWO FRAMEWORKS

IWRM advocates for a holistic view, coordinating the development and management of water, land and other resources. Its fundamental aim is to enhance both economic and social well-being without compromising the environment – a key principle highlighted by the United Nations Environment Programme. Crucially, IWRM moves beyond treating water merely as a consumable commodity; it recognises its significant social and economic value and acknowledges the deep interconnections between dependent sectors – namely, agriculture, energy and household needs.[1]



▲ **Figure 1. Integrated water resource management needs to account for climate variabilities within the hydrological cycle.**

The IWRM framework requires accounting for climate variabilities within the hydrological cycle (see **Figure 1**). IWRM takes a holistic approach, coordinating the development and management of water, land and related resources.[2]



▲ **Figure 2. The water–energy–food–ecosystems (WEFE) nexus illustrating the interconnections and interdependence between systems. (Adapted from Podvin, 2023[4])**

The WEFE nexus framework illustrates the vital interdependencies between its three core systems. Agriculture, for example, consumes over 70 per cent of global freshwater and requires substantial energy for irrigation, fertiliser production and distribution of agricultural products.[3] Conversely, energy generation often requires water, and the way we produce and consume food directly influences both water and energy demands (see **Figure 2**).

In the UK, the WEFE nexus is gaining traction among researchers and policy-makers. The Royal Academy of Engineering consistently highlights the necessity of joined-up resource management to address climate challenges and ensure equity. This nexus approach encourages planning across standard sectoral silos, focusing efforts on promoting efficiency and sustainability.[5,6]

DROUGHTS AND AGRICULTURAL VULNERABILITY

The UK has been severely affected by recent drought episodes, which have exposed the vulnerability of the agricultural sector. The summer of 2022 was a critical period, characterised by minimal rainfall that resulted in widespread crop failure and significant distress for livestock. This extreme weather led to depleted rivers and drastically lowered groundwater levels, sparking intense anxiety among farmers over securing enough irrigation water and ultimately impacting overall food production.

The challenges were compounded in 2023, with the Environment Agency declaring that spring the driest since 1959.[7] This exacerbation of water scarcity necessitated the introduction of emergency regulations. Farming communities in key areas, particularly East Anglia and Lincolnshire, suffered the worst consequences, with some reporting devastating crop losses of up to 50 per cent.[8]

Inadequate water supply leads to reduced crop yields and poorer quality and unpredictable harvests. Livestock health is also jeopardised by heat stress and water shortages. Financially, farmers face continuous significant strain from broken government promises, logistics and supply chain contracts, market volatility and increased operating costs. Furthermore, dry soil is more susceptible to erosion and nutrient loss (e.g. nitrogen, phosphorus, potassium, calcium, magnesium and organic matter). Plants rely on these key nutrients, and their removal reduces soil fertility and crop productivity. These effects clearly demonstrate the urgent need for smarter water management and robust contingency planning in UK agriculture.[9]

GRASSROOTS SOLUTIONS

UK farmers have been actively addressing water scarcity by investing in on-farm reservoirs. These structures are designed to store rainwater captured during periods of abundance for crucial irrigation use during the drier summer months. While representing a significant investment – sometimes exceeding £250,000 – they provide farmers with essential control and resilience, particularly for high-value crops such as potatoes and vegetables. For instance, during the 2022 drought, farmers in Norfolk and Lincolnshire with on-site reservoirs were able to maintain irrigation, saving both their crops and supply contracts. (see **Figure 3**).[10,11] Furthermore, some farmers are collaborating, sharing the costs and infrastructure in a growing display of community effort.

SUPPORT AND PLANNING CHALLENGES

In a significant move, in 2025 the UK Government announced its commitment to fast-track the development of new major reservoirs – the first such projects in over 30 years.[1] Two large schemes in East Anglia and Lincolnshire were designated as nationally significant infrastructure projects to prioritise addressing water security for both agriculture and households. However, several barriers persist. The process for obtaining planning permission remains arduous, involving complex environmental impact assessments and substantial bureaucracy. Financing is a major challenge, as the up-front capital costs for reservoir construction are high, and sufficient financial support is currently lacking. There are also ongoing ecological concerns regarding the potential impact of abstraction and construction on aquatic life and biodiversity. For long-term sustainability, these reservoirs must be integrated into broader catchment management plans that consider the entire ecosystem.[12]

APPLYING THE FRAMEWORK PRINCIPLES

Both IWRM and the WEFE nexus champion resource efficiency. In agriculture, this translates to practices like precision irrigation, which uses drip systems and soil sensors to dramatically reduce water wastage. Farmers are also increasingly adopting solar-powered pumps to cut costs and reduce carbon emissions. The use of data analytics, including artificial intelligence forecasting and satellite monitoring, is also positive for efficiency, helping to target water application where it is most needed. These innovations align perfectly with IWRM's focus on sustainable and equitable resource management.

A key principle is ensuring equitable access to water across all farming communities. Smaller farms often lack the capital for large reservoirs or sophisticated technology. Collaborative efforts, such as sharing equipment or building shared infrastructure, can help bridge this financial gap. Effective resource management also demands

▲ **Figure 3. A small reservoir in Penmaen. © Wirestock | Adobe Stock**

cross-sectoral teamwork. The Nexus Resource Platform advocates for farmers, energy providers and water authorities to cooperate on planning.[4]

When strategies are developed jointly, water provision does not just benefit crops; it can also support energy projects and improve overall environmental health. Jointly developed strategies allow water provision to nourish crops, power energy projects and restore environmental health. Shared planning allows water to be used for irrigation, hydropower and cooling systems, and supports energy projects while reducing waste. At the same time, integrated management protects ecosystems, improving soil health, biodiversity and water quality.

The protection of aquatic ecosystems is central to IWRM. Reservoirs and irrigation schemes must be designed to minimise ecological disruption. Furthermore, implementing nature-based solutions – such as wetland restoration, agroforestry and riparian buffer zones – can significantly enhance natural water retention and bolster biodiversity.

POLICIES AND STRATEGIC FRAMEWORKS

The Environment Agency's National Framework for Water Resources provides a comprehensive strategy for achieving resilient and sustainable water supplies in England.[2] Its core aims include integrated planning, ensuring sectoral water-use alignment, protecting rivers, aquifers and wildlife, and actively involving stakeholders (farmers, communities and businesses). Adhering to IWRM principles, this framework serves as a vital blueprint for building stronger, more reliable agricultural hydro systems.

The UK Government has introduced several policies to encourage water-saving practices in farming. Environmental land management schemes offer payments for water stewardship. Catchment-sensitive farming provides advice and funding specifically aimed at reducing agricultural pollution. Additionally, water abstraction reform is underway to update licensing to better reflect environmental capacity.

The UK's ongoing water abstraction reform is designed to modernise licensing by integrating it into the environmental permitting regime, creating a consistent framework.[13] Under the reform, the Environment Agency will gain stronger powers to vary, reduce or revoke licences if ecosystems are at risk or river flows fall below ecological thresholds.[14] Licences will also become more adaptive, reflecting climate change impacts, drought conditions and seasonal water availability, rather than remaining static.[13-15]

Farmers, industry and leisure operators will be required to demonstrate sustainable practices and comply with stricter monitoring and reporting requirements, while abstraction decisions will be aligned with river basin planning to balance human needs with ecological health.[16] A paradigm shift is intended to ensure that water use matches environmental capacity, preventing excessive abstraction and improving resilience in the face of climate pressures. Consequently, effective regulatory enforcement will be paramount, requiring enhanced resources for environmental agencies to manage the increased reporting burden and ensure compliance across all sectors.[15]

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CHALLENGES AND OPPORTUNITIES

Despite progress, significant obstacles hinder the widespread adoption of IWRM and the WEFE nexus. Governance is fragmented, with water, energy and food policies often operating in isolation. There is also a notable data deficit, with poor connectivity between information streams related to these three sectors. High initial costs for new infrastructure and technology present a financial barrier. Finally, a general lack of public awareness regarding the interdependencies of water, energy and food impedes collective action. Overcoming these requires genuine policy reform and capacity building.

Transitioning to smarter water management offers substantial rewards. It enhances resilience against extreme weather events (both droughts and floods), stabilises food production by ensuring reliable water access for crops, and provides clear environmental benefits through planned resource use and ecosystem protection. Economically, greater efficiency allows UK agriculture to maintain its competitive position. By fully embracing IWRM and the WEFE nexus, agriculture and its downstream industries can secure their future and become leaders in sustainable resource management.

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How weed science research aids agricultural systems

Lynn Tatnell challenges us to look differently at weeds and how we control them.

There has never been a more exciting time to work in weed science. Farming systems are changing dramatically, and there are multiple new technologies that are becoming more readily accessible to farmers to aid in the challenge of weed control. However, it is important not to forget that there is a never a quick fix with weed management and that a planned approach across a rotation will always pay off in the long run.

THE LIFE CYCLES OF WEEDS

Weeds compete with the crop for resources such as light, water and nutrients. Left uncontrolled, weeds will result in a lower crop yield and can hinder harvesting, as they can often still be green and clog up machinery. In the UK the main species found in arable (cereal and oilseed) crops include grasses, such as black-grass, wild oats, Italian ryegrass and bromes, and broad-leaved weeds such as poppy, chickweed, mayweed, cleavers, speedwell and shepherd's purse. Many of these species favour the autumn planting of cereal crops and prefer to germinate then. In horticultural systems (such as field vegetables) similar weed species occur; however, many vegetable crops are sown in the spring, so the weed species spectrum may favour more spring-germinating species such as fat hen, orache, black bindweed and spring wild oats.

For conventional farmers, herbicides have always been the most economical and effective way to control weeds in their crops. Herbicides are relatively cheap compared to purchasing expensive machinery for mechanical weed management and so are still the go-to control method. However, an over-reliance on chemical control and the use of a limited number of chemical modes of action has resulted in widespread herbicide-resistant weed populations in the UK.[1] These include several different annual grassweed and broad-leaved weed species. This has been further exacerbated by relatively limited crop rotation and no additional cultural control options, such as cultivations or delayed drilling.

When weeds are not controlled, they can complete their full life cycle in the crop and shed their seed into the soil. The weed seed bank is therefore always increasing. Different species have different seed longevity. For example, most grassweeds have a persistency of about 3–5 years, but some broad-leaved weed species such as common poppy have seeds that remain viable in the soil for decades; when conditions are favourable to them, they will germinate and grow in the crop.

CULTURAL WEED CONTROL

One way to overcome herbicide resistance is to reduce the reliance on chemical control and to increase the use of alternative methods, which are often biologically driven. These include cultural control tools such as varietal choice, sowing density and timing of sowing, which can all lead to weed suppression by lowering the number of weeds that can germinate from the seed bank.

One method that fits into the cultural control category but is often not considered a weed-control tool is grass and herbal leys in arable rotations – a grass crop as opposed to a combinable crop, which may be grazed or cut. These have the benefit of keeping weed seeds buried in the soil for several years, so there is natural decline of the seed bank through decay and predation. While this may not be suitable for all arable farmers, it has increased in popularity in recent years through the availability of subsidies for planting certain seed mixtures (sometimes referred to as cover crops or legume fallow mixtures). These systems have been closely monitored by weed scientists to determine their success in declining weed seed banks and to ensure plant species from the sown mixes do not themselves become weeds for future cash crops.

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There has been a more recent trend in arable farming systems towards reduced soil tillage, which is primarily done to retain soil structure and moisture. This has a big impact on the weed flora in a field, as the movement of soil and depth of cultivation will encourage weed species to germinate. With reduced tillage there is less mixing of the weed seed bank. On the one hand this may result in a natural decline of weed seeds at a lower depth but, on the other, if pernicious grassweed species (e.g. black-grass and Italian ryegrass) are allowed to set seed and not ploughed deep into the soil, they are more likely to germinate and grow into the next crop.

Understanding the biology of each species offers the opportunity to 'trick' the weeds by providing the perfect conditions to let them chit (i.e. germinate and sprout) and then destroying them, either mechanically or chemically, before the crop is even sown. The biology of different species has been studied extensively by weed scientists and is well-documented in scientific literature and guides, but we are constantly learning about how weeds can adapt and change to gain a competitive edge.[2] Weeds are extremely clever plants, and we need to keep pace with their adaptive abilities to stay one step ahead!

THE OPER8 NETWORK

Alternative methods of weed control are abundant but there are often barriers to their uptake. The recent Oper8 project, funded by the EU's Horizon Europe initiative, has created an EU-wide network for alternative weed management solutions, promoting alternative options to benefit farmers, advisers, researchers, government and the wider industry.[3]

The project began with a survey across seven countries to determine the needs and barriers to uptake of alternative methods. The results highlighted that these included overall cost, as they can involve the purchase of additional equipment; lack of access to equipment without an opportunity to test before purchasing; perceived reduced efficacy compared to herbicides; and a lack of available information. Potential solutions included grants for purchasing equipment, access to field trials, and demonstration events to see the equipment in action.

The Oper8 project filled this gap by providing multiple on-farm demonstration events to allow farmers to see equipment and learn about new techniques. The survey output also highlighted a need for increased access to information (both online and physical resources), consultations with specialists or users with experience of the technique or equipment, and recommendations from other farmers. Other aspects of the Oper8 project required a weed science input into the production of fact sheets, practice abstracts, and an e-learning module for weed-control solutions in arable, horticultural and perennial crops such as vineyards, which are all available online. Projects such as this are providing tools to support farmers and growers to integrate weed management options into their operations.

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THE FUTURE OF WEED CONTROL

The past decade has seen exciting changes in the technology available for weed management. This includes robots (both autonomous systems and robotic weeding on tractor-mounted systems), electrical weeding, laser weeding and many precision-spraying developments (targeted spot spraying in particular).

Electrical weeding was first used in the UK in the 1970s, but at the time the herbicide glyphosate was being launched, and it was so successful and considered cheap and easy to use that alternative options were not considered by growers. Now, with concerns of herbicide-resistance risk and wider environmental awareness there is a need to reduce reliance on glyphosate, and so interest in effective alternatives is increasing. The first electrical weeding trials phase used a hand-held probe system and a tractor-mounted rig – essentially, a piece of wire attached to a control system on the back of a tractor. The trials focused on controlling perennial weeds, mainly creeping thistle and docks in blackcurrants.

RootWave has since advanced this technology through many prototypes, and commercial equipment is now available. This includes a hand-held lance for the amenity markets and a tractor-based machine for orchards and vineyards (and other perennial crop rows). RootWave is now collaborating with Garfords to bring this technology into horticultural field and arable crops.[4]

Precision spraying is continuously improving, with advances in technology such as cameras and state-of-the-art detection software that can recognise weeds among crop plants and treat them in real time. This eliminates the need for field mapping of weeds, saving time and resources and allowing growers to apply less pesticide

▲ **Phacelia growing in a field: a ley, or cover crop/green manure, which also benefits pollinators. © Alan | Adobe Stock**

to crops and potentially extend their options for herbicide use. An example of this is the EcoRobotix ARA equipment currently used in field vegetables, which claims to reduce pesticide use by 95 per cent, and which uses targeted spraying to reduce the levels of residual non-selective herbicides in the whole crop, reducing crop phytotoxicity.[5] The spray nozzles are shielded by a hood, so any potential spray drift is minimal, and weed target precision is extremely high.

Another system used in arable crops is John Deere's See & Spray™ system, which can be activated for targeted spraying and use only certain nozzles to spray on detection of a weed. However, the same system can also be used as a 36-metre-wide conventional sprayer. The in-cab display unit records where herbicide has been applied, providing a spray map of the field, which is a useful tool for the farmer for future weed management planning.

The world of weed science is an ever-changing, exciting area for research scientists. New technologies are emerging all the time, but it is important that they are tested in field trials to produce robust data to support farmers' decision-making for future weed-control programmes. However, it all comes back to having a deep understanding of the biology of different weed species to be able to give informed practical advice to farmers and growers.

With this biology knowledge, scientists can predict how a change in agronomic system or weed-control method would impact the weed population in a given field. The use of integrated weed management in any farm planning system is vital; it is not a short-term strategy, but a long-term project that must be planned carefully if it is to succeed. By preventing weeds from seeding and shedding seeds into the weed seed bank, the cycle can be broken. But it does require determination if we are to outsmart those clever weeds! ES

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